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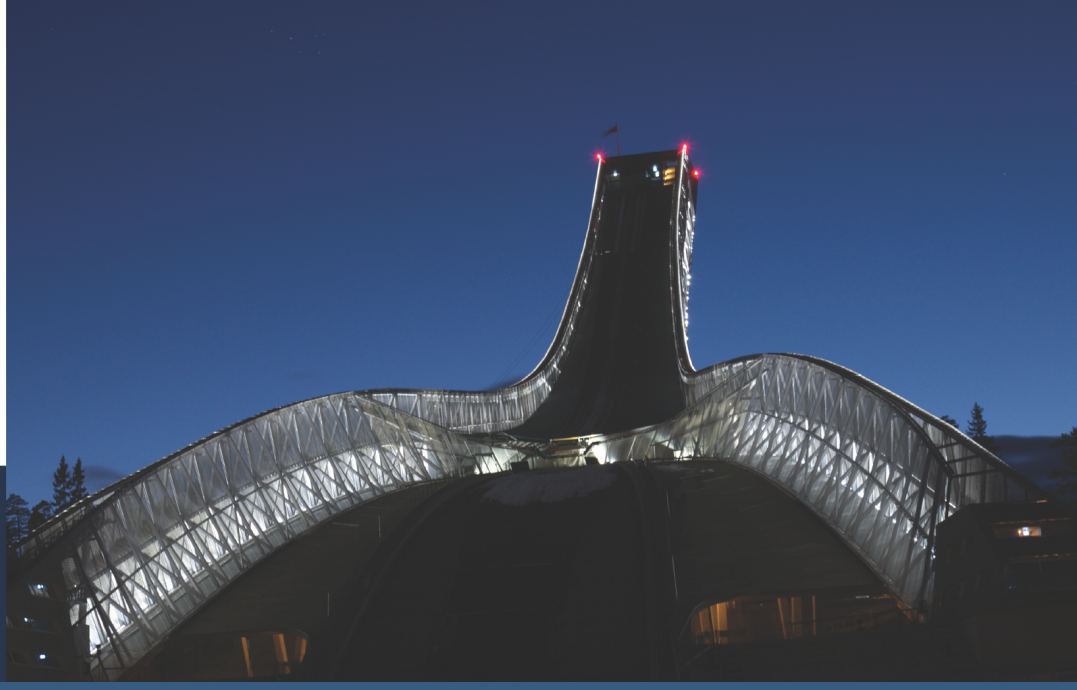

Abstracts and Proceedings of the Geological Society of Norway

The 34th Nordic Geological Winter Meeting

January 8th-10th 2020 , Oslo, Norway

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Edited by:
Hans Arne Nakrem and Ann Mari Husås

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34th Nordic Geological Winter Meeting

Oslo, January 8th-10th, 2020

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DEAR FRIENDS AND COLLEAGUES

Welcome to the 34th Nordic Geological Winter Meeting in Norway January 8-10, 2020. The meeting is organized by the Geological Society of Norway and is hosted by the University of Oslo as a joint effort between the Department of Geoscience, the Natural History Museum and the Science Library.

There is increasing awareness of the critical role of geoscience in addressing major challenges under the UN Sustainable Development Goals. The meeting covers a wide range of geological topics and is an arena for all disciplines in the field of geoscience, with the goal to contribute to knowledge sharing, networking, inspiration and professional fulfilment. At the conference you will meet geoscientists from all parts of our society – from academia, research institutes, industry, public administration, school administration and others. The posters will be displayed during the entire conference, providing ample time and opportunities for discussion on various topics of interest.

We hope you will join us for the social activities. The Ice Breaker Party on Wednesday afternoon will start just after the end of the conference day and will be arranged at the Science Library. The Conference dinner on Thursday will be at Gamle Logen, a grand building in the old part of Oslo.
At the opening session on Wednesday we are proud to present professor in bioscience, Dag O. Hessen giving the plenary talk on “Carbon and life - and intertwined history”. The plenary talk on Friday will be by the winner of the Nordic Geoscientist Award 2020. The winner will be announced at the conference dinner. There will also be several key-note speakers under the different sessions.

We thank all our sponsors for supporting us economically to arrange this conference, we are very grateful for your valuable support!
We also thank the many, many people that already put a lot of time and effort into the preparation of this conference: the organizing committee, the scientific committee and the local organizing committee.
We are happy to continue the long and proud history of The Nordic Winter Meeting, and we look very much forward to see you all here in Oslo. We wish you all a successful, scientifically rewarding, interesting and pleasant conference.

Brit Lisa Skjelkvåle
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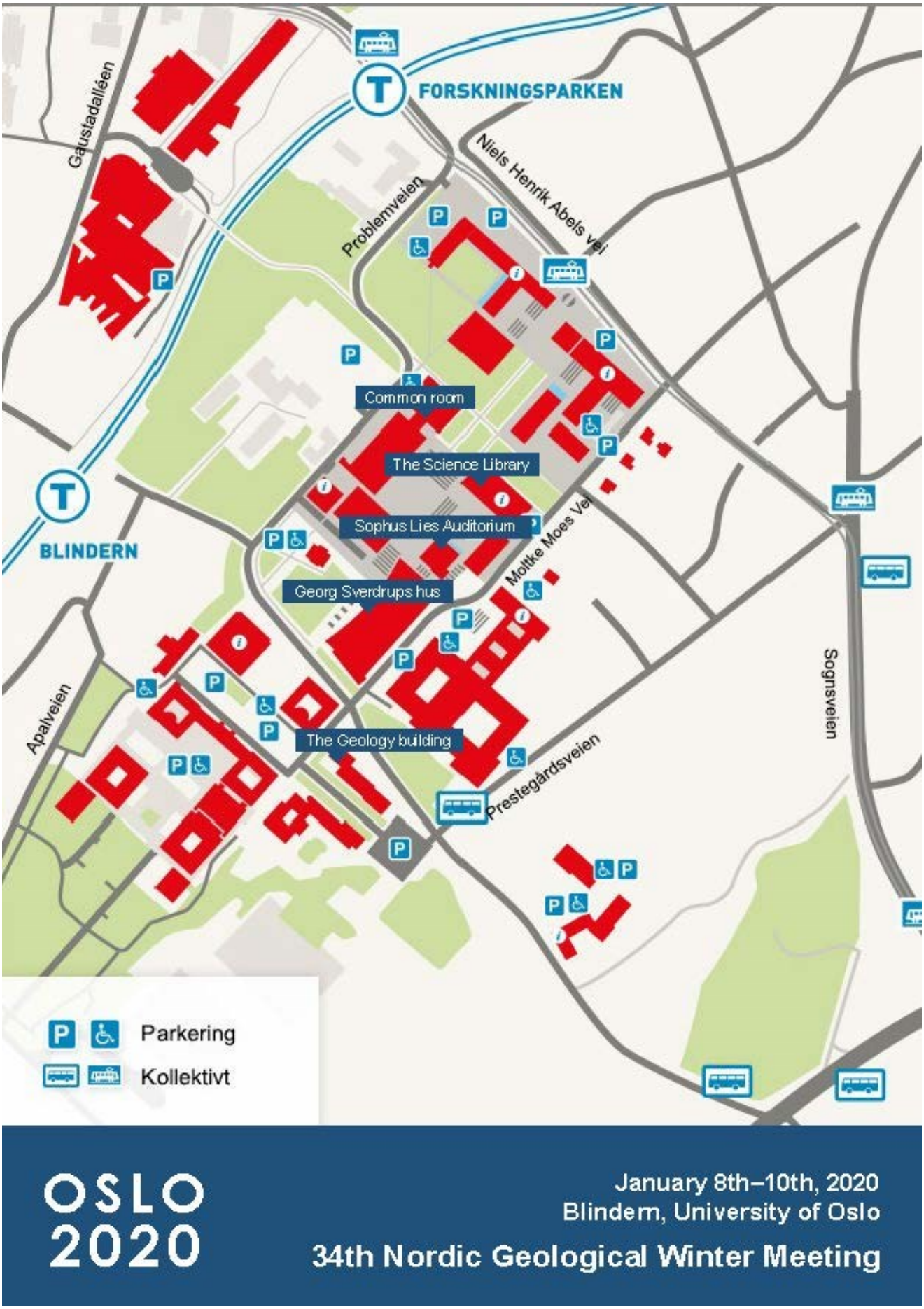
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Contaminant transport in groundwater – reactive groundwater transport in heterogeneous systems

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The dual porosity approach has been applied in solute transport in heterogeneous rocks, sediments and soils for quite some time (Gerke & van Genuchten, 1993). Evidently, transport simulations in fractured rock need the dual porosity concept (Gaus et al., 2000; Lipson et al., 2007), but also porous aquifer simulations on uranium contaminant remediation required a dual porosity (Johnson et al., 2016). Dual porosity schemes with biochemical processes have also been applied (see review by Steefel et al., 2015) Lately, biochemical processes have been simulated even down to pore-scale heterogeneities (Gharasoo et al 2015).
We have re-analyzed previous degradation experiments (Knudsen, 2003; Aagaard et al., 2005) of dissolved jet-fuel components in apparently rather homogeneous aquifer material, but where we observed that aerobic pyrite oxidation occurred at the same time as reductive dissolution of ferric hydroxide. This indicated simultaneous aerobic/anaerobic reactions in adjacent micro-domains. The column experiments reported in Knudsen (2003) have now been simulated by 1D-PHREEQC run with dual porosity. Biodegradation was expressed by Monod kinetics with growth, inhibition and decay terms. Reaction parameters were both taken from the literature and estimated by PEST, following the scheme used by Knudsen (2003), but adding mobile/immobile properties. Simulation results demonstrated that the apparent redox inconsistency noted by Knudsen (2003) can now be explained by mixing from mobile/immobile parts. These results call for more detailed analysis and application of dual porosity in hydrogeology and groundwater reactive transport.

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Holocene paleoenvironmental reconstruction from laminated lake sediments, Bødalsvatnet, Nordenskiöldland, Svalbard

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The Artic is warming faster than any other region on the globe and the arctic environment is very sensitive to local changes in the climate (Førland et al., 2011). Changes that can be seen in the local hydrology by a change in peak stream flow from spring snowmelt to late summer and/or fall rainfall (Nowak & Hodson, 2013). Local changes in hydrology and climate can be reconstructed using a number of proxies. In this study varved sediment from the proglacial lake Bødalsvatnet located in Nordenskiöldland central Spitsbergen, Svalbard is used to provide an annually paleoclimate record that indicates melt season processes and summer conditions. In April 2019 a surface core of approximately 52 cm from Bødalsvannet was collected and transferred to Bates Collage, US and University of Massachusetts – Amherst, US for core analysis. The surface core was split in half and visibility

logged, and thin sections were taken to log varve count. One half of the core was scanned with compositional analysis using ITRAX core scanning x-ray fluorescence. Magnetic susceptibility, bulk density and grain size were also measured every 1 cm. The results from Magnetic susceptibility and Grain size will be compared to results from analysis of surface cores from 2015. ITRAX results will be compared to a longer precession core collected in 2012. This study and its results are part of a larger regional study "Arctic hydrological regime shift in a warming climate" at western and central Spitsbergen. The study aims to determine the timing and impact of the warming trend and recent hydrological shit and place recent hydrological events in a longer-term context of the late Holocene.

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North Atlantic-Arctic tectonics related to the wider Barents Sea paleogeography and basin evolution

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The North Atlantic-Arctic region comprises a wide range of crustal structures and sedimentary basins developed as a result of a series of post-Caledonian rift episodes until early Cenozoic time. This complex tectonic history involves a variety of geological processes operating at different temporal and spatial scales. In order to understand the evolution of the region a multidisciplinary approach, including kinematic and paleogeographic reconstruction, should be applied. For the kinematic reconstruction, the post-Caledonian history of the region has been largely dominated by rifting as well as major extrusive and intrusive magmatic emplacements. Critically, Greenland lies at the centre of this region and its evolution is key piece for unlocking the kinematics of the surrounding regional puzzle. To the north of Greenland, the Eurekan Orogeny is a reconstruction challenge due to the heterogenous, distributed deformation and implications for proximal strike-slip motion.

To reconstruct the basin evolution and construct well-constrained paleogeographic/-tectonic maps we have to quantify the pre-drift extension through time and space. This is done using various techniques where the observed geometry of crustal thinning is compared to a reference thickness of the crystalline crust close to onshore areas, which have experienced limited or no crustal extension since Permian time, and tectonic modelling.

Ultimately, this workflow will deliver a new generation of paleogeographic maps and a discussion about the implications for the regional basin evolution and provenance (source-to-sink), including the role of structural inheritance, varying regional stress fields and North Atlantic- Arctic region.

Early Ediacaran age of the Nyborg Formation (Finnmark, Arctic Norway) confirmed via organic-walled microfossil biostratigraphy

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The Neoproterozoic strata in Finnmark, Norway provide a good sedimentary record of late Neoproterozoic glaciations on Baltica. The lower Vestertana Group exposed on the Digermulen Peninsula contains two such glaciogenic units, Smalfjorden and Mortensnes formations. Former studies applying chemostratigraphic correlation dated the Smalfjorden diamictite as Cryogenian Marinoan glaciation (650-635 Ma). However, its age was also proposed to be older, per correlation to glacial units in central and southern Scandinavia. The Vestertana Group diamictites are bracketing

shales and siltstones of the non-glacial Nyborg Formation.
Stratigraphic, palaeontological, and sedimentological data from the interglacial-glacial succession were collected and analysed for better temporal constraint on the age of these units, and an understanding of the extent of biotic changes through an interval of intense climate change at the end of Precambrian. Palynological analysis yielded well-preserved organic-walled microfossils (OWM) from the Nyborg Fm., and the fine-grained diamictite matrix in the Mortensnes Fm. using a modified extraction method.
The Nyborg Fm. hosts a moderate diversity of prokaryotic and eukaryotic microfossils, as well as diagnostic early Ediacaran acanthomorphic acritarchs (*Ceratosphaeridium*, *Eotylotopalla*, *Galeasphaeridium*), and a novel process-bearing form. These taxa are also present in early Ediacaran successions on the Eastern European Platform, Siberia, and China. Enigmatic organically-preserved, multicellular, eukaryotic microfossils also occur in the upper Nyborg Fm. The Mortensnes Fm. glacial assemblage is less diverse, dominated by bacterial filaments and cellular aggregates, and also contains leiosphaerid acritarchs and toroidal morphotypes.
The presence of Doushantuo-Pertataka type acritarchs in the Nyborg Fm. corroborate an early Ediacaran age for the interglacial-glacial succession on Digermulen. Along with trace and body-fossil record of Ediacara-biota in the overlying Stáhpogieddi Formation, the OWM biostratigraphy suggests Marinoan and Gaskiers glaciation equivalent ages for the Varanger glaciations in Finnmark. Diversity of microscopic eukaryotes recorded in the succession declined through and following the glaciation, until late Ediacaran.

Murtoos and subglacial meltwater routes are significant geomorphological features in the trunk area of the Finnish Lake District Ice Lobe

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Murtoos are new distinct landforms that occur in fields. The distribution of murtoos has been recently mapped in both Finland and Sweden utilizing LiDAR data. Based on their morphology and distribution, these landforms seem to present a continuum between distributed and channelized meltwater flow. This highlights their importance for the understanding the subglacial hydrology of the past glaciers and the behavior of the present and rapidly melting glaciers. Murtoos are present in routes that vary in length and width as well as in their morphology and margins. These routes haven't been previously mapped in detail in Finland. The role of these routes for the subglacial hydrology is still unknown. Therefore, we started the mapping of these routes from LiDAR data in the Finnish Lake District Ice Lobe (FLDIL) area. Ground penetrating radar profiles obtained in autumn 2019 supplement the mapping. We mapped the route positions by defining the position of the central axis of the route. The routes were preliminary divided into four classes which are: 1) the routes with murtoos 2) the routes without murtoos but with erosional escarpments 3) other routes 4) short and/or indistinct routes. The margins of the routes were not defined due to their varying character and difficulties in distinguishing the margin position. Several routes were found in the trunk area of the Finnish Lake District lobe. These routes were ca. 2-35 km long and 0,2-5 km wide. The routes were mostly found within the hummocky moraines flanking the eskers. The murtoos form distinct fields that are present only along the mapped routes. Single murtoos also occur outside the routes, but are rare. The routes had clear connections to current lake basins, river valleys and eskers. They also display branching patterns where routes are interconnected. Most of the routes in classes 1 and 2 have concentrated on the northeastern flank of the FLDIL. The routes have both incised into the substrate and have positive forms. The connections to topographical lows (lakes, river valleys) and to eskers imply the significance of these routes to subglacial hydrology. In addition, the low areas may present positions of former subglacial lakes that drained through the routes. In the future, we will map the routes in whole Finland. This will allow a thorough understanding of the nature of these routes, their relation to glacial dynamics and subglacial hydrology.

Holocene environmental history of lake Femmilsjøen, northern Svalbard

Allaart, L.[1,2,]*, Schomacker, A.[1], Forwick, M.[1], Rydningen, T.A.[1], Farnsworth, W.R.[3], Retelle, M.[2,4], Håkansson, L.[2], Brynjólfsson, S.[5] & Kjellman, S.E.[1]

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The 8-kilometer-long lake Femmilsjøen on the northern part of Svalbard contains an almost complete sedimentary record of the Holocene, recording the history and evolution of the >1000 km^2 Åsgardfonna ice cap. Femmilsjøen is one of the largest and deepest lakes on Svalbard, and it was isolated from Wijdefjorden due to postglacial glacioisostatic rebound around 11.5 cal ka BP. The main basin is east-west oriented, and a smaller northern sub-basin is separated from this by a shallow threshold of less than two m water depth. The surge-type glacier Longstaffbreen, one of the outlet glaciers of the Åsgardfonna ice cap, terminates in the eastern end of the lake. We present sub-bottom profiler data and single beam bathymetry from the main basin and the smaller sub-basin, as well as sediment core data from the sub-basin. The acoustic data reveal several ridges oriented perpendicular to the long axis of the lake, and acoustically stratified deposits filling the depressions between the ridges. The sedimentary record varies between gyttja-clay, claye gyttja and silty clay, reflecting a changing lacustrine environment in the Femmilsjøen sub-basin through the Holocene. Both the landform assemblage and the stratigraphy are correlated to the adjacent Wijdefjorden, in order to highlight similarities and differences between the Holocene environmental evolution in the fjord and in the lake. Taken together, the results from Femmilsjøen and Wijdefjorden give valuable insight on the Holocene environmental history of northern Svalbard.

Mesoproterozoic to late Paleozoic fault activity in central Sweden recorded by K -Ar dating of fault rocks

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The timing of brittle deformation events in the Fennoscandian shield is poorly constrained and based on only a few studies applying isotope geochronology to date brittle deformation. We present new results from central Sweden obtained by K-Ar geochronology of authigenic and syn-kinematic illite separated from fault rocks from key regional faults. The new dates are from the E-W striking Söderström fault (Stockholm), the Lovisa mine fault in central Bergslagen and two faults in the crystalline basement in Jämtland county that indicate reverse and normal sense movement, respectively. Clay minerals were separated from gouge samples into five different size fractions ranging from <0.1 mm to 6-10 mm, and their mineralogical composition was determined by X-ray diffraction. Dating of clay mineral fractions of two Söderström fault samples yielded ages from ca 661±9 to 362±5 Ma and ca 794±10 to 449±8 Ma, respectively. The finest fractions of the sample exhibiting the younger ages are composed mainly of illite and illite-smectite, and yield ages of 362±5 Ma and 393±6 Ma. The two coarser fractions mainly host K-feldspar as K-bearing phase and have ages of 647±9 Ma and 661±9 Ma. The second sample from the Söderström fault yields ages of 794± Ma and 755±10 Ma in the coarser fractions, whereas the finer grain size fractions yield younger ages, down to 449±8 Ma. Samples from the Lovisa mine fault show a large range in ages, from 1339±14 Ma to 295±20 Ma. The finest grain size fractions in the younger sample contain illite as the K-bearing phase and produce ages that may correlate with Permian rifting of the Oslo Graben. However, the finest grain size fraction of the second Lovisa mine sample yield an age of 891±18 Ma, ascribable to the late Sveconorwegian Orogeny. Samples from Jämtland are from faulted diabase dikes in basement granite, situated less than 20 km east-southeast of the present-day limit of the allochtonous units in the Caledonian front. Ages range from 822±12 Ma, in coarser fractions, to 425±6 Ma, in finer fractions (dominated by illite/muscovite). Ages obtained from the finer fractions can be related to brittle deformation during closure of the Iapetus Ocean and the onset of continental collision and nappe emplacement (ca 425 Ma) well within the Caledonian foreland. K-Ar ages obtained from the fault gouges in this study provide new insights into the brittle deformation history of central Sweden, which spans more than 1 Ga.

Is detrital zircon a reliable "source-to-sink" indicator?

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Detrital zircon has become a popular tool to trace the routing of clastic sediment "from source to sink". In most provenance studies based on detrital zircon U-Pb and Lu-Hf data, the argument must necessarily go the other way, from observation in the ”sink” - i.e. the age and epsilon-Hf distributions of zircons in the sediment - to some rock in crystalline basement with properties that match the observations, and which is thus a possible "source". Data on detrital zircon reflect the properties of the *protosource* (the rock in which the zircon originally formed) and not necessarily those of the immediate source that has supplied material to a sedimentary basin. If recycling of one or more intermediate sedimentary precursor(s) has taken place, the protosource information to be obtained from detrital zircon may be irrelevant for the problem of sediment transport to the final basin. There is an increasing amount of evidence that long-range and long-lived recycling processes may be the rule rather than the exception. For example, in southern Africa, such a recycling system has been active from ca. 700 Ma to the present day (Andersen et al., 2018).

The survival of zircon in the sedimentary environment is dependent on its crystalline state, radiation damaged zircon grains being far less resistant to abrasion during transport that fully crystalline grains. The degree of radiation damage depends on the accumulated alpha dose of the crystal (D_α), which is a function of age and U and Th concentration. Markwitz and Kirkland (2018) compared zircon age distributions in known source rocks to those of sediments derived from these sources. They found that zircons having accumulated $D_\alpha > 3 \cdot 10^{18}$ α/g were systematically depleted in the sediment relative to the source. This suggests that sedimentary transport may cause significant fractionation of detrital zircon populations, in which old and / or U-rich grain fractions are selectively removed.

Detrital zircons may give important information on, for example, the history of continental cover successions through time, but they are at best an unreliable and potentially erratic "source-to-sink" indicator which should not be used without support from other methods.

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Relicts of mafic-ultramafic cumulate rocks in the Romerike Gneiss Complex, Norway

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The Mesoproterozoic ("Gothian") Romerike Gneiss Complex consists of calc-alkaline gneisses, migmatites and granitoid intrusions. Small mafic and ultramafic bodies are found close to its north-eastern boundary, defined by the Mjøsa-Magnor shear zone (in Sweden known as the Mylonite Zone). These mafic-ultramafic rocks are very poorly exposed, but stand out as positive anomalies on aeromagnetic maps and ground magnetic surveys. Associated titaniferous iron ore has in the past been mined on a small scale.

Ultramafic rocks consisting of olivine and clinopyroxene with interstitial ilmenite, magnetite, orthopyroxene and minor apatite have preserved cumulate textures and an igneous mineral assemblage that is only partly replaced by metamorphic garnet + amphibole assemblages. Associated gabbroic cumulates are more heavily recrystallized, with abundant garnet and amphibole, and show gneissic foliation.

In the ultramafic rocks, olivine has uniform composition at Fa_{58}. Clinopyroxene has exsolved lamellae of orthopyroxene, and is overgrown by orthopyroxene along grain boundaries. The compositions of clinopyroxene and orthopyroxene are uniform within the individual sample, but show an overall variation from Hd_{29} and Fs_{44} to Hd_{58} and Fs_{48} between samples. There is no difference in composition between orthopyroxene exsolution lamellae in clinopyroxene and newly grown orthopyroxene in the same sample. Clinopyroxene and orthopyroxene geothermometry indicate equilibration temperatures at 800-900 °C, suggesting re-equilibration during cooling of the igneous protolith rather than recrystallization during amphibolite-facies metamorphism. Ilmenite-magnetite pairs give temperatures in the range 710-730 °C. Garnet is uniform in composition in the individual sample, but shows an overall range from $Pyr_{22}Alm_{58}Sps_4Gro_{16}$ to $Pyr_{15}Alm_{63}Sps_4Gro_{18}$. Amphiboles are pargasite to magensio-hastingsite.

The mafic-ultramafic rocks are interpreted as fragments of a larger mafic cumulate body, such as a layered intrusion belonging to the Romerike Gneiss Complex, that has been broken up, deformed and metamorphosed during development of the Mjøsa-Magnor shear zone.

Ore mineral textures, and critical and trace metal chemistry in the stratiform Lovisa Zn-Pb deposit, Bergslagen, Sweden

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The paragenesis, textural evolution, mineral chemistry, and critical and trace metal deportment of the ore assemblages in the Lovisa Zn-Pb deposit have been studied by combining ore microscopy, SEM-EDS, EPMA, LA-ICP-MS, XRD and novel XRT/XRF 3D imaging (GeoCore X10 drill core scanning) as part of the on-going X-Mine project. The X-Mine project is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 73027.

The economic ore in the Lovisa deposit is dominated by sphalerite with variable amounts of galena and pyrite. These assemblages are characterised by textures related to metamorphism and brittle-ductile deformation variably overprinting primary depositional features. Primary textures are readily recognised in the 'Sphalerite Ore' in the form of relict, partly sphalerite-enriched layers. This sequence is stratigraphically overlain by more massive sphalerite-galena ore of the 'Main Ore' showing a distinctive 'Durchbewegung' texture. Other features related to metamorphism and deformation of the ore assemblages include partly cataclastic and porphyroblastic pyrite, folding of primary sphalerite-bearing layers, and remobilisation of sulphides into piercement veins and domains of reduced strain. Late sulphide assemblages comprise fracture fillings with sphalerite ± galena ± pyrite and calcite that locally cross-cut the primary layering. In the Lovisa Fe Formation, which stratigraphically underlies the Lovisa ore zone, a metamorphosed and deformed assemblage of mainly magnetite, galena, chalcopyrite, pyrrhotite and sphalerite is locally cross-cut by discordant complex sulphide-sulphosalt veins. These vein assemblages comprise, amongst others, chalcopyrite, galena, pyrite, a freibergite series mineral, pyrargyrite and other Ag-rich phases.

Of the sulphides at Lovisa, sphalerite is the main carrier of Cd, Hg, In, Mn and Sn, pyrite is the principal host for As, Au and Co, and galena is the primary carrier of Ag, Bi, Sb and Tl. Sphalerite from the Main Ore exhibits the overall highest In concentrations (20 ppm) compared to the Sphalerite Ore (<4 ppm). In the Sphalerite Ore, sphalerite is slightly enriched in As, Bi, Ge, Sb and Se relative to sphalerite from other ore types; pyrite blasts similarly show elevated As, Bi and Se concentrations. The highest Co concentration, reaching 2300 ppm, is hosted by massive pyrite overlying the Main Ore, while pyrite from both ore types shows lower concentrations (<150 ppm). Galena and pyrite from the late sulphide-sulphosalt veins are both characteristically enriched in a similar suite of elements (Ag, Cd, Cu, In, Sb, Tl and Zn; Fe and Mn also in galena) compared to the ore.

Soft docking of Baltica and Avalonia?

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The source area for the Early Ordovician Holberg Quartzite Formation ("høifjeldskvartsen"), part of the Hardangervidda Group, South Norway, is enigmatic. The Holberg quartzarenite deposit is atypical compared with the intra-cratonic shale and carbonate deposits of similarly age in the Oslo Region. A cryptic "Telemark land", located either SE or W of Hardangervidda, has been called upon as a likely source area. Others have linked the Holberg Formation and overlying green calcareous schist to an early Caledonian foreland basin. Based on stratigraphic variations in the detrital zircon populations within the Hardangervidda Group, and sedimentary structures within the Holberg quartzite it is argued that the sand is derived from a forebulge developed south of Hardangervidda as Baltica was thrust underneath Avalonia following closure of the Tornquist Sea. On southern Hardangervidda, between Hallevassbu and Litlos, a series of decollement folds (D2-structures) with axes oriented NW-SE (cross-folds) are developed. These folds are superimposed a more extensive thin-skinned fold-thrust belt with axes trending NE-SW (D1) and reverse faults dipping towards NW. These structures dominate the central and northern Hardangervidda. The D2 structures are interpreted as having developed during progressive subduction of Baltica underneath Avalonia contemporaneous with collision of Baltica and Laurentia during the Scandian phase (Late Silurian/Early Devonian) of the Caledonian orogeny. A commonly observed SE-dipping cleavage (D3) seen in pelitic units throughout Hardangervidda is linked to late-

orogenic collapse of the orogen, most likely of early Devonian age.
Support for the above model is seen in detrital zircon populations within the Hardangervidda Gr.; the Holberg and older formations having a typical Baltican signature, with a dominance of Meso-proterozoic clastic zircons and no Neoproterozoic zircons, whereas the detrital zircon population in the metasedimentary units overlying the Holberg Fm. have a peri-Gondwana signature with a distinct population of Neoproterozoic zircons in addition to Paleoproterozoic and Archean detrital zircons. The Neoproterozoic zircon population is linked to the Cadomian orogeny which affected the margin of old Gondwana prior to opening of the Tornquist Ocean.
It is furthermore speculated that the c. 471-458 Ma old Garborg eclogites within the Jæren Nappe the Stavanger area are derived from a suture zone between Baltica and Avalonia rather than the Iapetus suture zone, as generally thought.

Structural influence on Triassic deposition on the Northern Barents Shelf

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Although generally tectonically quiescent, deposition during the Triassic on the Northern Barents Shelf is far from devoid of structural influence, and there is marked difference between lower and middle Triassic sedimentation. From around the mid-Carboniferous through Early Triassic, southward propagating uplift along N-S oriented elements occurred along the incipient North Atlantic margin, resulted in uplift, tilt and erosion and erosion of the Sørkapp-Hornsund and paleo-Stappen highs, and the Ringsel and Selis ridges. The flanks of these features were progressively onlapped up until the Ladinian. Two structural elements (Selis and Capria ridges) experienced a Late Permian-Early Triassic uplift, pre-dating a phase of uplift of the Gardarbanken high. Triassic deposition across the Gardarbanken high is complex, owing to the advance of the prograding deltaic systems which advanced northwestward across the Northern Barents shelf. Structural influence largely waned through the Ladinian and Carnian, and sediment blanketed large parts of the shelf, although the Svalbard platform remained comparatively shallow as witnessed by lowered clinoform angle and rapid deposition.
Detailed analysis of the Triassic succession on Edgeøya provides some important findings on how the sedimentary architecture and sand distribution in the system was affected by the shallowing across the Svalbard Platform. The tidal signal was amplified, which led to increased sand deposition at the delta-front. The previously dominantly muddy sub-aqueous clinoforms in the compound clinoform system, were replaced by a lower-angled and sandier tidal dune field. The tidal regime kept coarser sediment confined up-river and there is a marked contrast between the distal deep, wide, highly meandering tidal channels with mud-rich inclined heterolithic strata, and the straighter symmetric sand-filled fluvial channels up-river. Limited fluvial influence and sand and mud redistribution by both waves and tides indicates a coast characteristic of an open coast tidal flat setting.

Geosites: How important are they – Really?

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What happens when geosites disappear because of human activities such as infrastructure development? The Norwegian Nature Diversity Act states that nature diversity, including geological diversity, should be included in the management of land-use. However, there is no system to ensure that geosites are considered during the process of producing environmental impact assessments.
Geosites are sites that represent a specific part of geological history. They are important for the nature land-use management and is essential to ecosystem services. A geosite is also an important research site that should be protected for future scientific purposes. Equally important is their value for teaching/communication within the local community to exemplify geological principles or important geological nature experiences through Earth history.
A new model evaluating geosites has been developed in the Interreg project GEARS (Geological Heritage in the Inner of Scandinavia). The model uses both literature and fieldwork studies and has been implemented to a selection of geosites in Hedmark, Norway and Dalarna, Sweden.
The system is composed of a consistent method of mapping and registration, including an unbiased and reproduceable descriptive part as well as an analytical part based on a set of assessment criteria. The challenge is to break down each part to the smallest possible relevant component, that first is described, and then evaluated according to a specific workflow. The analytical assessment must be as objective as possible and subjective information should have minor influence.

When the assessment system is set, a uniform mapping of sites can be performed, and the information can be digitized and stored in a database. This will create possibilities for users to extract the information they require, e.g. specialized maps and combined layers of information that are important for either land-use planning, nature-based tourism or for education.

Cosmogenic surface exposure dating of the deglaciation of Finnmark and Northern Finland

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The northern coast of Finnmark county, northern Norway, forms the northernmost edge of mainland Europe. During the Last Glacial Maximum this region was covered by the Fennoscandian Ice Sheet (FIS), which coalesced with the Barents Sea Ice Sheet (BSIS) off the coast. The region is thus important for our understanding of the dynamic interactions between the BSIS and the FIS, but despite this it remains one of the least dated regions covered by the FIS. In this project, we present 23 cosmogenic surface exposure ages (^{10}Be) from eight localities in northernmost Norway and Finland, and discuss implications for the pattern and timing of ice sheet retreat in the region. The samples were collected along a 240 km long north-south transect ranging from the outer coast of the Nordkinn peninsula (Norway) to Lake Inarijärvi (Finland). With the exception of two old outliers, the new deglaciation ages are reasonably consistent with existing deglaciation chronologies. The new exposure ages indicate deglaciation of the outer coast around 14.5 ka. From there, the ice retreated southward until it reached the Main Line position (Younger Dryas) just north of the Norwegian-Finnish border. South of the Main Line the deglaciation appears to have become more rapid, eventually reaching Inari, at the southern end of our transect, around 11-10 ka.
Highlights:

- Twenty-three cosmogenic surface exposure ages (^{10}Be) from eight localities in northernmost Norway and Finland.
- For the outer coast, our new exposure ages suggest a deglaciation around 14.5 ka, which fits with a deglaciation during Bølling.
- The study presents the first geological ^{10}Be samples measured at the National Laboratory for Age Determination, Trondheim.

Plate tectonics controls on mantle plume dynamics

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Mantle plumes cross the Earth's mantle and interact with the lithosphere. Hence, they potentially carry information on the whole convective system. For instance, it has been proposed that the mobility/stability of plumes depends on plume intrinsic properties, on how slabs interact with the basal boundary layer, on the so-called *mantle wind*, or on mid-ocean ridges.
Here, we build on 3D-spherical models of mantle convection generating self-consistent tectonics to extract the mechanisms linking tectonics to plume dynamics. Our models produce fully dynamic mantle plumes with excess temperatures, rising speeds and buoyancy fluxes comparable to Earth, which rise vertically with deflection < 10°. With stagnant lid, i.e. without plate tectonics, plumes are stable and their lifetime exceeds hundreds of million years. With plate tectonics, plumes are mostly mobile, and we classify them into four groups, corresponding to four physical mechanisms. The first is fixed plumes, located at saddle points of the basal mantle flow. The second group, moves at speeds of 0.5-1 cm yr^{-1}, slowly entrained by passive mantle flow. The third group displays fast motions of 2-5 cm yr^{-1} lasting several tens of Myr, caused by slab push. Plumes from the last group are rare and drift at speeds > 5 cm yr^{-1}, over less than 10 Myr through plume merging. We do not observe systematic anchoring of plumes to mid-oceanic ridges. Both the existence of tectonics or dense chemical material at the base of the system restrict the lifetime of plumes to < 50 My on average. Plume age, temperature excess or buoyancy flux are not diagnostic of plume lateral speed. The fraction of plumes moving by less than 5 mm yr^{-1} being > 25 % suggests that fixed hotspot

reference frames can be defined from careful selection of hotspot tracks.

Managing an increasing number of medium risk unstable rock slopes

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NVE started periodic monitoring of large rockslides classified with a medium risk in 2016. Mostly, they are rockslides with an annual probability of 1/1000 -1/5000 and with significant consequences, though there may be exceptions. The number of medium risk objects are increasing every year as the national mapping program progresses. The monitoring of these objects should provide necessary movement data to ensure warning of increased risk and be cost effective.
The InSAR Norway project (where NVE is a partner) developed automatic InSAR processing of the radar data from the Sentinel-1 satellites, and NVE is increasingly relying on this technology. The use of periodic dGPS measurements and ground based InSAR measurements are expensive in terms of work- and transportation hours, while the use of satellite based InSAR has a low cost when the infrastructure is in place.
For the periodic satellite based InSAR monitoring of medium risk rockslides, we use two data types: 1) a national map of PSI data, which is updated biannually showing distributed movement of vegetation and snow free surfaces, and 2) corner reflectors placed in the rockslides with a reference reflector in a stable area. The corner reflectors provide time series of movement with a resolution of 3-6 days, which work year round independently of snow and vegetation. This method gives a higher temporal resolution and better precision than annual dGPS measurements, although it only measures in the line of sight. The use of double corner reflectors implements both ascending and descending orbits providing movement directions.
The purpose of the periodic monitoring is to identify increased movement, and upgrade the monitoring when necessary. The building codes and exception rules allows planning and building within the tsunami hazard zones of continuously monitored high-risk objects (Tek17, § 7-4). Today there is no exception for land hit by the rock avalanche itself or hazard zones for medium risk objects monitored periodic. The new possibility of monitoring by InSAR data can provide the base for an exception also for rock-slope failures underlain by periodic monitoring.

A systematic study of basaltic regolith fragments from Imbrium and Serenitatis Basins offers potential insights into new basalt types

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From remote sensing data obtained by different lunar orbiters, the Moon presents a clear dichotomy between a KREEP-enriched terrain, characterized by high concentrations of incompatible and heat-producing elements (K, REE, P, and also U, Th) and covering most of the nearside of the Moon, and KREEP-depleted terrains. Most of the lunar nearside volcanism occurred within this KREEP-rich terrain where the lunar crust is also thinner. The Imbrium Basin is located within the KREEP-enriched terrain, whereas most of Serenitatis Basin is outside of it. Visible and spectral images of the interior of the Imbrium and Serenitatis Basins reveal 30 and 29 spectrally different lava flows, respectively. Considering the continuous "gardening" of the lunar surface resulting from the continued cratering of the lunar surface, it is conceivable that ejecta material formed by small craters on different lava flows 100-1000 km away travelled and accumulated in the vicinity of Apollo 15 (Imbrium) and 17 (Serenitatis) landing sites. This enabled access/sampling of basaltic fragments (2-4 mm, ~50 mg) and small pebbles that originated outside the areas visited by the Apollo missions. Later small craters in the vicinity of the landing sites excavated both the local stratigraphy and, potentially also, exposed some of this distant allochotonous material.
Samples and Methods: Here are reported results from the systematic study of Apollo 15 and Apollo 17 basaltic regolith fragments collected along the ejecta of small craters. Each fragment was characterized petrographically (SEM), mineralogically (EMPA), chronologically ($^{40}Ar/^{39}Ar$ step-heating & in-situ U-Pb), and trace-element composition (LA-ICP-MS). The whole rock com-

positions were estimated by considering the mineral compositions and their relative abundance.
Results: Data show that the Apollo 17 regolith basalts are heterogeneous in composition, including potential previously unknown lunar basalt types. The ages obtained for 7 regolith samples thus far investigated range between 3.66 Ga and 4.01 Ga extending the known range towards older ages. The studied Apollo 15 basaltic regolith fragments ages are comprised between 3.16 and 3.90 Ga, also extending the age range for basaltic samples obtained by this mission. Mineral trace-element data suggest compositions outside the known range, which deserves further investigation. Thermobarometric calculations using the estimated whole-rock compositions, produced pressure (depth) and temperatures for basaltic magma genesis similar to those calculated when using Apollo 15 and 17 bulk compositions reported in the literature.
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Quartz-zircon de-coupling in sandstone: petrographic and quartz cathodoluminescence case study from the Triassic continental Buntsandstein Group in Germany

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We illustrate how de-coupling of quartz and zircon can be used advantageously in provenance research. 38 fine-grained to coarse-grained arkose samples of the Early Triassic intracontinental Buntsandstein Group from the Central European Basin in Germany were analysed for their petrography and 1200 grains in 23 of these for their detrital quartz cathodoluminescence characteristics. The samples represent the Hessian and Thuringian subbasins with the Eichsfeld-Altmark Swell separating them. The Hessian Subbasin includes more metamorphic lithoclasts than further east in the Thuringian Subbasin with a larger content of plutonic grains. More than 90 % of the detrital quartz from the eastern Thuringian Subbasin produce medium to bright blue cathodoluminescence colours and corresponding spectra that are typical for igneous or high-temperature metamorphic origin. Differently, the quartz from the Hessian Subbasin mostly luminesces brown and dark to medium blue, typical for low-temperature metamorphic origin. Quartz from the Eichsfeld-Altmark Swell and the western Thuringian Subbasin is a mixture between these origins. The quartz indicates different catchments for the subbasins, possibly the Bohemian Massif and the Massif Central, with converging transport routes on and close to the eastern fringe of the swell. Taking published zircon data from the same samples into account, light mineral-zircon grain-size shifts are 0.7-2 F units. That can be explained by mineral de-coupling due to different transport modes for quartz and zircon and different zircon-size availability in the source areas, exaggerated by combined aqueous-aeolian transport, as well as sample preparation-induced sorting. We conclude that submerged highs significantly can influence continental sediment transport. Hence, vast, flat continental areas with submerged morphological highs and a seemingly straightforward transportation pattern may be more complex than expected. The results also illustrate that analysis of detritus that has been affected by different dominating transport modes and further sorting during sampling and preparation can reveal additional source information.

Retreat chronology and margin stability of the Scandinavian Ice Sheet using high-resolution landform mapping and varved sediments

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Annual silt-clay alternations in eastern and southern Sweden have, since the late 1800's, been used to map Scandianvian Ice Sheet retreat by recording the site-to-site onset of proglacial lake sedimentation. The ensuing Swedish Varve Chronology is an unparalleled tool for linking the deglacial history of Sweden with associated palaeoenvironmental change at an annual timescale. However, the construction of the chronology, especially for the earlier deglacial picture, has been fraught with problems arising from misidentifications, miscorrelations, and missing varves. Southeastern-most Sweden (eastern Blekinge and southern Småland) is particularly problematic, with few varved records successfully connected to reconstruct local ice retreat, nor connected to existing robust regional chronologies. However, this region also encapsulates the abrupt warming of the Lateglacial Interstadial (~14.7 ka BP) and

associated highly-dynamic ice margin retreat across the marine-terrestrial transition. We revisit varve sequences in Blekinge-Småland, along with high-resolution digital terrain analysis to reconstruct the timing, pattern, and magnitude of ice sheet response to late-glacial warming. Digitisation and reanalysis of existing unpublished varve thickness records, alongside acquisition and analysis of new varve sequences both on land and at sea, has enabled us to connect local varve sequences to extend an existing robust chronology east and northwards by at least 70 km and 330 vyr. Detailed mapping of glacial landforms from new terrestrial and bathymetric terrain data informs and supports the varve correlations, revealing the pattern of ice flow and retreat in this area. The distribution and size of the eskers and meltwater channels draining the area indicate high meltwater flux to the ice margin, with ice likely funneled into the Kalmar Strait (between the Swedish mainland and the island of Öland) as grounding line retreat responded to the local bathymetry. We present an ice retreat framework for the Blekinge-Småland region and interpret ice margin response to late-glacial warming.

Quaternary evolution of the North Sea Basin and its relevance to hydrocarbon exploration

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Early Quaternary to Cretaceous strata is strongly tilted and truncated below the upper glacial unconformity along the southwest coast of Norway whereas, large quantities of sediments are deposited in the deep basin areas during the Quaternary. Isostatic effects caused by the loading and unloading of the sediments during the Quaternary may have contributed to the increased subsidence and uplift in the area and hence causing increased tilting of the strata. Not many studies have attempted to address the dynamics and timing of this tilting. Previously we mapped the distribution of Quaternary sediments in the entire central and northern North Sea and also estimated the erosion of sediments along the North Sea basin margin areas. The current study seeks to combine results from these two in-house studies and use these as initial constraints to model the Quaternary evolution of the North Sea Basin. Reverse modelling is used to sequentially restore the stratigraphy from present-day back to the beginning of the Quaternary without incorporating external dynamic effects into the basic backstripping method. Assuming there was no tectonic activity and instead post-rift basin development during the Quaternary was driven by the thermal subsidence, flexural isostatic, and sediment compaction processes. The present-day seabed was used as the initial model surface for the subsequent backstripping models and the entire Quaternary succession was sequentially restored in three main steps from seabed to the base Quaternary. The modelling results suggest that early Quaternary to Cretaceous strata were shallow dipping before the erosion of sediments below the angular unconformity but strongly tilted after the development of the Norwegian Channel due to erosion of sediments. This tilting of strata could have diverse effects on geometry of petroleum systems and hydrocarbon migration routes.

Record of climate and environmental changes in a dead-ice lake close to Gardermoen told by a 10 000 years old freshwater fish and a Viking King

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We studied a six-meter long sediment sequence retrieved from the kettle lake Ljøgottjern, close to Oslo-Gardermoen Airport, to reconstruct environmental and climate changes during the last millennia. The lake is 18 m depth and located at 185 m a.s.l., under the maximum postglacial sea level. The largest burial mound of Northern Europe was built in the mid-6th century on the shore of this lake allegedly for King Rakni and makes this place ideal to study human-environment interactions in a paleo-perspective approach.Using a multi-proxy sedimentological analysis of this record, including 14C dating, paleo-secular variations, XRF and CT scans, and pollen, this study highlights different climate patterns throughout the Holocene. At the bottom of the core, a carbonated sandy-clayey layer with centimetric twigs overlays an organic rich black peaty-type layer, suggesting a continental environment. On top of that, a disturbed clay layer containing fish bones from a

freshwater Carpinidae species was found. The fish could have been buried by the massive (70 cm) sandy carbonated deposit covering it. A sharp transition separates a clay cap on top of the deposit and the start of a finely laminated lacustrine sedimentation dated 9.3 ka cal. BP. The massive deposit could be associated to the outburst flood from the glacial lake Nedre Glomsjø dated 10-10.4 ka cal BP (Longva, 1984; Høgaas and Longva, 2016). A major change in the sedimentation occurred around 8 ka cal. BP, with darker sediments and a lower sedimentation rate. This change could be related to a warming climate and stabilization of the catchment by soil and forest development around the lake in the mid-Holocene. The sedimentation rate increased again between 2000 and 3000 years cal. BP as a result of the development of first human activities and major change in the vegetation (Høeg, 1997). We reconstructed temperature changes during the first millennia and compared it to societal dynamics. The period between 300 and 800 years cal. CE is colder than the period 800-1300 years cal. CE. After 1600 years cal. CE, an increase in erosion could be associated to the extension of the population and agriculture in Scandinavia and revealed a chronicle of the major floods in this area. The presence of freshwater fish older than 9,3 ka attests of their early and natural colonization of Scandinavian lakes. The comparison of this record with archaeological data will allow us to discuss socio-environmental dynamics following the deglaciation in the area.

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An alternative depositional environment for the Lange Formation: prograding delta deposits in the Gråsel sands of the Skarv field

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Numerous discoveries within the Lange Formation of the Norwegian Sea has given this play a better reputation in recent years. Cretaceous sediments continue to become increasingly more interesting for exploration and thereby a better understanding of the regional geology has become increasingly more relevant. The depositional environment of the Lower Turonian sands overlying the Skarv field has been intensively debated by experts for many years. As the Gråsel oil and gas discovery approaches field development, efforts have been put into fully understanding the reservoir. A reinterpretation has been made of the depositional environment, provenance, stratigraphic architecture and distribution of candidate barriers / baffles, as well as potential connectivity to a semi-regional aquifer to the west of the accumulation. A re-evaluation based on integration of new seismic data, log data and interpretations of the 6507/5-A-4 H core has revealed a regionally anomalous scenario for the Lange Formation: the Gråsel reservoir is interpreted in terms of a tidally influenced prograding deltafront (upper Gråsel sands) overlying upper slope channel-fills (lower Gråsel sands). This interpretation is supported by seismic amplitude extracts, sedimentological interpretations, paleocurrent indicators and ichnofacies derived from core. The extent of the delta front sands is considered to be influenced by underlying Jurassic structures and increasing accommodation space off the local structural high. A thorough understanding of the sand extent and character has been crucial for the ongoing development strategies for the field.

Flow pattern controls and sensitivity analysis in paleokarst reservoirs

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Paleokarst is a product of deactivation and degradation of karst by collapse and infill during burial. Geometries and petrophysical properties derived from these processes are preserved and frequently form key elements of petroleum reservoirs in carbonates. With nearly 30% of the world's carbonate oil and gas reserves being associated with fracture cavities (Jiang et al. 2008), understanding the effect of paleokarst features on dynamic behavior is crucial. In this study, test simulations were done on a generic base model measuring 614x100x30m and cells of 2x2x2m. The model represents a collapsed and infilled cave system, including many interconnected branches

and loops of varying sizes and complexity. Passage-diameters range from 2-18m. Two horizontal wells (an injector and a producer) were positioned in the reservoir to mimic uniform inflow from the left hand side and outflow through to the right hand side. At background/host rock permeability less or equal to 0.1mD, the flow closely follows the collapsed cave resulting into a relatively early water cut. However, when the background permeability is increased to 40mD or more, the entire reservoir pay zone is uniformly swept with no preferential flow along the paleokarst structure. In instances where the cave sections consisted of a combination of sand infill at the base and collapse breccia at the top inside the collapsed cave system, oil sweep efficiency was observed to be better in sand infill than in the collapse breccia (only in section of at least 10m diameter) while in sections of 6m, the sweep was uniform and the flow pattern was non-selective. Upscaling from 2m grid resolution to 6m and 10m yielded comparable results of total field oil production and retained preferential flow patterns along the collapsed cave. Further upscaling to 14m, 15m, and 30m grid cell resolution resulted in overestimation of the original total field oil production obtained from the high-resolution model and loss of the original flow pattern. The overestimation is mainly as a result of the complex geometry of the cave network.

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Decameter-scale, flow-parallel ridges in a submarine megaslide: Tampen Slide, North Sea

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Submarine landslides can be orders of magnitude larger than their terrestrial counterparts and pose a significant hazard to offshore infrastructure and coastal communities. Elongated ridges within landslide debris provide important information about the kinematics of failure. For subaqueous landslides, these ridges are typically perpendicular to the flow direction and confined to the head and toe regions of the slide, where they are associated with extension and compression, respectively. Any ridges present within the central, translational region of the slide debris tend to be localized, <1 m high, and result from the diversion of evacuated debris around topographic features. Here, we use high-resolution 3D seismic data from the headwall region of the Tampen Slide to characterize the ridges present within the slide debris. The 3D seismic data were acquired by TGS in 2017 and cover approximately 16,000 km^2 with vertical and horizontal resolutions of ⍰2 m and ⍰10 m, respectively. We extracted the upper and lower surfaces of the Tampen Slide through dense horizon picking at up-to-150 m increments, and performed geomorphological and statistical analysis on the time and amplitude surfaces. The upper surface of the up-to-180 m thick Tampen Slide is irregular and can be divided into distinct morphological categories that correspond with variations in the internal deformation of the slide. Contrastingly, the Tampen Slide's basal glide plane is smooth and laterally continuous, and consists of a variable amplitude positive reflection overlain by a very high amplitude negative reflection. We identify elongated ridges within the Tampen Slide debris that are parallel to the flow direction, up-to-40-m higher than the surrounding slide material, unrelated to variations in topography of the basal plane, and geomorphically distinct from extensional and compressional ridges. Flow-parallel, elongated ridges, such as we find within the translational region of the Tampen Slide, are frequently found in terrestrial and volcanic settings; however, this is the first time that ridges of this nature have been identified in a deep marine setting. This poses questions about the substrate conditions and failure mechanism required for the formation of such longitudinally orientated ridges, as well as their prevalence in the deep marine environment. Based on our characterization of the deposits, we provide a new three-stage model for the emplacement of the Tampen Slide: an initial, translational failure (>720 km^3) was followed by extensional spreading along the side- and headwalls, and several smaller volume (<40 km^3) retrogressive debris flows or collapses.

Distribution and characterization of Acid sulfate soils in Sweden

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Acid sulfate soils (AS-soils) can increase acidity in water bodies, release metals and therefore cause fish death and decreased water quality. In Sweden AS-soils are mainly found along the northernmost coast and recent findings show that these soils also occur in southernmost Sweden and along the west coast. These AS-soils are usually associated with organic-rich clay and silt sediments that were deposited, and reduced during anoxic conditions, in brackish-water environments. Due to the postglacial isostatic rebound potential AS-soils have been uplifted in many coastal areas and can thereby be exposed to oxygen causing formation of active AS-soils. The Geological Survey of Sweden (SGU) have during the last five years worked in different EU-Interreg projects together with the Geological Surveys of Finland (GTK) and Norway (NGU), the County Administrative Boards along the Bothnian coast, and other institutions in Finland and Sweden. The projects have focused on increasing the knowledge of AS-soils properties and geographical distribution and how this geo-hazard affects the surroundings. This is accomplished through fieldwork sampling and laboratory analyses, data which then are used as input data together with environmental variables to produce maps and consulting documents.

Active AS-soils are more common in flat areas with fine-grained sediments close to the sea level, whereas potential AS-soils occur at higher altitudes. However, in these projects we have discovered that the occurrence of AS-soils is more complex than this and can for example be found in coarser sediments as well as in peat. This can be seen in *the distribution map of acid sulfate* soils along the coast of northern Sweden that has been governed by machine learning techniques. Furthermore, it has been shown that a significant portion of leached heavy metals from AS-soils does not sediment at the river's outlets, as shown in Finland, but rather in the lakes of the catchment, at the water's way towards the outlets.

The knowledge earned from these collaborative projects can for example be used during planning of infrastructure projects, ditch cleaning and for recognising sites suitable for restauration of wetlands to further prevent the negative influence from acid sulfate soils.

Sandbanks, sandwaves and megaripples on Spitsbergenbanken, Barents Sea

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MARENO (www.mareano.no) recently acquired multibeam echosounder data from the shallowest part (26-53 m depth) of Spitsbergenbanken in the western Barents Sea. The datasets reveal a variety of bedforms, including megaripples, sandwaves and sandbanks. The bedforms exhibit varying degrees of superimposition which was possible to investigate thanks to 20 cm resolution of the bathymetry grid. The bedforms differ in their age of formation and present depositional regime, being either active or moribund. These are the first observations of co-occurring current induced bedforms in the western Barents Sea and provide evidence of a high energy environment in the study area. Indeed, the bedforms indicate both sediment erosion and transport and confirm that there is enough sand available in this area to maintain them, even the largest one which is the NW-SE sandbank. Such conditions are not known to be common in the western Barents Sea and reflect the unique oceanographic and benthic environment of Spitsbergenbanken.

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Permo-Carboniferous Salt Messing Up the Cenozoic Stratigraphy of the Sørvestsnaget Basin, SW Barents Sea

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Salt can strongly deform and may form structural traps of hydrocarbon accumulations in the overburden. The tectonically complex Sørvestsnaget Basin, SW Barents Sea, is characterized by a thick Quaternary sediment package and ongoing movement of Permo-Carboniferous salt. Here we study the interaction between glacial sedimentation and salt movement, and discuss the implications for petroleum exploration. We use 5,500 km^2 of high-quality 3D seismic data to establish the stratigraphy from Mesozoic to present-day. 11 horizons have been picked with an inline spacing of 200 m, followed by gridding to 12 m, horizon attribute extraction, potential field data integration, and seismic geomorphological interpretation.

The Base Cenozoic structure map shows multiple N-S oriented fault blocks, a well-expressed Senja Ridge, and three salt structures. Faults above these salt structures shape the basin geology of the overlying Paleogene, Neogene and Quaternary strata. The Eocene stratigraphy is characterized by strong soft seismic anomalies with underlying horizontal hard reflections above the salt structures. Faults originating from the salt structures limit these anomalies to a lateral extent of c. 10 km^2. During the Quaternary, the anticlines above the salt evolve both at the paleo-shelf and the paleo-slope, and shape radial basins with faults expressed above the crest. The Quaternary sequence includes multiple horizons with high-amplitude hard polygonal depressions and softly infilling strata around these faults, as well as stratigraphy-bound soft seismic anomalies above the salt structures.

Faults above the three salt structures act both as fluid-migration pathways and form structural traps for Eocene hydrocarbon accumulations, shown by positive-amplitude flatspots. Stratigraphy-bound soft anomalies in the lower Quaternary are interpreted as gas-charged early Quaternary sand beds, also identified in the surrounding wells. The rapid glacial sedimentation resulted in salt movement in different geological environments, with salt growing both in the shelf and slope domains. The polygonal depressions expressed along the crest of the salt basins are interpreted as glaciotectonic landforms. The cause for these repeated polygonal depressions along Quaternary reflections might be a combination of increased heat and/or fluid flow along faults and increased glacial erosion. This study shows that salt growing into overlying sequences results in a rich variety of morphologies kilometres above the salt bed, and an active hydrocarbon system. Salt movement is further shown to affect the thermal regime of the Barents Sea Ice Sheet. The well-constrained timing combined with the preserved landforms of the Quaternary sediment package allow a detailed modeling of salt movement in future.

Relative shore-level changes in Denmark after the last deglaciation: a review

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In the northern part of Denmark raised marine and littoral deposits are widespread, whereas such deposits are missing in the southern part of the country. In 1856 this led the Danish geologist Georg Forchhammer to suggest that the northern part had been uplifted, whereas the southern part subsided. This is still repeated by some textbooks on Danish geology. However, satellite data and precision levelling now show that all of Denmark is being uplifted. The rate of uplift is 2.2 mm in the north and 0.5 mm in the south-west. The lack of raised marine deposits in the south shows that the eustatic sea-level rise has surpassed the glacio-isostatic rebound. A number of new curves showing relative shore-level changes has been worked out over the past years. A relative sea-level curve from Limfjorden in northern Jutland shows a 'normal' trend, in contrast to an older, extremely steep curve. In southern and central Denmark large lakes existed during the Early Holocene, and lake level rose gradually until the marine transgression began. In southern Denmark, the relative sea level rose steadily until today, but approached modern sea level already 6000 cal. years ago. In northern Denmark, the relative sea level peaked about 6000 cal. years ago, when the relative sea level was up to 12 m above present sea level. A new palaeogeographical map showing the coastline in Denmark ca. 6000 cal. years ago is presented and compared with some older versions.

Ore-forming processes in volcano-sedimentary hosted massive sulphide deposits in the Mofjell Group, Nordland

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This study concerns ore-forming processes in the Mofjell Group, which is situated in the Mo i Rana area in Nordland. It is in the Uppermost Allochthon of the Scandinavian Caledonides, in the Rödings-

fjell Nappe Complex. Here we are studying deposits in the Hesjelia and Stangfjell-Hellerfjell ore zones in the Mofjell Group. Previous studies in 2008 and 2009 by NGU and GEXCO suggested that the occurrences may be classified as volcanogenic massive sulphide (VMS) deposits that formed in an oceanic island arc environment. Nine main ore zones are identified in the Mofjell Group, all at different stratigraphic and/or structural levels. Because of extensive deformation, it is challenging to unravel the original spatio-temporal relations between the different ore zones and deposits. The geochemistry of the host rock lithologies are quite similar for some of the ore-bearing zones, but more studies are required to decide if they belong to one or several stratigraphic horizon(s). The Stangfjell-Hellerfjell and Hesjelia-zones are two of the most promising zones, and further work was recommended. The zones have large economical potential for Zn, Cu, Pb, Ag and Au.

The aim of this project is to map out and characterize the sulphide mineralizations and the zones of alteration and to unravel if there is any connection between the mineralizations, e.g. if they are at the same structural/stratigraphic level and to describe differences and similarities. Also, mineralogical and chemical zonation patterns akin to the mineralising processes will be unravelled. Field work was completed in August 2019, and two drill cores were logged and sampled. Data from samples collected in the field and from 36 thin sections, as well as supplementary drill core mapping, SEM and EPMA will be discussed at the Nordic Winter meeting.

Why the Platåbergen district, SW Sweden is an aspiring UNESCO Global Geopark

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Aspiring Platåbergens Geopark is situated in west Sweden, in the region of Västergötland. Covering nine municipalities and approximately 3600 km^2, the main attractions are the 15 classic table mountains, which has been an important area for geological research since 18^{th} century.

The cultural landscape surrounding the mountains is one of the most prominent in Sweden, with a history going back to the Megalith culture 5000 B.P.

The Pre-Cambrian terrane, dominated by ca. 1.65-1.7 Ga old granitoids, is transected by a prominent, N-S trending, Sveconorwegian shear zone, the Mylonite Zone, separating somewhat younger rocks to the west from older rocks to the east. Underlying the table mountains is the well exposed and preserved sub-Cambrian peneplain. This denudation surface represents intense weathering of Pre-Cambrian rocks during the Cryogenic Snowball Earth event and the succeeding Ediacarian.

The table mountains are themselves relicts of a Palaeozoic cover of sedimentary rocks and stands out as prominent features in the landscape. They offer excellent exposures of Cambrian to early Silurian sediments deposited in the epeiric Iapetus Ocean but also of a cap rock of dolerite on top of these sedimentary rocks. The dolerite magma intruded as sills during the Carboniferous-Permian transition into a much thicker sedimentary sequence than present today. These sediments, on top of the sills, have been eroded so the dolerite sills are uncovered and exposed as cap rocks. The region also contains landforms created during two of the most important events during the late Quaternary of Sweden; the Younger Dryas cold interval and the catastrophic drainage of the Baltic Ice Lake.

The aspiring geopark will demonstrate the importance of geology and its influence on human life through times. Storytelling is a central part of our interpretation work and used on our website, in our app, in brochures and on YouTube. The four storytelling themes, covering geology, cultural history and outdoor life are 1) “A piece of Earth’s history – a journey in time through 1700 million years”, 2) “Earth brings life – the first communities”, 3) “Rocks for living – the humans and the mountains as resources”, 4) “The mountains are alive – nature and the outdoors today”. For visitors and inhabitants in our area, it will be easier to understand our geological heritage, and directly engage in the geopark’s development.

Determination of palaeotemperatures from the magnetization of rocks. An example from the Barents Sea

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Single domain magnetic grains are produced by bacteria, so called magnetotactic bacteria, that lived and live in a variety of sedimentary environment. Single domain grains are very favourable for palaeomagnetism since they retain their magnetization for a geologically long time, whereas multi-domain grains have the ability to constantly adapt to the ambient field by moving domain walls accordingly. Due to the additive nature of induced magnetization it is under favourable condition possible to define the different magnetic components, which may subsequently be related to geological events such as rotation, tilt, uplift etc. An analysis

of a well core from the Barents Sea revealed two secondary components which could be related to the palaeotemperature. Based on the result, we have subsequently estimated the burial depth in the Quaternary at that specific location using available data on the palaeo-geothermal gradient and thereby calculated the recent uplift. The result is compared to other results published on the uplift of various areas of the Barents Sea.

Establishment of a chronostratigraphical framework for the Fur Formation

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The Fur Formation in Denmark contains the ash series which is a result of the volcanic activity causing renewed opening of the North East Atlantic in the Eocene. The ash beds correlate over very large distances. The chronostratigraphic resolution, however, is poor due to uncertain dating of the ash beds. It is documented that the formation was deposited during the reverse chron C24R, (55.9-53.4 m.y.). Cande & Kent 1995 established and calibrated the geomagnetic polarity scale for the Eocene based on ocean floor basalts and found within C24R a number of short term (10 000 year) anomalies which they dated and called cryptochrons because of their uncertain origin. They could be caused by excursions in the geomagnetic field, or they could be due to mineralogical changes in the oceanfloor basalts. A detailed magnetostratigraphic study of the ash series at the Ølst locality was carried out by Beyer et al 2001 with the purpose of detecting these cryptochrons. Four short anomalies were found. However, the same problem arose, namely whether these anomalies were cryptochrones, or whether they had a mineralogical cause. It was therefore decided to investigate the equivalent stratigraphic intervals in the Fur formation, which is located 100 km from Ølst and consists of diatomite, while the sequence at Ølst consists of clay. If anomalies are present at the same levels in both formations, it is reasonable to ascribe them to variations of the geomagnetic field in which case they may be used for improving the time resolution of the ash series. In 2019 samples were taken in the relevant intervals in the Fur Formation. Three of the intervals showed normal polarity. The fourth and oldest anomaly found at Ølst may not be present in the Fur Formation because it is slightly younger than the oldest part of the Ølst Formation. With the three cryptochrones present in the Fur Formation we now have three dated intervals (54956-54965ky, 55066-55075ky, 55286-55296ky). The fourth one with the age 55.565-55 574 ky is probably only present in the sequence at Ølst.

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Magnetic characteristica of Quaternary sediments in Denmark

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Magnetic analyses of several localities with Quaternary sediment in Jutland, Denmark, showed a close relation between magnetic properties and the palaeoclima. Magnetic intensity and particularly susceptibility vary in accordance with variation in palaeotemperature. This is explained by different chemical processes occurring in the sediment as well as the palaeo environmental conditions prevailing at different times during the Quaternary. The accuracy of the palaomagnetic results is also affected, as the mean angular deviation is highest in the sediment deposited during warm periodes. The palaeomagnetically best data are therefore obtained in sediment deposited in a cold clima. Despite the very large variations in the magnetic properties of the sediments, the inclination of the magnetic directions were consistently negative, that is the whole sequence studied is of reverse polarity implying that the deposition occurred in the Early Pleistocene. Part of the sequence included the Harreskovian Interglacial which traditionally has been referred to the Middle Pleistocene. This was now dated to the Early Pleistocene and is more than 100 ky older than hitherto thought. Based on the data from one outcrop of a glacio-lacustrine deposit, a geographical mean direction of the primary magnetization could be determined. This pointed to an age of approximately 875 ky corresponding to the MIS 22. The lacustrine deposit comprises 25 m of rythmic beds of a thickness of approximately 40 cm. Based on sporadic varvs in the sequence a minimum sedimentation rate of 3-4 cm/year was estimated which implies that the rythmic beds are deposited within approximately 10-12 years each. This periode is similar to the 11 year solar cycle which may thus be the cause of the rythmic nature of the deposit. Besides showing the close connection to palaeoclima, this work dated the oldest Quater-

nary sediments found in Denmark in one of the boreholes, possibly reaching back to 1 million years, due to a normal polarity interpreted to indicate the Jaramillo Subchron.

Information on a new National Norwegian IAG Geomorphology Group (IAG National Scientific Member GeoNor)

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The new National Norwegian IAG Geomorphology Group (IAG GeoNor, 2019 -) shall increase the national and international visibility of Norwegian geomorphology and will stimulate the active communication, collaboration and exchange between senior and early career scientists from geomorphology and from other bio-geophysical disciplines working at different universities, research institutes and companies in Norway. In addition, GeoNor shall serve as a catalyst for the development of international scientific contacts and collaborations for Norwegian senior and early career scientists. GeoNor shall significantly reach out internationally by being closely linked with the four other Nordic geomorphology groups/communities from Sweden, Finland, Denmark and Iceland, and by showing appreciation for the geomorphological research achievements and the published scientific work of international colleagues that have carried out relevant geomorphological research in Norway. As an active National Scientific Member of the International Association of Geomorphologists (IAG), GeoNor is part of a global network of senior and young geomorphology groups and communities. GeoNor is initiated and headed by Dr. Achim A. Beylich and will initially be run by an efficient core group of eight scientists: Dr. Achim A. Beylich (Chair), Dr. Katja Laute, Professor Dr. Dieu Tien Bui, Dr. Benjamin Bellwald, Adjunct Assoc. Professor Dr. Ola Fredin, Assoc. Professor Dr. Chantel Nixon, Professor Dr. Stefan Winkler (Representative for GeoNor members from outside Norway), and a national early career/young geomorphologists representative that will be selected as member of the GeoNor core group following an application procedure widely announced for early career/young geomorphologists in Norway. Concrete activities of GeoNor include: (i) The development of an active and frequently updated GeoNor website which will serve as relevant information and communication platform for senior and early career members of GeoNor; (ii) The compilation and email distribution of a bi-annual GeoNor newsletter; (iii) The biennial organisation of national GeoNor meetings at varying field locations in Norway. At the varying meeting locations relevant ongoing research projects will be presented by GeoNor members and discussed within the group. The biennial GeoNor meetings will include scientific presentations from senior and early career scientists, extended scientific discussions, field excursions, and training courses for early career scientists. Further details on IAG GeoNor and contact information are available under http://www.geomorph.org/national-scientific-members/.

Information on a new Nordic IAG Network of National Geomorphology Groups from Norway, Sweden, Finland, Denmark and Iceland (IAG GeoNorth)

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The new Nordic IAG Network of National Geomorphology Groups (IAG GeoNorth, 2019 -) will stimulate the communication, collaboration and exchange between national geomorphology groups/communities from Norway, Denmark, Finland, Iceland and Sweden in Northern Europe. By serving as an international IAG umbrella network, GeoNorth shall foster the initiation and/or further development of national geomorphology groups in the five Nordic countries. Being an official organ of the International Association of Geomorphologists (IAG) (IAG National Scientific Member GeoNorth, Regional Group), GeoNorth is connected with the global IAG network of national senior and young geomorphology groups and communities. The new IAG National Scientific Member and umbrella network GeoNorth is initiated, coordinated and chaired by Dr. Achim A. Beylich (Norway) and is run by the GeoNorth representatives of the five Nordic national geomorphology groups: Dr. Achim A. Beylich, Dr. Katja Laute and Professor Dieu Tien Bui (Norway), Dr. Mikkel Fruergaard and Dr. Verner Brandbyge Ernstsen (Denmark), Professor Jukka Käyhkö and Dr. Eliisa Lotsari (Finland), Dr. Thorsteinn Sæmundsson (Iceland), and Dr. Lina Polvi Sjöberg and Professor Arjen Stroeven (Sweden). In addition, each of the five national geomorphology groups/communities will have an own early-career/young geomorphologists representative that will be selected after application procedures widely announced for early career/young geomorphologists in the respective countries. Concrete GeoNorth network activities include: (i) The development of an active and frequently

updated GeoNorth website which will serve as information and communication platform for senior and early-career members of the five national geomorphology groups/communities; (ii) The biennial organisation of joint meetings of the five national geomorphology groups/communities. These meetings will be organised in varying Nordic countries at field locations where relevant ongoing research projects will be presented and discussed, and will include scientific presentations from senior and early-career scientists, extended scientific discussions, excursions, as well as well-selected high-quality training courses for early-career scientists. The first GeoNorth joint meeting will be held in Trondheim (Norway) in October 2020; (iii) In addition to regular business meetings, the senior representatives and the early-career/ young geomorphologists representatives of the five Nordic countries will meet and hold additional planning/strategy meetings during international conferences (e.g., EGU, AGU, Nordic Geological Winter Meetings, IAG International and Regional Conferences). Further information on IAG GeoNorth is available under http:// www.geomorph.org/national-scientific-members/.

Permafrost as a top seal for natural gas accumulations in Svalbard

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Although geologically short-lived, permafrost possesses good sealing properties. In Svalbard this is highlighted by methane emissions at natural migration pathways, particularly pingos and groundwater springs. The analysis of these seeps demonstrates the regional sealing nature of permafrost. Furthermore, several petroleum exploration boreholes throughout Svalbard have encountered flowable hydrocarbons directly at the base of permafrost. Recent uplift and gas migration post-dating permafrost formation has led to Svalbard exhibiting significant and widespread hydrocarbon accumulations that are demonstrably sealed by permafrost.
In 1967 Store Norske encountered gas at the base of permafrost in Cretaceous sandstones in Adventdalen during coal exploration drilling. The well was allowed to periodically flow between 1967 and 1975, with pressures and flow rates being intermittently recorded. Conservative estimates indicate that more than 2.5 million cubic metres of gas were produced without stimulation. Sub-permafrost gas of mixed biogenic and thermogenic origin was also confirmed in the Longyearbyen CO_2 Lab boreholes drilled in Adventdalen. Furthermore, seven out of eighteen hydrocarbon exploration wells in Svalbard have documented the occurrence of gas at the base of permafrost. These documented occurrences occur throughout the archipelago in a variety of geological settings and stratigraphy. The most compelling examples of sub-permafrost gas are from two boreholes near Tromsøbreen drilled in south-eastern Spitsbergen in 1977 and 1987, and two boreholes on Hopen drilled in 1971 and 1973. At Tromsøbreen both wellbores exhibited significant and continuous gas influxes, likely of biogenic origin, from and below the interpreted base of permafrost at approximately 160 m below sea level. The gas influxes occurred stratigraphically near the middle of a thick sandstone with no evidence of lithological changes to indicate internal sealing. On Hopen the first well encountered thermogenic gas influxes, apparently below permafrost at approximately 150 m below sea level. The second well drilled at 310 m elevation to the north encountered thermogenic gas at around 60m above mean sea level, possibly indicating the base permafrost also provides the trap. It is possible that, given the higher proportion of ethane and propane in this gas, some of the encountered gas at Hopen could occur as natural gas hydrates. In this contribution we review the available borehole data to characterize the various sub-permafrost accumulations in Svalbard and discuss these in view of the potential impact of thawing permafrost throughout Svalbard.

Glacial dynamics and ice retreat pattern of Kvitøyrenna, Northern Barents Sea – an improved reconstruction of deglaciation based on new high-resolution data

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Kvitøyrenna is a large trough in the northern Barents Sea, located between Nordaustlandet and Kvitøya on Svalbard. In 2018, the MAREANO programme surveyed large parts of the trough with multibeam echosounders and sub-bottom sediment profilers. The acquired bathymetry covers the southern part of the trough (about 6000 km^2) and is of higher resolution (5 m) than pre-existing data from the area. In October 2019 MAREANO followed up with a sampling cruise to the area, acquiring additional sub-bottom profiler data, visual (video) and physical seabed samples (grab, multicore, gravity core). The new bathy-

metry and sediment profiler data were used as a basis for mapping seabed geomorphology, and both the thickness and distribution of sediments in the trough in unprecedented detail. Distinct variations in seabed rugosity, landform and sediment distribution were observed between the southern and northern part of the study area, to a large degree coinciding with different bedrock types in the area (crystalline in the northern part and sedimentary in the southern part). The observed landform assemblages reflect different processes and glacial dynamics throughout the area during deglaciation and provide a good basis for improving and extending previous ice sheet reconstructions for Kvitøyrenna. Furthermore, the outcomes of this study provide valuable empirical evidence for comparison with numerical modelling results. Here, we will present the new geomorphic map and acoustic stratigraphy including some preliminary results from the sampling cruise, and an updated and more detailed reconstruction of the glacial dynamics and pattern of ice retreat during the last deglaciation of southern Kvitøyrenna.

Museum exhibitions as an arena for science education – insights and experiences from the new deep-sea exhibition at the Natural History Museum in Bergen

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New museum exhibitions offer a unique opportunity to present scientific results to a diverse group of people – including children, youths and adults. Modern museum exhibitions have a responsibility not only to show their collections, but also to engage with the public. When the University Museum in Bergen were granted funds to renovate and upgrade their historical building at Muséplassen 3, an exhibition featuring deep-sea research was requested. The background for the exhibition is coming from more than 20 years of deep-sea exploration at the University of Bergen.
In this presentation, we evaluate and discuss the process from the early stage of planning until the day of opening. In the exhibition, the audience will learn about volcanoes, hot springs and unique life forms that use chemosynthesis. An important part of the exhibition is to illustrate the technological evolution and the development of tools, which has made it possible to enter and explore the deepest parts of our oceans. Michael Sars' discovery of life at 800 meters depth in the mid-1800s sparked a renewed interest for marine exploration. With the advent of new technology comes the ability to visualize the depths of the ocean in unprecedented detail. In this regard, we aimed to facilitate learning and understanding by using both hands-on objects and interactive technology.

An Early Cambrian age of the Vassbo lead-zinc Deposit, Sweden

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Many ore deposits occur in sediments above major unconformities. Most common are copper, uranium, lead and zinc deposits. Lead-zinc deposits occur in marine sandstones and carbonates. Uranium and copper on the other hand are closer related to fluvial environment with sandstones and shales. It has been an increasing interest in the role tectonic movements in the basement to explain the location of these deposits.
Several sandstone-hosted lead ± zinc deposits occur on Baltoscandia close to the Ediacaran-Cambrian peneplain. One of those is the Vassbo deposit located at the southeastern border of the Swedish Caledonides near the Norwegian border. The deposit is hosted by marine and aeolian sandstones directly under the Hawke Bay unconformity. Galena and sphalerite occur together with barite and fluorite as cement in the sandstone close to faults in the basement. Aeolian sand with absorbed iron and phosphor was probably important for high organic production and early formation of H_2S.
The Hawke Bay event represent a hiatus of 6 to 7 Ma and the conglomerate deposited during this event contains boulders of lead mineralized sandstones. The difference composition of the Sulphur isotopes in the boulders compared to the matrix in the conglomerate show that the mineralization must have taken place before the erosion and formation of the conglomerate. This age is in accordance with lead isotopes studies of the Trysil Granite in Norway and the lead isotope composition of the Osen deposit.

The weathering of the Ediacaran – Early Cambrian peneplain at Bidjovagge, Kautokeino, Northern Norway

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The search for copper and gold in the Bidjovagge area, Northern Norway, has resulted in several boreholes cutting through the Lower Cambrian sediments and the paleo-weathered zone in the upper part of the Precambrian basement. This has given us a unique opportunity to study the Precambrian weathering process.

The Precambrian basement consists of the Paleoproterozoic Kautokeino Greenstone Belt containing greenstones, schists, carbonates and sandstones, formed in a rift environment. Most of the units in the belt is altered by a sodium metasomatism probably related to evaporites in the rift. The Greenstone belt is intruded by highly magnetic diabase dykes and 1.8 Ga granitic intrusions. The copper and gold mineralizations were formed by highly saline probably magmatic hydrothermal solutions related to granites intrusions, and they were constrained by shear zones.

The magnetite-rich diabase dykes play an important role in the weathering process. When magnetite meets oxygenated water at the surface, a strong exothermic reaction starts, where magnetite alters to ferruginous iron-hydroxides. This alteration creates a volume increase, that is causing mechanical instabilities in the rock, with the formation of fissures and enlarged pores. The next reaction step is a de-hydroxylation of the iron-hydroxides with the formation of solid hematite. This process is decrease in volume and includes an increased permeability of the rock. The enhanced permeability allows the migration of iron-bearing solutions deeper into the basement and explains why hematite veins are found several tens of meters below the paleo-surface. The Timanian collision could have caused faulting in the Precambrian shear-zone causing hydraulic pumping of oxygen-rich water into faults and fractures. A potassium-argon dating of clay minerals from the alteration zone gives an age of 540 Ma, which is within the period of the assumed weathering process.

Geoscience Education in Norway. Importance of applied disciplines in geology and geophysics

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To what extent should the education at the universities reflect the need for geo-personnel in the industry, government institutions, universities and research institutions?

Geology was up to about 1960 a small subject in Norway including only about 60-70 professional geologist, mostly educated at the University of Oslo. Teaching and research was mostly related to studies of basement rocks in Norway and palaeontology. The mining industry was then in decline and hired few geologists and some mining engineers from NTH. Most of the geology graduates became schoolteachers.

The onset of petroleum exploration from 1965-80, dramatically increased the need for geologists and geophysicists, changing the need for expertise. The universities were in many cases reluctant to establish petroleum education programs to meet the demands of a rapidly growing oil industry. Many professors claimed that a general geology degree would be sufficient. At NTH in Trondheim the teaching was focussed on mining geology up to 1973 when five petroleum geologists from international oil companies were appointed professors to teach petroleum geology and engineering.

Research at the universities is to a large extent controlled by funding from research councils, government institutions and from industry, and academic freedom is rather limited. This is not the case to the same degree for university teaching. What is taught at the universities is mostly controlled by the Faculty (professors), as a part of their academic freedom.

The professors normally have a high degree of control on the choice of textbooks and what is included in the lectures. To what extent should the teaching reflect the professor's qualifications and research interests relative to the students' needs for qualifications?

The recruitment of geoscience professionals and researchers in Norway is far from satisfactory. The output of qualified geoscientists from Norwegian universities has been too low most of the time. As a result, 60-80% of the geo-personnel at the universities, research institutions and petroleum industry have been recruited from other countries, mostly due to lack of qualified Norwegian applicants.

It seems that research and an academic carrier is not sufficiently attractive to many young students in the field of geology, particularly in applied disciplines where the competition for highly qualified candidates is high.

We need to discuss teaching in geoscience subjects at the universities in Norway, particularly in the applied subjects.

Modelling contaminant transport in fractured bedrock – examples from waste disposal in an abandonned mine

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Safe disposal of waste material in abandoned mines depends on both the stability of the waste that is planned for storage as well as the hydrogeological conditions in the mine and the surrounding rock matrix. Fractured zones are often critical in the aqueous transport of contaminants. Modelling of transport through fractures is challenging. Plans to store stabilised flyash in a mine at Brevik has required a better understanding of potential contaminant transport in the fractured limestone. Two approaches to model long-term transport based on a simplified 2-D and a more extensive 3-D approach will be presented and discussed.

Characterization of a Jurassic transgressive lag deposit in the SW Barents Sea

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Coarse conglomerates mark the transition between Jurassic sands and the unconformable overlying Fuglen formation, indicating a transgressive event. This event is also visible at the boundary between the Wilhelmøya and Janusfjellet subgroups on Svalbard, implying a regional influence. A major sea-level rise occurring at the end of the Bajocian has by previous work's been considered the depositional event.
This project aims to improve the understanding of the transgression, how it affects the distribution of sediments and the processes responsible. Linking the mineral content to the petrophysical response and assessing the lags possible influence on hydrocarbon distribution are other objectives. The main database of the study includes core samples, sedimentological descriptions and well log data from selected wells across the Barents Sea.
The conglomeratic bed consists of reworked and in-situ, early diagenetic products, making it a lag of mixed ages. Nodules of phosphate and siderite, coarse chert and quartz make up the bulk of the clast assemblage. The transgressive lag has a patchy distribution both in the cored wells and on Svalbard, with variable thickness and content. A thickening northwards trend is discovered in this study, which may be linked to paleotopography and net erosion. The matrix of the lag is observed to be well cemented by carbonates or apatites, possibly representing fluid barriers given some lateral extent. However, such thin and cemented beds are likely to deform in a brittle manner when exposed to unloading and stretching, which are crucial parts of the burial history in the Barents Sea.
The clasts and cemented constituents of the lag generates significant peaks in the density and velocity logs at the base of the Fuglen Formation. In geophysical analyses, the peak from the transgressive lag may obscure the response from the lithology and fluids of the underlying Stø or Tubåen formations.

UNFC – meeting the need to manage resources sustainably and attain the SDGs.

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The United Nations Framework Classification for Resources (UNFC) provides a tool for managing resources sustainably in support of a growing population that is coming out of poverty. UNFC was developed for solid fuels and minerals and is today expanded to cover all essential energy and raw material resources. This helps to understand and manage the resources in a coherent framework. In response to the needs of the 2030 Agenda for Sustainable Development and to attain the UN Sustainable Development Goals (SDG) a resource management system, United Nations Resource Management System (UNRMS), is being developed by the United Nations Economic Commission for Europe (UNECE) Expert Group on Resource Management (EGRM), with UNFC as its core. Initiatives for developing regional integrated resource management systems are being pursued as well as the establishment of regional and national centres of excellence on resource management for sustainable development to support UNRMS and the uptake and adoption of UNFC and UNRMS.

The presentation will focus upon these issues and provide an update on this important global initiative.

Evidence of prehistoric landslide-generated tsunamis in the outer parts of Storfjorden, Western Norway?

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Large rock avalanches in the inner parts of Storfjorden must have triggered many tsunamis in prehistoric times, but geological evidence is lacking. The obvious reason is the absence of archives where tsunami deposits could be preserved, such as lakes and bogs, along the steep fjord and mountainsides. In this project, we investigate the outer parts of the fjord where such archives exist.
Tsunamis triggered from rock avalanches must have propagated out the fjord, but the waves become smaller with distance to the avalanche impact and from propagating into a deeper and wider fjord. Nevertheless, numerical simulations (Harbitz et al., 2014) show that the largest avalanches should have generated tsunamis capable of inundating lakes and bogs close to sea level in the outer parts of the fjord.
So far, we have investigated five basins below the marine limit in the outer Storfjorden area:

- High run-up of the Storegga tsunami (8150 år BP). Engjavatnet (58 m a.s.l.) in Solnørdalen was about 40 m above sea level at that time and has tsunami deposits dated to Storegga time. Such a high Storegga tsunami run-up is a record-breaker.
- In Late Glacial lacustrine gyttja-silt in Engjavatnet we found a sand- and gravel layer, 3 to 10 cm thick. The layer rests on an erosional boundary we traced throughout the basin. This sand and gravel layer could have been deposited from a tsunami 13,300-13,100 years ago. In Sunnylvsfjorden there are deposits older than Younger Dryas from rock avalanches of at least 150 mill m^3, that possibly could have generated this tsunami.
- Litletjørna (14 m a.s.l.) has a favorable location to capture tsunamis between 8000 and 3500 yr BP, but we found none. At this time, the basin was 0-2 m below sea level until 6400 and < 8 m above sea level until 3500 yr BP.
- In Igletjørna (2.2 m a.s.l.) there is a sand layer with shell fragments in gyttja. This layer must be studied better before we can reach a conclusion. The layer is probably younger than 2000 yr BP.

Reference:
Harbitz et al., 2014: Rockslide tsunamis in complex fjords: From an unstable rock slope at Åkerneset to tsunami risk in western Norway. Coastal Engineering 88, 101-122.

Groundwater fluctuations in an unstable hillslope during the storm 'Hilde' 2013 in western Norway

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Pore pressure is important for the trigger of shallow debris slides and debris flows. But how exactly does the pore pressure vary just before a slide happens? And how much does it rise and how quickly? We collected data, between 2010 and 2013, from a piezometer installed 1.6 m below the ground in a slope susceptible to debris flows. One of the most distinct pore pressure changes happened during the storm 'Hilde', in November 2013, and caused a debris flow to happen in this slope.
More than 100 landslides were registered after this storm in western Norway, most of them were debris slides and debris flows. In the last 20 years, this event is one of the biggest slide events in Norway. Luckily, no one was hurt or killed, but many were evacuated, houses and cars damaged, a bus drove into a slide deposit and many roads were closed. It rained about 80-100 mm in 24 hours, locally up to 129 mm, but an important factor for the trigger of the sliding was the rapid rise in air temperature that caused snow on the ground to melt.
In the slope that had a debris flow that night, we measured the ground water level and ground water temperature. The 15 November it came 48.5 mm of precipitation in 11 hours, ground water in the slope rose 10 cm pr. hour until it reached 44 cm below the surface. The air temperature rose from 0°C to over 8°C at the same time, and the ground water temperature sank by 1.5°C. The debris flow was likely triggered late in the evening on the 15th, or during the night to the 16th, when the groundwater level was at its highest.
Measurements of the ground water in the slope through the years 2010-2013 show that the event in 2013 was exceptional. However, there are also a

few other similar episodes with rapid rise and high ground water level that did not cause any sliding on this slope. The most distinct of these episodes happened during the storm 'Dagmar' 25-26 December in 2011. At that time the groundwater also rose 10 cm pr. hour and reached 36 cm below the surface, without causing any slides.

New mapping of the Palaeic Relief in southern Norway

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The large-scale landscapes of southern Norway have previously not been mapped in detail, but since long they have been described in broad terms of the undulating Palaeic Relief at high elevation in contrast to the deeply incised valleys along the flanks and the re-exposed Mesozoic surfaces at low elevation.
Here we present detailed maps of the three major erosion surfaces that have developed across different types of bedrock within the Palaeic Relief in Norway south of 60°N. The mapping was carried out by applying the method of stratigraphic landscape analysis and was funded by the Norwegian Petroleum Directorate.
The most extensive surface that includes Hardangervidda, defines the bottom level of the Palaeic Relief. In general, this surface is a tilted plain, reaching from elevations of about 1300-1400 m a.s.l. in the west to 800-900 m a.s.l. in the east. In the west, between Hardangerfjord and Sognefjord, it rolls over to lower elevations. Its eastern flank coincides with the Oslo rift, but the mapping suggests that the plain can be traced into Sweden, where it cuts off a sub-Mesozoic surface. Towards the south, south-east and south-west it cuts off more inclined Mesozoic surfaces as high as 1000 m a.s.l.
The mapping also defined two surfaces at higher elevations, separated from each other by erosional escarpments. The middle surface is most developed in the area around Jostedalsbree, while the highest surface is most developed in Dovre, Rondane and Hallingskarvet.
The relative chronology defined by the mapping, suggests that the three surfaces of the Palaeic Relief were graded towards former base levels in post-Mesozoic time. The preservation of Mesozoic surfaces indicates that they were covered by sediments until late, and thus that the uplift of the Palaeic Relief occurred stepwise in the late Cenozoic.

Devonian extensional tectonics in Svalbard; Raudfjorden's synclinal basin above the Keiserhjelmen detachment

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Svalbard's large Devonian basin remains underexplored compared to other basins in the realm of the Caledonian orogeny. With the recognition of the Keiserhjelmen detachment (Braathen et al. 2017; https://doi.org/10.1111/ter.12305) in NW Spitsbergen, a tectonic setting similar to that of the Norwegian and Greenland Caledonides has been established, reflecting a late-post Caledonian major extensional tectonic event. In this contribution, we explore the link between the crustal-scale extensional Keiserhjelmen detachment and its hanging wall Devonian basin in Raudfjorden (NW Spitsbergen).
The Keiserhjelmen detachment truncates Caledonian nappes overlain by Late Silurian to Devonian sediments, and places them in tectonic contact with underlying high-grade gneissic units. Devonian strata dip moderately southward into the detachment for more than 30 km. The detachment records top-north movement of its hanging wall, parallel to broad antiforms and synforms that represent crustal-scale corrugations. These folds are more open in the hanging wall, with folds disconnected from similar structures in the footwall. Raudfjorden Syncline is one of these N-S trending structures.
Raudfjorden's synclinal basin is bound on the west side by the Raudfjorden fault (part of Keiserhjelmen detachment), which dips moderately-steeply to the east, towards the Devonian basin that makes up the hanging wall. The nearly 100-200 m thick shear zone include a fault-rock succession expected for an unroofing long-lived, major fault zone, including strongly deformed Devonian conglomerates along the top. Steeply dipping conglomerate units are truncated by the fault. Along the eastern margin of the syncline, Caledonian nappes are truncated by an angular unconformity below gently SW-dipping conglomerates. This fundamental unconformity is offset by numerous steep faults. The Devonian basin fill consists of blocky conglomerates (alluvial fan) along the margins that gradually changes into pebbly sandstones (fluvial plain) towards the basin

axis. Thick basin-margin conglomerates, the grain-size fining trend towards the basin centre, and several low-angle angular unconformities, suggest the basin was filled with growth-sections during progressive folding interacting with block-faulting.

3D modelling of groundwater rise due to flooding in the river Sima, Eidfjord

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Simadalen in Eidfjord, Norway is prone to flooding from the river Sima. The construction of a flood embankment on the river's south bank is planned in order to protect future industries from flooding. The soil consists of fluvial deposits of sand and gravel which are more than 30 m thick, overlain by a 5-8 m thick layer of highly permeable flood debris containing large boulders. Due to the soil's high permeability, flooding in the river will cause the groundwater level to rise. Moreover, future industrial development in the area will cause the ground level to be lowered in some areas and there is a risk that the groundwater level might rise enough to cause groundwater flooding of the industrial area. The planned embankment might not be enough to protect to area from flooding and damage to sensitive infrastructure. To ensure adequate flood mitigation, the rate and magnitude of groundwater rise has been studied by performing steady-state and transient 3D modelling of groundwater flow using Visual MODFLOW Flex. Modelling is a useful tool to test the sensitivity of different model parameters as many important soil parameters are unknown and the soil is likely to be heterogenous. The model has also been used to determine the effect of several additional flood mitigation measures, like sheet piling and drainage, to reduce the risk of groundwater flooding.

Capping of tailing deposits at an abandoned copper mine using a capillary barrier cover

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After closure of the Folldal mine in central Norway the tailings were left unreclaimed and have been continuously generating acid mine drainage (AMD). To achieve the environmental objective of restoring life in the strongly impacted river Folla, capping of the tailings is considered. Several cover designs exist and have proven efficient to limit the generation of AMD. In a humid climate such as in Norway an oxygen barrier was considered the most efficient option for the reclamation of acid generating mine sites. Laboratory column tests were conducted to assess the performance of a cover with capillary barrier effects (CCBE) to control acid mine drainage generation. Results showed that the pre-oxidized tailings used as the moisture retaining layer remained at a high degree of saturation (Sr > 85%) throughout the tests, thus efficiently limiting oxygen diffusion to the reactive tailings and reducing metal leaching.

Evolution of the Edvard Grieg Field (Southern Utsira High) – first assessment of seismic-scale faults versus deformation bands in drill core

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The ongoing structural geology study on the Edvard Grieg Field addressed in this contribution covers (i) seismic-scale faults of the field and (ii) deformation and diagenesis found in drill core of Triassic continental deposits of most likely Triassic ages that make up the reservoir. Scopes of the work consider a half-graben or deeply eroded horst-graben system as the setting for the field and the timing of fault activity beyond Permo-Triassic rifting. By combining signs of fault segment growth, considerations around subsidence versus rebound patterns may constrain the amount of uplift (erosion) in footwall regions of faults, which are made up of prospective, partly weathered granite.
Drill core from the field shows overall 3 types of deformation bands in aeolian sandstone. (1) Initial shear-related, mildly compactional disaggregation bands are overprinted by (2) shear-compaction bands with mild cataclasis (grain breakage and abrasion). Cataclastic deformation may relate to patches of calcite cement, but this needs to be further explored. Later deformation is by (3) mainly shear-isochoric disaggregation bands, in places seen to cut the cataclastic bands. With granular flow as the domineering deformation mechanism (band populations 1 and 3), in places possibly counteracted by grain-welding calcite cement (band

population 2), encountered small-scale structures are those expected of basically unconsolidated sediments in a shallow burial position.
The combined seismic-scale and microtextural analyses suggest active faulting during or just after deposition of Triassic aeolian sandstones. Some of the deformation could also relate to Triassic or Jurassic faulting during significant uplift and unroofing of the preserved reservoir units. Further work on the structural geology datasets will expectedly narrow the range of possible tectonic scenarios for the Edvard Grieg Field.

Karst Caves in Lomsdal- Visten National Park, Nordland

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Lomsdal-Visten National Park contain areas of high cave density of national significance. For the purpose of adequate protection and management, precise spatial data documentation, speleological and geological mapping and detailed description of the various findings and their contents was conducted during 2018-2019. The area has previously been described by British cave explorers (Faulkner and Newton 1990, Faulkner 2006). Elgfjellet is a mountainous plateau, at 600 – 650 m a.s.l. The study area consists of two different marble bands; “Gråryggen” (grey, calcite marble) and “Gulryggen” (yellow, muscovite, magnesian marble). They contain twelve caves of > 2.6 km total passage length. Cave surveying was conducted using current standard techniques, producing vector-based maps in desired projection. Structural and dissolutional features were mapped on surface and subsurface. A high-resolution terrain model was constructed using drone photogrammetry and the cave surveys were superimposed into the DEM to understand their spatial distribution and their genetic connection with surficial landforms. Concurrently, bones, old speleothem and sediments from collected further lab analyses. Our field observations suggest a genetic connection between the cave geometries and the marble foliation, where passages often follow the foliation planes. Our preliminary results, based on scallop observations (for paleoflow determination), sediments and glacial truncation morphology of entrances point out that pre- Holocenic speleogenesis, that can be attributed to subglacial conditions. Glacier flow direction has been reconstructed based on striae and roche moutonées, indicating mainly an east to west direction of movement. The project will result in five MSc theses that are to be submitted medio 2020, proposing a conceptual model for quaternary landscape evolution and speleogenesis. This study is part of a larger ongoing, regional analysis of speleogenesis and dating of marble caves in Norway. Our results from cave architecture, structural geology and cave contents is not consistent with previous ideas of neotectonic, or late-glacial seismotectonic creation of the caves as proposed by previous researchers (Faulkner and Newton 1990).

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Serpentinization and carbonation of Leka ophiolite complex – analogy to the Jezero Crater on Mars.

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Jezero Crater is the landing site of the Mars2020 NASA rover. The crater in its early history hosted a paleolake with at least two deltas remaining. The Jezero lake belongs to a larger system - the Nili Fossae region – which exposes a mineralogical assemblage interpreted as a serpentinization/carbonation system [1]. While the main alteration minerals in Jezero are identified, little is known about the accessory minerals. The latter could reveal critical information about the conditions of serpentin-

ization/carbonation [2; 3]. Moreover, several aspects are yet to be solved: Are the carbonates resulting of primary alteration or reworked origin [4]? Is the mineralogical assemblage modified after deposition in the lake (weathering)? What is the nature of the protolith that could contains up to 30% of olivine [5]?

The Nili Fossae-Jezero system has its potential analogue in terrestrial serpentinized and carbonated rocks, such as the Leka Ophiolite Complex, Leka Island, Norway, (PTAL collection, https://www.ptal.eu), which records complex weathering of serpentinite formed from mafic to ultramafic rock [6].

We perform petrological and mineralogical analyses on thin sections to characterize the weathering products in Leka samples, and combine with Near Infrared Spectroscopy measurements. We study the significance of the mineralogical assemblages including solid solution composition and nature of accessory minerals. The consequence for habitability potential might be important. Indeed, the amount of H_2/CH_4 production in mafic or ultramafic system vary significantly [2; 7]. This could represent crucial information that could guide future in-situ operations but could also help for a better interpretation of the remote sensing data.

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Spectral analysis and mapping of all Apollo/Luna landing sites to assist re-evaluation of lunar cratering chronology models

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Dating of geological events on planetary bodies is based on crater counts, a method originally calibrated on the Moon [1, 2]. Crater counts are linked to isotopically-dated Apollo and Luna samples and provides calibrated absolute model ages (AMA). The observed crater size frequency distributions (CSFD) on defined units are fit with crater production functions. Diverse CSFD measurement has led to suggest several lunar chronology models [3, 4]. Reliable CSFD measurements are therefore key parameters for the definition of lunar cratering chronology. Indeed, the CSFD measurement must be performed on large enough homogeneous geologic units. Several problems have risen regarding this method such as the uncertainty in linking mission samples with terrains where the crater count is obtained and used as templates [5].

Here we focus on the determination of large homogeneous geological unit to perform CSFD measurement at each Apollo and Luna landing site for the re-evaluation of lunar cratering chronology models. While most similar study focus on the morphology to define geological units [6], our study first focus on infrared spectral measurement acquired with the Moon Mineralogical Mapper data (M3) in supplement of considering the morphology. Spectral parameters used are from [7] and they illustrate the different depth of absorption near 1,00 µm, near 1,25 µm and near 2,00 µm. The spectral analysis is compared to the known mineralogy of samples and when available to laboratory NIR measurement performed on samples. For each unit, areas with secondary craters have been identified and removed by combining morphologic observations and spectral mapping. We then determined CSFDs on craters with diameters in the range of 250 m to 1 km. Craters were counted on Kaguya Television Camera data [8] at a resolution of 10 m per pixels. Our results are combined with corrected ages to define a new lunar cratering chronology [Werner et al, this meeting].

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Modelling the serpentinization and carbonation of the martian crust: a step towards the understanding of the Mars2020 future playground

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Both serpentine and carbonates have been detected on Mars by remote sensing [i.e.: 1, 2] and in situ analysis confirming the presence of hydrothermal carbonates [3]. So far, only remote sensing analysis allow the study of the geological context of the serpentinization-carbonation of the martian crust. However, the next NASA rover will land in the Nili Fossae-Jezero system, which correspond to such context. Systematic studies of Noachian crust hydrothermalism such as [4, 5] suggest that hydrothermal carbonates are mostly associated to chlorite and saponite but also serpentine in some cases. These analyses suggest that in all case either chlorite or saponite are major alteration minerals, while carbonates, serpentine and sometimes talc are minor components. Only little is known on the conditions of hydrothermalism leading to these diverse mineralogical assemblages. Variation of protolith, fluid composition as well as temperature may all be key factors at play, and exact conditions may have consequences for the H_2/CH_4 production generally accompanying these reactions [6].
Efficiency of crustal production of H_2/CH_4 could be the determinant ingredient for additional greenhouse effect allowing protracted stability of liquid water on Mars [7, 8] and habitability of Mars [9]. Therefore, the study of serpentinization-carbonation system is crucial.
Here we use geochemical modelling with EQ3/6 to explore the effect of diverse protolith and more importantly fluid composition on the formed mineralogical assemblages and more specifically solid solution of carbonates. Preliminary results suggest that the composition of the crust might be more heterogeneous than postulated for Mars, which agrees with the review of martian crust composition [10]. Our results suggest that H_2/CH_4 production is more limited and maybe too little to have an effect on climate [7, 8]. Thus, hydrothermalism may contribute less to the warming of martian climate and challenge the habitability potential through time.

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Evolution of Mars polar caps extent from CRISM observations

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We study the evolution of the size of the polar ice caps on Mars using data collected by the CRISM spectrometer onboard MRO. The presence of H_2O and CO_2 on the surface is determined with the help of spectral indices. This study represents an extension of previous works [1] to the latest data available, and aims at validating methods which could then be applied to observations of similar kind by the NOMAD spectrometer on TGO. The dataset analyzed in previous studies is expanded to include the latest observations overlapping with the first science measurements from NOMAD.
The signature of surface ice in these spectra is detected by studying the strength of absorption bands typical of H_2O and CO_2 ice. The most prominent ones within the set of wavelengths sampled by CRISM are those centered at 1435 nm for CO_2 ice and around 1500 nm for H_2O ice. In addition, absorption bands in the region between 2.2 and 2.3 μm are considered, both because they fall in the range of wavelengths detectable by NOMAD and because may prove helpful in the determination of the ice grain sizes. The absorption bands are modeled with simple linear models, so that their band depth (BD) is described by algebraic spectral indices. The depth of the absorption band (and thus the value of the ice index) for each spatial pixel is not directly related to the abundance of the corresponding substance on the surface, for it depends also on factors like the contamination from dust and the size of the ice grains. Moreover, mesoscale simulations using MarsWRF model will be performed to be compared with the observations.

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Selection of appropriate landslide mitigation measures – LaRiMiT (Landslide Risk Mitigation Toolbox)

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There are several ways to mitigate landslide risk. Risk mitigation strategies can include the identification and the implementation of suitable structural measures as well as non-structural measures, such as policies to reduce risk to acceptable/tolerable levels. Structural measures can either reduce the potential probability of the landslide taking place, or reduce the expected consequences if the landslide has taken place.
However, the selection of the most suitable option can be difficult because it depends on many technical and non-technical factors, including the site-specific conditions, socio-economic and environmental constraints. The web-based portal LaRiMiT (Landslide Risk Mitigation Toolbox) has been developed within the centre for research-based innovation (SFI) Klima2050 (www.klima2050.no) with the aim of helping practitioners in the process of selecting structural risk mitigation measures.
In a societal perspective, LaRiMiT is also intended to be a website that takes into account criteria other than purely technical ones that decision makers are most likely to address.
The selection criteria is based on user inputs and scoring of an extensive expert-based set of candidate mitigation measures. Users are allowed to remotely input site-specific information related to landslide characteristics (type and depth of movement, material, rate of movement) and site features (groundwater and surface conditions), as well as specifying constraints related to timeliness of implementation and economic and environmental suitability.
The portal provides users with a hierarchized list of mitigation measures based on their inputs and on expert-assigned scores and ratings for each candidate mitigation measure. Scores and ratings are retrieved from a database, which can be dynamically and continuously updated remotely through the portal by a panel of experts.
Currently a total of 80 measures are collected in the LaRiMiT database, grouped in 11 categories depending on the physical contribution they give to the landslide mitigation and whether they are aimed at reducing the landslide hazard (active control works for ground stabilization), or at reducing the landslide consequences (passive control works to control the landslide movement). Of special interest are the mitigation measures grouped into two new categories related to Nature Based Solutions (NBSs).
LaRiMiT does, however, not include design procedures, but is most suitable for the early stages of a project process.

The PHUSICOS project: Nature-based solutions to reduce hydro-meteorological risk in rural mountain areas

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Nature-Based Solutions (NBS) are increasingly finding consensus among the European community as sustainable solutions to address climate change impacts and improve the quality of life in urban areas. In rural and mountainous regions, where the hydro-meteorological risks are amplified, NBSs can offer an effective alternative to grey solutions for the risk mitigation, by also increasing environmental benefits and improve the human well-being.
PHUSICOS, meaning “According to nature” in Greek, is a project funded by the EU Horizon 2020 program. The intention of the four-year project is to support the implementation of NBSs as sustainable and cost-effective measures for reducing the hydro-meteorological risk in rural mountain landscapes. The primary aim of PHUSICOS is to implement and verify NBS solutions, by integrating existing technologies in practical settings and including all aspects of the process from planning, implementing, verifying performance and up-scaling of solutions.
Three large-scale demonstration sites have been selected; in Italy, the Pyrenees and Norway as representative of the hydro-meteorological hazards in European rural regions. Additionally, two small-scale concept cases are established in Austria and Germany to test specific challenges and methods.
Within the four-year duration the key actions will regard: i) the governance innovation, to enhance the implementation of NBS in policy planning; ii) the service innovation, to involve the stakeholders

in co-designing NBSs and iii) the technical innovation, to assess the NBS performance from technical, ecological and socio-economic point of view.
New products and services showcase the project results, among them an evidence-based platform of NBSs and a learning arena to encourage knowledge exchange of NBS for risk management in rural landscapes.
This presentation gives an outline of the project, focussing on methodologies adopted and preliminary results obtained from the first two years of the project.

Norwegian high-level mountain plateaus were not produced by the "glacial buzz-saw"

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Nielsen et al. (2008) suggested that the high-level mountain plateaus of Norway were produced by the same "glacial buzzsaw" process that modified the landscapes of the Cascade Mountains, Washington State, USA (Mitchell & Montgomery, 2006).
Here I compare the landscapes of the Cascade mountains with those of Norway.
Pleistocene ice erosion in the Cascades was limited to interfluve ridges between deep fluvial valleys. The ice reduced the height of the ridges as cirques eroded backwards from the headwaters of secondary streams. This process reduced the gradient of the highest part of hypsometric curve in the Cascades above the equilibrium line altitude (ELA) for glaciers - the so-called buzzsaw effect.
In contrast, the high-level plateaus in Norway existed prior to dissection by river valleys with a V-shaped cross-section (Bonow, 2003). River erosion must, therefore, have been pre-Pleistocene. Later Pleistocene ice erosion deepened the V-shaped valleys into U-shaped cross-sections, but remnants of the older fluvial valley slopes are still preserved in many places.
The glacial erosion process in Norway during the Pleistocene differed from that in the Cascades because the ELA in Norway was well below present-day sea-level whereas the ELA in the Cascades was at about *** asl. So the "buzzsaw" in Norway produced the deeply-incised glacial valleys and fjords, not the high-level plateaus that existed prior to the onset of ice erosion.

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Sub-annual moraine formation at an active temperate Icelandic glacier

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We present findings from detailed geomorphological and sedimentological investigations of small recessional moraines at Fjallsjökull, an active temperate outlet of Öræfajökull, southeast Iceland. The moraines are characterised by striking sawtooth or hairpin planforms, which are locally superimposed, giving rise to a complex spatial pattern. We recognise apparent systematic variations in moraine morphology, with sets of small (~0.2–0.5 m high) moraines often occurring between more prominent (~0.8–1.5 m high) ridges. Using a representative subsample of the moraines, we establish that they form by either (i) submarginal deformation and squeezing of subglacial till or (ii) pushing of extruded tills. Locally, proglacial (glaciofluvial) sediments are also incorporated within the moraines during pushing. For the first time, to our knowledge, we demonstrate categorically that these moraines formed sub-annually using repeat unmanned aerial vehicle (UAV) imagery. We present a conceptual model for sub-annual moraine formation at Fjallsjökull that proposes the sawtooth moraine sequence comprises (a) sets of small squeeze moraines formed during melt-driven squeeze events and (b) push moraines formed during winter re-advances. We suggest the development of this process-form regime is linked to a combination of elevated temperatures, high surface meltwater fluxes to the bed, and emerging basal topography (a depositional overdeepening). These factors result in highly saturated subglacial sediments and high porewater pressures, which induces submarginal deformation and ice-marginal squeezing during the melt season. Strong glacier recession during the summer, driven by elevated temperatures, allows several squeeze moraines to be emplaced. This process-form regime may be

characteristic of active temperate glaciers receding into overdeepenings during phases of elevated temperatures, especially where their englacial drainage systems allow efficient transfer of surface meltwater to the glacier bed near the snout margin.

Integrating glacial-geological and near-surface geophysical methods to investigate moraines in Sarek, northern Sweden

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Ice-marginal moraines, as delineators of former glacier margin positions, undoubtedly represent some of the most important empirical archives for examining past glacier retreat and ice-marginal dynamics. This is significant in the context of observed and predicted glacier retreat globally, as moraines potentially offer long-term records of glacier retreat that can considerably extend and/or contextualise short-term (often decadal-scale) observations of contemporary glacier change. Major challenges to maximising the full potential of moraines as glaciological and climatic proxies are understanding (a) how moraines form and (b) the post-depositional evolution and stability of such landforms. Traditionally, moraines have been examined using either a 'surface-only' approach or standard glacial sedimentological analyses. Relying solely on surface form is potentially problematic and can lead to erroneous glaciodynamic interpretations, while it is frequently not possible to obtain sedimentological data due to a lack of sedimentary exposures and/or restrictions on 'destructive' glacial-geological investigations. Near-surface geophysics could address this problem and offer the means to undertake non-destructive subsurface investigations of moraines (and other sedimentary sequences). The potential of geophysical surveying has yet to be fully exploited in terrestrial ice-marginal and proglacial environments, and they have not been widely tested against 'baseline' glacial-geological data. This study aims to integrate near-surface geophysical methods (e.g. ground penetrating radar, seismic reflection and refraction) with standard glacial-geological methods, as well as remote sensing, in a holistic approach to examining moraines. We will apply this multi-method approach to moraine complexes in Sarek, northern Sweden. The large moraine complexes that typify this region are ideal test cases for examining the capabilities of geophysical surveying as the moraines are thought to comprise complex sedimentary sequences and multiple substrates (e.g. sediment, water-saturated sediments, ice, and debris-rich ice). Using our multi-disciplinary methodology, we aim to provide new insights into the formation and significance of the moraines in Sarek.

Modelling past and future peatland carbon dynamics across the pan-Arctic

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The majority of northern peatlands were initiated during the Holocene around 8–12 thousand years ago. Owing to their mass imbalance, they have sequestered huge amounts of carbon in the terrestrial ecosystem. Distribution of soil organic carbon is widespread and uneven across the pan-Arctic. Recent syntheses have filled some existing gaps; however, the extent and remoteness of many locations pose challenges to develop a reliable regional carbon accumulation estimate. In this work, we combined three published peat basal age datasets with some independent measurements to form a most up-to-date peat basal age surface for the pan-Arctic region which we then used to constrain the model in order to reduce the current and future uncertainties related to the northern peatlands carbon cycle. We employed an individual– and patch– based dynamic global vegetation model (LPJ–GUESS) with dynamic peatland and permafrost functionality to quantify the long-term carbon accumulation rates and to assess the effects of historical and projected climate change on peatland carbon balance. We divided our analysis into two parts– the carbon accumulation changes detected within observed peatland boundary and at pan-Arctic scale under two contrasting scenarios (RCP8.5 and RCP 2.6). Our results are largely consistent with published long-term carbon accumulation rates. We found that peatlands would continue to act as carbon sink under both scenarios but their sink capacity would substantially reduce under RCP8.5 scenario after

2050. The 286 sites within the observed boundary showed similar behaviour as pan-Arctic scale but their carbon sink capacity would be further strengthened under RCP 2.6. Additionally, areas where peat production was initially hampered by permafrost and low productivity would accumulate more carbon because of the initial warming, moisture rich environment due to permafrost thaw, higher precipitation and elevated CO_2 levels. On the other hand, areas which experience reduced precipitation rates and without permafrost will lose more carbon in the near future, particularly, peatlands located in the European region and between 45-55°N latitude.

Spatial scales of permafrost change in the Arctic and sub-Arctic Greenland

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Sporadic to continuous permafrost is found across Greenland's latitude, elevation and continentality gradients, and the role of permafrost in affecting slope stability is an active area of investigation. Regional-scale mapping based on climatic zones, sparse in situ observations and, increasingly, remote sensing shows substantial variability in permafrost occurrence and change. However, the currently available datasets lack the fine-scale spatial detail needed in slope stability studies dealing with local geology, subsurface temperatures and surface atmospheric forcing. This is especially limiting under the ongoing and predicted warming because, from a geohazards perspective, we aim at quantifying the pace of permafrost warming and degradation before it may produce major changes in the landscape. A further difficulty results from most permafrost research and field observations being focused on soils in flat areas, while slope instabilities of concern in sparsely populated regions like Greenland typically involve bedrock deformation.
The downscaling of atmospheric climate models is a promising approach which is both practical over wide regions such as Greenland and can deliver high spatial resolution information about past, present and future temperature forcing at the ground surface. Modelling air and ground temperatures at 100x100 m horizontal grid cell size over all ice-free Greenland allowed estimating and correcting the elevation bias of coarser climate models, as well as accounting for the effects of self and cast shadows in steep terrain and, as a future step, including snow cover information from optical remote sensing. The results can be discussed in view of the first data from thermistor strings drilled 1 to 2 metres into the bedrock at 15 rock walls and outcrops surrounding the Vaigat Strait in Greenland, with available knowledge of the geographic location and time of year of past instabilities, and with geomorphological observations of active landforms produced by near-surface permafrost degradation.
At depth, quantifying permafrost conditions and change over scales of significance for large slope instabilities requires knowledge of the thermal properties of the materials, the geothermal heat flux, and heat advection due to water and air circulation. A growing permeability of the rock mass, even seasonal in character, may lead to the formation of perched aquifers or to increased neutral stress at the depth of potential sliding surfaces, with obvious slope stability implications. Transient heat transfer models exist but including air and water circulation may pose unrealistic requirements in terms of input field data. However, experience from instrumented boreholes may assist in this effort.

Magnetotelluric constraints on upper mantle viscosity structure and basal melt beneath the Greenland Ice Sheet

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Mass loss from the Greenland Ice Sheet has accelerated during the past decade due to climate warming. This deglaciation is now considered a major contributor to global sea level rise, and a serious threat to future coastlines. It is therefore vital to measure patterns and volumes of ice sheet mass loss. However, measurements of the ice sheet's mass and elevation, both of which decrease as the ice melts, are also sensitive to ground deformation associated with glacial isostatic adjustment (GIA), which is the solid Earth's response to ice loss since the last ice age. For Greenland, GIA is poorly constrained in part because

Greenland's complex geologic history, with a recent passage over the Iceland Plume, probably created large lateral viscosity variations beneath Greenland that complicate the GIA response.
The Norwegian MAGPIE project (Magnetotelluric Analysis for Greenland and Postglacial Isostatic Evolution) seeks to develop new constraints on mantle viscosity beneath Greenland by collecting magnetotelluric (MT) data on the ice sheet. MT images the Earth's electrical conductivity, which is sensitive to two of the major controls on mantle viscosity: temperature and water content of mantle rocks. We therefore plan to use MT data, together with existing seismic data, to map viscosity variations beneath Greenland. During the summer of 2019 we deployed 13 MT stations in a 200 km grid centered on EastGRIP camp on the North-East Greenland Ice Stream. Good quality data were recorded at periods up to 10,000 s, providing good resolution of upper mantle conductivity structure. We compare these new data to MT data collected in 2018 at Summit camp, which lies on the Iceland Plume Track ~350 km south of EastGRIP, to analyze the present-day signature of the Iceland Plume. We also collected a broadband MT traverse across the NE Greenland Ice Stream, which allows us to directly compare MT and radar data and investigate the role of basal melt on ice flow dynamics. Here we show preliminary results from this first MAGPIE deployment and discuss plans for future MT data collection on the Greenland Ice Sheet.

A link between seamount volcanism and thermochemical piles in deepest mantle

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Most active hotspots today can be linked to the "plume generation zones" located on the edges of two of the Large Low Shear Velocity Provinces (LLSVPs) at the base of the mantle beneath Africa and the Central Pacific. Many singular volcanic events in Earth's history, such as the eruption of large igneous provinces and kimberlites, can also be tectonically reconstructed to the edges of the LLSVPs. This association of intraplate volcanism with the LLSVP edges is thought to result from a stable large-scale mantle flow toward the LLSVPs, which causes plumes to rise at the LLSVP edges and also helps to maintain the the LLSVPs as chemically-distinct "thermochemical piles". Here we present evidence of another link between the LLSVPs and seamounts, which are perhaps the most common, and least understood, examples of intraplate magmatism. Using a database of satellite -detected seamounts, we map regional variations in their density by computing layer thickness that would define a volume equal to that of all large (> 1 km height) seamounts within a 500 km radius of each location on the seafloor. This "seamount equivalent layer thickness" (SELT) averages 18 m across the seafloor, but ranges from near zero to well over 50 m. We also used a recent tectonic reconstruction to compute the time that each point on the seafloor has spent above the edges and interiors of the LLSVP zones during its lifetime. By comparing the SELT and residence time maps, we demonstrate a statistically-significant regional correlation between seamount volumes and time spent over either the LLSVP edges or their interiors. Indeed, we show that seamount volumes increase with the length of time spent above the LLSVPs, for both the Pacific and African LLSVPs. This correlation suggests, and our preliminary numerical models confirm, that two types of upwelling are associated with the LLSVPs. Plumes that are generated on the LLSVP edges produce the large-volume volcanism associated with major hotspots, kimberlites, and large igneous provinces, while broader-scale upwelling associated with the thermochemical pile itself brings heat to the base of the lithosphere. This additional heat facilitates low-volume magmatism on the seafloor, and makes seamount eruption more likely.

Past methane emissions in the Vestnesa Ridge (NW Svalbard)

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The Arctic region is highly sensitive to climate change, and the effects of global warming are there more amplified than elsewhere. The Vestnesa Ridge, located at 79°N in 1200 m water depth offshore NW Svalbard, is one of the northernmost deep-water gas hydrate provinces in the world and is characterized by subseafloor fluid flow system, several seafloor pockmarks, and gas flares in the water column. Recent studies suggest that the stability of gas hydrates in the Arctic Ocean has already been affected by global warming and that

the methane release activity has possibly increased. It is therefore critical to understand the frequency and the trigger mechanisms of methane emissions from the seafloor in relation to past climate change and especially during periods of climate warming.

Multiproxy investigations on different cores from the area have shown that several seepage events occurred in the Vestnesa Ridge during the Last Glacial Maximum extension of the Svalbard Barents Sea Ice Sheet (24-23.5 ka) and during the Heinrich Event 1 (17.7-16.7 ka). In addition, multiple events were recognized in early Holocene host sediments (Panieri et al., 2014; Consolaro et al., 2015; Sztybor and Rasmussen 2017; Schneider et al., 2018). Here we present an overview of the available data of the area to discuss possible trigger mechanisms and the potential influence of climate warming on seafloor methane release.

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Far-field tectonic stresses triggered post-impact deformation of the Mjølnir Crater (Barents Sea)

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The Mjølnir structure (Barents Sea) is one of the best-preserved marine impact craters on Earth. Since impact on the paleo-seafloor, about 142 Ma ago, the crater experienced a major vertical deformation of its central peak. In this contribution, we aim at characterizing the effect of far-field tectonic stresses on the central peak vertical motions. We interpreted ~50-km of 2D high-resolution P-Cable and conventional reflection seismic data in the crater area and tied the interpretation to nearby wells on the Bjarmeland Platform.

The mapping of the crater sedimentary infill supports a subdued original central peak relief: a 5 km-wide, gentle mound lying ~15 m below the rim level. We found that subvertical, outward-dipping, impact-induced faults were reactivated, elevating segments of the central peak during at least one post-Albian event. In previous studies, the main mechanism for the central peak rise was attributed to differential compaction. We found that the sedimentary load increased the original central peak height by only ~10 meters after burial by marine shales. In contrast, tectonic stresses triggered a ~500 meters uplift, thereby accounting for 98% of the total vertical deformation.

The mobilization of Triassic-Jurassic impact-shattered rock by tectonic pressurization beneath the central peak provides a robust explanation for the structural uplift. We postulate that a post-Late Cretaceous tectonic compression linked to the initiation of the transform margin in NE Atlantic triggered the structural uplift of the central peak and reactivation of nearby salt structures in the SW Barents Sea. Central peak faults are prone to reactivation and can severely alter the original crater morphology. The example of Mjølnir demonstrates that the structural geology of central peaks combined with the regional tectonic context should be considered when studying terrestrial impact crater morphology.

2D thermal modelling of unstable rock walls in Norway: Examples from Mannen and Gámanjunni 3

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Recent rock wall temperature data and modelling studies indicate that many rock walls in Norway are underlain by permafrost. During ongoing atmospheric warming, permafrost in such steep slopes will warm to critical temperatures, at which the shear strength of the ground materials decreases drastically, possibly leading to slope destabilization and eventually rock-slope failures.

In this study, we model the temporal and spatial distribution of rock wall permafrost using a two-dimensional thermal heat flow model CryoGrid 2D (Myhra et al., 2017), where lateral heat fluxes can be modelled along a transect. The model is implemented with the Dirichlet boundary conditions at the upper boundary and is forced with observational or modelled climate data. We will present the results of CryoGrid 2D simulations from two unstable rock slopes in Norway that are currently monitored due to the risk they pose to population or infrastructure within the estimated runout zones. The “Veslemannen” unstable rock slope in southern Norway comprises a volume of c. 120 000 -180 000 m^3. The rock slab shows a seasonal increase in the movement rates, even up to 1 m d^{-1} during autumn 2018. Another slope in northern Norway, Gámanjunni 3, is a slowly creeping rock-

slide of c. 26 million m^3 that moved on average ~28 mm yr^{-1} during the last 5.3 ky based on results of cosmogenic ^{10}Be dating technique or up to 54 mm yr^{-1} during the recent years based on the differential global navigation satellite system (dGNSS) surveys (Böhme et al., 2019). The dynamics of the two slopes might potentially be related to the ground thermal regime, hence the interplay between these factors should be investigated in detail.

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"Nordland blir til" (The birth of Nordland county): Combining biological, historical and cultural information with geology

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Nordland County, Northern Norway, encompasses a variety of spectacular landscape diversities and iconic tourist destinations, most of them made by a combination of multiple and unique geological processes. The landscape and geological resources have been important for the cultural history. "Why does the landscape look like this?" and "How can people live here?". These are typical questions asked by the visitors. The answers are found in the geological history and in the record of inhabitants utilizing the geological resources.

Nordland contains important geosites of different kinds. In cooperation with the County Council and the regional museums, NGU has mapped and described around 700 geological sites. The main aim of the inventory has been to include these sites in the national geosites database. The inventory has revealed that Norland comprises a large diversity of geological sites, showing evidence of important geological events in Norwegian natural history; Dating from some of the oldest outcrops in Norway in Vesterålen, via some of the youngest rocks at Andøya, quaternary sites, karstic sites and strandflat landscapes and into mining sites of cultural heritage. It has also revealed that there are localities suitable for science, education and tourism in several regions on the county.

The inventory has led to several outreach initiatives, celebrating the geodiversity of Nordland. The most significant one will be the production of a book about the geological history and geological resources, and its implications on biology, history and culture in Nordland County. The book is due to be published in 2020.

The book will be written by geologists, biologists, historians, and archaeologists, and the target group will be visitors and locals with a genuine interest for nature, but without specific knowledge of geology. Topics will include geological history, landscape and climate development, submarine landscapes, the migration of plants and animals and human utilization of geological resources in the past, present and future.

The presentation will display some of the results and experiences from the geosite inventory, topics covered in the book, and some other outreach projects derived from the geosites registration in Nordland County.

REE mineralization in the Fen Carbonatite Complex, Telemark, Norway – A world-class exploration target for the Hi-Tech and "Green-shift" Industry?

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Rare Earth Elements (REE) are metals that are fundamentally important in the production of Hi-Tech and green technologies. The global demand for REE's is expected to rise substantially in the future. Today almost all REE is mined in China. REE's are important metals for the European industries, and thus the EU has classified the REE's as highly critical. Most of the world REE's has been mined from carbonatites, and consequently geological investigation and exploration of carbonatite complexes is being performed world-wide. New investigations reveal that the Fen Carbonatite Complex may host a world-class REE deposit.

The Fen Carbonatite Complex, situated in the county of Telemark, is the eroded remnants of an ancient volcano that produced magmatic limestones (carbonatites). On the surface of the Fen Complex the rock unit formerly called "rauhaugite", now termed "Fe-dolomite carbonatite" (FDC), is by far the dominant one. The FDC is a very inhomogeneous rock unit, but the content of Fe-rich dolomite is typical for all varieties. Certain FDC varieties commonly contain abundant REE mineralization.

A new geological study program has revealed a large near-surface extent of the REE-mineralized

FDC-rocks, as well as having confirmed their extent downward to at least 1 km depth. The REE minerals are micron to mm-sized and typically occur in aggregates. REE-mineralized zones reveal grades of up to 2,6-4,5 % TREO. Given the probable volume of the FDC unit and the frequency of the REE mineralization found in this preliminary study, the potential for a world class REE deposit emerge. A total TREO of more than 30 Mt is likely. This emphasizes the need for an extensive exploration program at Fen.

The Kloran gorge at Fulufjället, providing a unique opportunity to study the depositional environments of the Mesoproterozoic Dala sandstone, west central Sweden

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The Kloran canyon is one of several gorges along the eastern side of Fulufjället, cutting through more than 200 meters of the 1,5 Ga Dala sandstone. In 1997, during a dramatic rainfall, the rivulet Kloran was flooded by enormous amounts of water clearing the gorge from soil, debris and vegetation. The event created clean bedrock surfaces and hillside exposures up to 30m high, along the rivulet, providing a unique opportunity to study several hundred meters of the Dala sandstone in overlapping sections. The INTERREG project GEARS (Geologiskt Arv i inre Skandinavien), has provided a possibility to study the geology of the Kloran gorge in more detail before it gets too overgrown by vegetation.
There are only a few previous studies of the depositional conditions of the Dala sandstone and they show a variety of different environments. Aeolian sand dunes with ephemeral lakes have been described from Mångsbodarna; fluvial deposits were interpreted from Stora Moberget near Transtrandsfjällen and delta environment has earlier been suggested for Fulufjället, based on a few small outcrops.
The outcrops along Kloran illustrate a variety of depositional settings, ranging from alluvial to offshore transition environments. The predominant lithology is sandstone, but silt- and mudstones are also present. Characteristic sedimentary structures of the sandstones are planar beds and different types of cross laminated beds, from small -scale ripples to large-scale migrating dunes. At some levels, distributary channels are present. Fine -grained sediments exist in a variety of facies, from low energy interdistributary deposits (small lagoons and crevasse plays) to offshore transition muds in deeper settings. The deposition style ranges from fluvial to shoreline processes and the sediments are interpreted to have been deposited in, and close to a delta.

The true symmetry of the ancylite-group minerals

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The ancylite-group consists of ancylites, calcio-ancylites, gysinite-(Nd) and kozoites all of which are hydrous REE-carbonates. The ideal formula for the former three is *Me*REE$(CO_3)_2OH{\cdot}H_2O$ where *Me* is Sr, Ca or Pb, respectively. Kozoites differs in not having water molecules nor a divalent dominated site resulting in the ideal formula REE$(CO_3)OH$. Despite these minerals being common late-stage minerals in alkaline systems they have not received much attention by the scientific community. Like some other REE-carbonates this group is very sensitive to changes in geochemical environments and although being enriched in light REE some samples will be almost devoid of Ce, indicative of change in Ce oxidation state and consequently mobility. As such, the ancylite-group is ideal for understanding late stage processes in alkaline system. To fully utilize their potential as geochemical markers we started to explore the structural variations within the group. There are only a few structure refinements available of these minerals and for kozoite-(La) and kozoite-(Nd) only powder Rietveld structure analyses are available. The majority of published structures are refined in the orthorhombic space group *Pmcn* and all the cells are approximately $a \approx 5.0$, $b \approx 8.5$ and $c \approx 7.3$ Å. However, there are some indications that the true symmetry is not *Pmcn*. For example, Petersen et al. (2001) analysed ancylite-(La) from the Ilímaussaq alkaline complex, South Greenland and solved the structure in *Pmcn*. Although the refinement converged to $R_1 = 3.2\%$, their precession pictures revealed forbidden reflections suggesting the true space group to be *Pm*. We carried out structural solution of the same material and were able to refine it in *Pmcn*, but with some of the C and O atoms NPD, unreasonable high GOF and many forbidden reflections. We then re-integrated the data in *P*1*m*1 with the pseudo-orthorhombic cell of $a = 7.262(1)$, $b = 5.001(1)$ and $c = 8.501(1)$ Å and $\beta = 90.004(1)°$. For the final refinement we applied

the [100/0-10/00-1] twin that is usually used in cases of monoclinic settings where β is close to 90°. The refinement was stable with all atoms anisotropic, meaningful GOF and no issues with forbidden reflections. The lowering of the symmetry results in four non-equivalent REE/Me-sites that have different REE/*Me* content. Preliminary results as well as previous studies (Szymanski & Chao, 1986; Orlandi et al., 1990) on other members of the ancylite group support that the true symmetry is monoclinic rather than orthorhombic.

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Crystal chemistry of wöhlerite-group minerals

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The wöhlerite group (WG) includes ten approved mineral species that are defined by the general formula $M_8(Si_2O_7)_2X_4$. *M* denotes a wide range of cations with variable ionic radii and charges that can be six- to eight-fold coordinated. So far the following elements have been reported in substantial amounts on the *M* crystallographic sites: Na^+, Fe^{2+}, Mn^{2+}, Ca^{2+}, Y^{3+}, Ti^{4+}, Zr^{4+}, and Nb^{5+}. *X* denotes anionic sites that are not bonded to the Si_2O_7 groups, and that can be populated by F^-, OH^- and O^{2-}. One of the most recent reviews on this subject is provided by Biagioni *et al*. (2012).

WG minerals are usually characteristic of alkaline environments, although some of them (e.g. baghdadite) are observed in skarn deposits. The crystal structure of these minerals is based on so-called "octahedral walls", and Si_2O_7 diorthosilicate groups (Merlino and Perchiazzi, 1988). The walls are typically made of four columns of face-sharing *M* sites that run along the *c* axis. The walls are interconnected both by corner sharing and by the Si_2O_7 groups. One topological wall is observed in cuspidine, baghdadite, burpalite, låvenite, normandite, niocalite, janhaugite, wöhlerite and marianoite, while two distinct topological walls are observed in hiortdahlite I and *hiortdahlite II*.

The difficulty to study and develop a mineral nomenclature for the wöhlerite-group minerals arise from several points: (1) the incorporation of a broad spectrum of chemical elements through several coupled heterovalent substitutions; (2) the changes of the position of the Si_2O_7 groups relative to the walls lead to minerals with either triclinic or monoclinic symmetry; (3) the walls are not topologically equivalent from one species to another.

The current work aims to establish a nomenclature for the WG minerals. This nomenclature proposal is based on observations and data from the literature, but also on new structural and chemical data collected recently on material from the NHM collections. Additional investigations are also required to solve the issue regarding the series wöhlerite-marianoite (Chakhmouradian *et al*., 2008), and to properly described *hiortdahlite II*, as this mineral has never been submitted and therefore approved as a valid mineral species (Merlino and Perchiazzi, 1987).

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Tectonic evolution of Ordovician-Silurian rocks in the Oppdal area, southern Trondheim Nappe Complex

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Iapetus-related volcanic and sedimentary successions are preserved all along the Scandinavian Caledonides, representing mainly remnants of marginal basins formed in suprasubduction-zone settings. Volcanism, sedimentation, uplift, erosion and deformation of these marginal basins tell a complex story of "Taconian" (i.e. Ordovician) tectonic events related to the closure of the Iapetus ocean. In this contribution we present a tectonic model for Iapetus-related rocks from the Oppdal area, central Norway, which have received little attention until now. Detailed mapping, geochemistry and geochronology reveal the following

sequence of tectonic events: (1) opening of the Trollhøtta extensional basin at c. 475-469 Ma, with MORB pillow lava, chert and turbiditic sandstones, interfingering with extremely enriched trachytic to rhyolitic rocks of the Kinna volcanic succession; (2) tilting, local tight folding, inversion and erosion of the Trollhøtta-Kinna basin; (3) deposition of the Skuggliberga unit, consisting of green, cross-bedded sandstones overlain by andesitic volcanic breccias with a suprasubduction-zone chemistry. The age of the Skuggliberga unit is unclear; detrital zircon spectra suggest a Silurian (<430 Ma) deposition age; attempts on dating the volcanic rocks have been unsuccessful. (4) Greenschist-facies metamorphism and open to tight NW-vergent folding of the Skuggliberga and underlying units, as well as formation of top-E low-angle extensional shear zones and normal faults.

The mid-Ordovician (475-469 Ma) rifting event (including highly enriched mantle-derived partial melts) has not been documented in other Iapetus-related successions from the Scandinavian Caledonides so far, but might correspond to formation of the Appalachian Lloyds River ophiolite or the Tyrone Volcanic Group in the Irish Caledonides. It represents a distinct tectonic phase after the formation of the more wide-spread Early Ordovician (ca. 487-480 Ma) supra-subduction zone ophiolites. The deformation of this rift basin points to a <469 Ma accretion event prior to renewed deposition and volcanism, with subduction-related volcanism possibly stretching far into Silurian times (<430 Ma). No clear evidence for "Scandian" (i.e. <430 Ma) top-to-the-south-east directed thrusting or folding has been observed in the Oppdal area, whereas extension-related top-NW and top-SE structures are abundant.

Calcite cement in the København Limestone Formation

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The København Limestone Formation (Late Danian) from the Danish Basin has been subject of many excavations in Copenhagen. It forms one of the most important units in the subsurface of the city, due to it being a great foundation stratum for major building projects, including the metro. The limestone shows great strength variations ranging from unconsolidated lime mud to strongly hardened limestone within centimeters, making the limestone both a sediment and a rock from a geotechnical perspective. This causes great challenges when drilling in the limestone, as the strength variations are not predictable.

The strength variations is a consequence of differentiated cementation, in which the stronger parts of the limestone are more cemented. The København Limestone is the only Danish carbonate rock to have this high degree of cementation. Coccoliths are the main biogenic component together with abundant occurrences of echinoderms. The non-biogenic parts of the limestone consists of euhedral–anhedral sparite of low Mg-calcite composition. Flint is also a major component of the limestone, and it occurs in various shapes, sizes and color, possibly due to different concentrations of silica.

The reason for the strength variations seems to have formed early in the history of the limestone as it is possible to do a regional correlation of more indurated layers. Broken flint resembling glass shards occurring in the stronger parts of the limestone suggest, that the majority of the sparite cement have precipitated sometime after flint formation. The sparite in the softer parts of the limestone shows visual signs of being exposed to dissolution and are also enriched in Fe, Mg, Si and S compared to the stronger parts of the limestone.

Late Jurassic- Early Cretaceous marine reptiles in shifting Arctic seaways

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Marine reptiles dominated the seas in the Mesozoic, and their rich fossil record is a vast source of knowledge on marine ecosystem evolution. In the Boreal areas, the Late Jurassic to Early Cretaceous was a time of change, and relationships between marine reptiles in different areas have been poorly understood. This has changed the last years due to new fossil localities at Spitsbergen, Greenland, Russia and Poland. In the Late Jurassic-Early Cretaceous Slottsmøya Member Lagerstätte on Spitsbergen, 26 ichthyosaur and 31 plesiosaur specimens have been excavated by the Spitsbergen Mesozoic Research Group, covering a time span of approximately 12 million years. More than half of the specimens are now taxonomically analyzed, and have given new phylogenetic insights as well as information on the evolution of key skeletal features in these groups. Tectonic movement and a sea level fall caused a characteristic provincialism and endemism for many marine taxa in the area, but the marine reptiles from Spitsbergen do not constitute endemic clades. Rather, they display interesting relationships to taxa from

neighbouring areas. Marine reptiles from the Volga region in Russia, as well as contemporaneous specimens from Poland shed light on the eastern, shallow seaway between Boreal and Tethyan waters (the Tima-Pechora-Moscow-Precaspian Seaway). However, there are still controversies surrounding the phylogentic relationships and taxonomy for ichthyosaurs and plesiosaurs, as well as the relationships of the European taxa to North American ones. In Greenland, newly discovered marine reptile fossils might illuminate the evolution of the western, Norwegian –Greenland seaway, as they derive from a key area situated between the cooler Boreal Sea to the north and the warm Tethys Sea to the south.

The complexity of karst as recorded by the cored Ørn Formation of the 7220/11 -3 well in the Loppa High

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In approximately 100 m of core of the Ørn Formation (Gzelian to early Sakmarian) in the 7220/11 -3 well considerable variability in the nature of karst deposits resulting from the Permo-Triassic subaerial exposure related to the uplift of the Loppa High can be observed.
In the lower part of the Ørn Formation, dissolution of intercalated evaporites resulted in the formation of collapse breccias. In the middle part of the cored Ørn Formation, a cave developed and became filled with breccia and conglomerate with fine grained matrix of different origin. The top of the Ørn Formation consists mostly of fractured and brecciated bryozoa boundstone. The degree of brecciation decreases upward and eventually the bryozoan boundstone is mostly fractured. This could reflect a transition from collapse brecciation to differential compaction or foundering of a large bryozoan buildup. The Ørn Formation is overlain with an undefined unit of conglomerate. The conglomerate consists mostly of carbonate rocks eroded from the exposed Carboniferous-Permian sediments updip.
The diversity of karst sediments and textures in the Ørn Formation in the 7220/11-3 core illustrates the high degree of variability of karst on a small scale.

Towards real-time monitoring and multi -risk assessment using seismic/acoustic and remote sensing data in the Oslo region

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The production and usage of increasing amounts of electronic data in geosciences play a critical role in many societal challenges. For managing and utilizing the increasingly voluminous data, it has been demonstrated that machine learning (ML) has huge potential.
Two departments of the Oslo Administration are interested, for different purposes, to use these electronic data: (i) the Emergency Administration for infrastructure monitoring and detection of unusual events based on data collected in line with GDPR and (ii) the Water and Sewage Administration, currently involved in building a tunnel for securing freshwater supply in Oslo, for mapping and classifying fracture zones, faults and other geological features that could present risks for constructions and/or affect water flow paths. While the employed data are different, they can be both used for the same purpose, i.e., risk assessment.
In the Oslo-region, small and man-made seismic/acoustic events are generally not taken in account when analysing natural seismicity at larger scale, and the existing lineament databases for Norway are too heterogeneous and imprecise to be used for predictive and operational purposes at low scales.
With this project we propose to conduct real-time monitoring, early warning and multi-risk assessment in target areas of the Oslo region using seismic/acoustics data and remote sensing implemented as an autonomous, intelligent systems. The common methodology approach involving ML will be beneficial for identification and classification of both (i) seismic/acoustic events and (ii) lineaments from remote sensing data.
Real-time event detection and classification is currently being done by NORSAR at the Åkernes rock slope, implemented for early-warning purposes based on supervised learning methodologies. Furthermore, preliminary analyses of data from the newly installed Oslo Fjord Seismic Network (OFSN) have shown that the detection threshold can be lowered significantly towards smaller magnitude events (M≤1), and small blasting/quarry events relocated with larger accuracy. Also, NGU has recently started an automatic lineament detection based on image analysis and algorithms (Torgersen et al., this meeting), where manual interpretations and field data were already available for QC (FINE project).
Synergy between both main objectives is expected not only by using common ML-based approaches,

but also by combining the results of the lineament analysis and the spatial distribution of detected seismic events which occur in the target areas. If potentially active geological structures and natural or induced seismicity are identified, a hybrid approach correlating both seismogenetic faults and small earthquakes can be applied to produce hazard maps and risk scenarios.

Reference:

Torgersen et al., 2020. What to do with a lineament, Abstract Nordic winter meeting 2020.

Tin in tourmaline

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Tourmaline is a common mineral in Sn-W mineralizations. It is commonly strongly zoned, both optically and chemically, and may host a range of trace elements. High levels of Sn have been observed in tourmaline throughout the world, whereas W is typically very low, even in mineralized areas. Tourmaline from subeconomic cassiterite mineralizations and hydrothermally altered granite from the Land's End granite, SW England, was analyzed by EPMA in order to identify Sn-rich zones. LA-ICP-MS is typically the go-to instrument for trace element analyses, but spatial resolution is strongly compromised compared to EPMA. The behavior of Sn in tourmaline varies from patchy to concentric zoning between different samples, and the highest recorded value was 2.48 wt% SnO_2 in a patchily zoned rim. A high resolution WDS map of the area did not show any major Sn spikes, and TiO_2, a common minor element in cassiterite, is low in the Sn-rich regions. Also, cassiterite in these samples is commonly light brown in plane polarized light, and the Sn-rich zones can be related to dark green zones. This indicates that the high Sn-values are not due to cassiterite inclusions, and may be structurally bound in tourmaline, most likely substituting into the Y-site. The highest Sn-values (>0.4 wt% SnO_2) are coupled with a substantial substitution of Fe for Al in the Z-site, and the structural formula calculation indicate that some Fe is present as Fe^{3+} in the analyses with over ca. 20 wt% FeO. Trends between Sn and other elements are erratic, except for a weak positive correlation with Sr. The Sn-content in tourmaline combined with the inferred Fe^{3+} and the observed cassiterite in the samples may indicate that oxidation of the ore fluid caused cassiterite precipitation.

Norwegian Laboratory for Mineral and Materials Characterization (MiMaC) – A new microanalytical facility in Trondheim

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In 2017, a consortium comprising two departments at NTNU, the Geological Survey of Norway, and SINTEF Industry was awarded a grant from the Research Council of Norway to establish a national infrastructure for mineral and material analyses called MiMaC. MiMaC is a national center for multi-scale (atomic- to microscale) and multi-dimensional structure characterization, and high-sensitivity chemical analysis of minerals and materials down to sub-ppb level. The combined laboratories are primed to supply new and important data for the complete value chain from raw mineral resources to advanced materials. State-of-the-art equipment for mineralogical, chemical, and isotopic analyses of solid materials is already installed and producing results at the four respective nodes. Five instruments are included in MiMaC, and cover a wide array of analytical approaches and requirements, including 3D mapping with sub-nm spatial resolution (Cameca LEAP 500 XS Atom Probe), automated mineralogy and particle analyses (Zeiss Sigma 300 FE-SEM, Mineralogic software), major and trace element analyses (JEOL 8530 FPlus EPMA), and trace element and isotope analyses (Teledyne/Nu Plasma/Agilent LA-SS-(MC/QqQ)-ICP-MS, Teledyne/Agilent LA-QqQ-ICP-MS). The capabilities, limitations, and early results from all instruments will be presented.

The Norwegian Laboratory for Mineral and Materials Characterization is a Norwegian national infrastructure. Therefore, all instruments are available for both Norwegian and international users. Skilled personnel are available at all nodes and all instruments for support. More information can be found at: https://www.ntnu.edu/mimac

The MiMaC national laboratory is indebted to The Norwegian Research Council, NGU, SINTEF and NTNU for financial support.

Identification and characterization of precious metal bearing phases from Fosen, Norway – A combined AMS and EPMA study

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The Fosen peninsula hosts numerous small, polymetallic deposits related to the regional Møre-Trøndelag fault zone. In particular, two localities, Skaudalen and Flintheia, show significant anomalies of precious metals. Samples from Skaudalen show an average of 0.83 µg/g Au and 29 µg/g Ag, and there have been reported observations of electrum. Flintheia has an average Ag content of 158 µg/g, and has negligible Au. Both localities are Cu-rich, average 2 and 4 wt%, respectively, and Flintheia has minor Zn and Pb (0.6 wt%). Ag at Flintheia occur as inclusions of Pb-Ag-Bi-S minerals in chalcopyrite and pyrite, and as a minor element in galena, typically around 1 wt%. Galena is strongly altered and oscillatory zones of secondary minerals are deposited. Some zones are rich in Ag, with significantly higher concentrations compared to the typical galena composition, whereas other zones are Cu-rich. A challenge in characterizing the Ag-bearing minerals from Flintheia, and Au-minerals from Skaudalen is identifying them efficiently. The Ag-minerals occur commonly as small (<100 µm) inclusions in other sulfides. There are numerous galena inclusions in the same minerals. These have similar backscatter contrast to the Ag-minerals, and an EDS analyses is required in order to identify them. This is very time consuming to do manually. The automated mineralogy system can search for particles with high backscatter brightness , do a subsequent EDS analyses, and save the coordinates of the particle of interest. By discriminating the results by Ag content, the coordinates of interesting particles can be imported into the EPMA software, and a list of quantitative analyses of Ag-rich can be set up.

Delineating the geological settings of the southern Fram Strait with state-of-the-art aeromagnetic data

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Here we present preliminary findings from a state-of-the-art aeromagnetic data in the southern Fram Strait, funded by the Geological Survey of Norway, the European Plate Observation System – Norway, and the Norwegian Petroleum Directorate. Previous bathymetric and seismic studies have described the Knipovich Ridge as an asymmetric ultraslow spreading ridge with a thick sediment cover on its eastern flank, supposedly hindering its magnetic signature. However, due to the difficulty to conduct geophysical investigations, the settings, magmatism, magnetization and development of the Knipovich Ridge remained poorly understood. As the region undergoes frequent polar magnetospheric substorms causing large disturbance of the Earth's magnetic field, this large amplitude magnetic noise required thorough planning of the acquisition with careful and leading-edge data analysis and processing.
The new survey provides new geophysical and geological insights about the Knipovich Ridge configuration and spreading evolution since the continental breakup reevaluated in this study. Our analysis combined with pre-existing gravimetric and bathymetric data reveals, for the first time, the complexity the Knipovich Ridge and Fram Strait oceanic segment. The new findings questioned the limit of the oceanic domain in the region and allowed us to identify a set of magnetic chrons on both sides of the present day Knipovich Ridge. Our preliminary interpretation suggests also the presence of a failed spreading system before the complete reorganization of the spreading system.

Sedimentological and palynological investigations of the Neoproterozoic Valdres Group

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The last few years the Valdres Group (Cryogenian) has been sedimentologically and stratigraphically studied and sampled in a few key sites (Grønsennknippa, Mellane, Ormtjernkampen) by a research group from the University of Oslo. The search for fossils in selected formations has been one of the goals, and one acantomorphic acritarch was discovered along with other organic matter of more uncertain heritage. The Grønsennknippa, Mellane (Skarvemellen, Rundemellen) and Ormtjernkampen sites can be lithostratigraphically correlated, not at least due to the diamictite/tillite beds present. In addition to the diamictite/tillite, the fossil discovery facilitates a correlation with the well-known Hedmark Group to the East.

Reservoir quality and diagenesis of sandstones in the Realgrunnen Subgroup in 7324/8-2 (Bjaaland), Barents Sea

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The Bjaaland well situated in the Hoop Fault Complex displays poorer reservoir properties compared to sandstones of similar strata in other wells from the Wisting field area. Lateral and temporal changes in mineralogy, texture and reservoir quality will be documented and compared to previous work done on other wells in the Hoop Fault Complex. Factors governing the distribution of high- and poor-quality sandstones are of particular interest. This is important to capture on the Wisting project as input to both the static geological model and the dynamic simulation model, as this will influence the fluid flow and the drainage strategy of the reservoir. The sandstone properties will be documented from sidewall core data and compared to previous work conducted on drill cores from the Wisting field and nearby wells. Sedimentological, petrographic and petrophysical methods will be used for analyses in this MSc.

Structural controls on fault-related hydrocarbon leakage: insights from three case studies in the Barents Sea

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Evidence of hydrocarbon leakage has been well documented across the Barents Sea and has been largely associated with fault activity and exhumation in the Cenozoic. However, further study is required to understand why some faults appear to seal and others appear to leak. To address this, we use 3D seismic and well data from three study areas in the Barents Sea. They are the Alke discovery and adjacent area to the west positioned between the Troms-Finnmark Fault Complex and the Ringvassøy-Loppa Fault Complex, the Snøhvit field in the Hammerfest Basin and the Johan Castberg field located along the Bjørnøyrenna Fault Complex. Trap height and hydrocarbon column height measurements are used to calculate what proportion of the drilled structure is occupied by hydrocarbons. Depths of oil shows are recorded to assess if the hydrocarbon column may have previously been taller. To document the timing and style of fault growth, throw-depth plots, expansion indices and isochron maps are constructed based on horizon and fault interpretations. Topology is used to analyse the number and nature of fault-fault intersections. Incorporation of uplift maps alongside present-day subsurface stress measurements show which fault strikes are prone to reactivation and are therefore potential sites of hydrocarbon leakage. Preliminary results show that many trap-defining faults have been reactivated after the first major charge event in the Late Cretaceous. Shallow seismic amplitude anomalies located above many fault tips indicate that hydrocarbons have migrated up these reactivated faults. An increased number of fault intersections, particularly in areas containing two major sub-orthogonal structural grains are likely locations of enhanced leakage and may explain the large number of dry wells with shows in the area west of Alke. Whereas, structures present within the Snøhvit and Johan Castberg fields that are defined by parallel and sub-parallel fault trends contain a number of discoveries, some of which are filled-to-spill. Integration of work that documents and quantifies local fault activity, fault complexity and fault geometry plus regional effects of uplift related to tectonics and multiple phases of glaciation is essential to capture the numerous factors that affect fault-controlled fluid flow. Given that the majority of boreholes in the Barents Sea target structural traps and the main cause of dry wells is seal failure, it is recommended that this holistic approach is used to reduce uncertainty when risking the seal of a prospect, and when estimating the hydrocarbon column heights during pre-drill volume calculations.

An empirical approach to estimating hydrocarbon column heights for improved pre-drill volume prediction in hydrocarbon exploration

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Pre-drill volume estimation in exploration involves a number of input parameters that each carry a degree of uncertainty. The largest contributor to this uncertainty is almost always the hydrocarbon column height, which in turn is controlled by both charge and seal behaviour. However, it is this parameter that exploration and production companies often find the hardest to predict, partly due to the lack of sufficient empirical data from existing fields and discoveries. This study introduces a new empirical dataset from the Norwegian Continental Shelf, which aims to improve confidence in hydrocarbon column height prediction. The column height, trap height and overburden thickness have been measured for over 240 discoveries across the Norwegian Continental Shelf. Using this dataset, the trap-fill ratio for each discovery is calculated to assess what proportion of each structure is filled by hydrocarbons. The data from the 242 measured discoveries have been aggregated into a probability tree to calculate the likelihood of a discovery containing different ranges of trap fill, depending on its burial depth and trap height. Results show that for a discovery with a given trap height, the probability of recording 100% fill increases when the overburden thickness increases. Equally, when the trap height increases for a given overburden thickness, the probability of discovery 100% trap fill decreases. These findings, among others, challenge commonly held assumptions on column height probability distributions. Results strongly indicate the need to integrate a structure's dimensions when assessing seal capacity, and suitable ranges of hydrocarbon column heights to use when estimating pre-drill volumes. It is not suggested that this numerical approach replaces detailed geological evaluation of the prospect and trap specific geology. Best practice lies in integrating the probability- and geological-based approaches to create a multi-disciplinary workflow for improved assessment of hydrocarbon column uncertainty, and thus improved pre-drill volume prediction.

Towards a revised stratigraphic framework for the Triassic in the Norwegian Barents Sea

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This contribution outlines a proposal for a revised stratigraphic framework for the Triassic in the Norwegian Barents Sea, where we present the working draft and invite audience and users to provide feedback before the new stratigraphic framework is formalized. The current stratigraphic scheme in the Triassic of the Barents Sea was originally created by Worsley et al. (1988), based on a series of wells from the Hammerfest Basin available at the time. Since then, more than one hundred new wells have been drilled in the Norwegian Barents Sea, and a dense grid of high-resolution 2D seismic lines covers the area. Because of this large volume of data and more than 30 years of continuing research, the understanding of the Triassic deposits has evolved greatly.

A primary concern with the existing stratigraphic framework is that it does not describe and create order the lithologies in the basin, it rather consists of a set of chronostratigraphic prograding clastic wedges. This creates a set of problems: (1) the understanding of the lithology in the basin is not reflected in the existing stratigraphic framework, (2) current formation names give little more information than the stratigraphic ages, (3) the existing stratigraphic framework creates ambiguity when communicating expected lithologies of drilling targets, and (4) one often has to wait for biostratigraphy to determine which formations have been drilled. The existing stratigraphic framework also does not include several formations now proved to be present in the basin (such as Early Triassic conglomerates on the Loppa High, Induan coarse-grained sandstones along the Northern Norwegian coast, and an organic rich shale just above the Permian-Triassic boundary across the basin), and does not include the basin-wide unconformity above the Fruholmen Formation.

In 2018, the Norwegian Petroleum Directorate initiated a project to refine the lithostratigraphy of the Triassic of the Norwegian Barents Sea. The revised stratigraphy (1) should be based on lithology of the deposits, (2) should be simple to use and work on seismic data, well logs and core, (3) should retain names for the established reservoir units where possible, (4) should have a structure where groups reflect the large lithological changes across the basin, (5) should be a compilation of existing data, not a reanalysis, and (6) should be complimentary to the lithostratigraphic scheme used on Svalbard. The revised stratigraphy should also contain a set of figures that explain the

current understanding of distribution of lithologies in the basin.

In this contribution, we propose a revised stratigraphic framework that fulfils the aims stated above, and we ask for input from the audience to improve this draft. The main changes include: (1) clinoformal mudstones which were previously part of the prograding clinoformal units (Havert, Klappmyss Kobbe, Snadd and Fruholmen) are now assigned to the Tschermakfjellet Formation, (2) the formation names of the topset deposits of the prograding clinoformal units are retained, (3) the topset of the existing Snadd formation is split into two formations at the middle Carnian flooding surface, and the upper formation is termed the De-Geerdalen Formation, (4) several previously unknown formations are now included, (5) the Subgroup-division is abandoned and (6) the Rhaetian unconformity is now highlighted more clearly.

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Glacial millennial-scale climate variations and changes in bottom water temperature at intermediate water depth in the western Svalbard margin

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The western Svalbard margin is a key area for the reconstruction of the inflow of Atlantic water into the Arctic Ocean and intensity of deep water convection in the Nordic seas in relation to past climate changes. The reconstruction of variations in bottom water temperature (BWT) constitutes a tool to estimate the rate and vigour of deep-water formation in the past. Piston core HH15-1252PC, was collected at a water depth of 1273 m north of Vestnesa Ridge (NW Svalbard margin; 79°N). The purpose is to reconstruct absolute BWT and bottom water conditions from benthic foraminiferal Mg/Ca, the faunal species composition and benthic and planktic stable isotopes. BWT in the area is in average -0.7°C and the Atlantic subsurface water, occupying today the uppermost 750 m of the water column, has a temperature of <0.5 to 4°C. The core record spans Marine Isotope Stage (MIS) 4 to 2, resolving most of the millennial-scale climate oscillations including Greenland Stadials (GS 20 to 2 including Heinrich Stadials 7 to 1) and Greenland Interstadials (GI 20 to 2). The BWT increase sharply during stadials and in particular during Heinrich Stadials, where we calculate BWT as high as 4.5°C during HS1 (5.2°C above modern annual average BWT), whereas the interstadials are characterised by more stable BWT (0.5°C on average, except for GI11 and GI12, where the average is 2.51°C, probably due to the low resolution of the core in that interval) During the LGM, the BWT varies up to 3°C, reaching a minimum of -1.23°C at around 19.5 ka. The distribution of benthic foraminiferal faunas generally follows the temperature variations. Carbon isotopes show generally higher values concomitant with abrupt BWT increases, indicating better ventilated bottom waters than when bottom water temperature was stable as during interstadials. Our results suggests, as shown previously for southern latitudes in the Nordic Seas, that in the Greenland Sea during some stadials and Heinrich stadials deep water convection was reduced at least for a short time interval, allowing the subsurface Atlantic water to thicken and deepen down to at least the core site depth (>1200 m). During the interstadials and by the end of the LGM conditions were similar to modern and convection could be re-stablished. This shows that changes in bottom waters might have had an important role in the dynamics, and perhaps onset mechanisms, of abrupt millennial scale climate changes.

A CO_2 monitoring experiment for pressure-saturation discrimination at the new Svelvik CO2 Field Lab

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The establishment of SINTEF's new ECCSEL Svelvik CO_2 Field Lab was completed in August 2019. The main purpose of this unique small-scale field laboratory is to enable rapid and cost-efficient development and testing of methods and equipment for CO_2 monitoring.

The site occupies an inactive part of a sand and gravel quarry, located in a glaciofluvial – glaciomarine environment. The upper glaciofluvial layer extends down to 30 m, with heterogeneous sand and gravel. Below, in the glaciomarine environment down to the basement at 330 m,

heterogeneous alternating layers of sand, silt and clay exist (Mørk et al., 2013).
The field laboratory consists of injection facilities for brine or CO_2 injection, an injection well with an interval at 65 m (for injection below a clay layer) and four monitoring wells. Each monitoring well is equipped for a range of different geophysical measurements, including electrodes for Electrical Resistivity Tomography (ERT), downhole pressure sensors, and capillaries for gas and fluid sampling. In addition, SINTEF has invested in a fibreoptic system (DAS, DTS, DSS) covering all monitoring wells and (at the surface) the area between the wells. All those monitoring systems have been installed outside the casing, leaving space for seismic crosswell equipment and other downhole sensors, making the site appropriate for a wide range of experiments.
The first experiments at the new laboratory have been performed in the SINTEF-coordinated Pre-ACT project (2017-2020). This research project involves SINTEF, NORSAR, BGS, PML, TNO, and GFZ and is funded by the ACT program and four industry partners (Equinor, Shell, Total, and TAQA). The objective of Pre-ACT is to equip operators and regulators with pressure-driven decision support protocols that enable them to establish a safe and efficient monitoring system and to assess quantitatively site conformance.
The goal of the Pre-ACT experimental campaign is to acquire new data to support the development of a strategy for discrimination and quantification of pressure and saturation during CO_2 injection. To achieve this, three separate experimental phases were performed while acquiring data from direct pressure measurements and crosshole ERT and seismic. During the first phase, brine was injected to build up pressure at reservoir depth without a simultaneous change in CO_2 saturation. In the second phase CO_2 was injected to achieve a simultaneous change in pressure and saturation. Finally, data was acquired during a trail-off phase in which pressure had normalized, while CO_2 saturation was decaying.

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Large-scale lateral trends in palaeoenvironment and oxygenation in the Middle Triassic Botneheia Fm. on Svalbard

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The Middle Triassic Botneheia Fm. is a succession of phosphatic, silty shales (the Muen Mb.) transgressing into black and organic-rich shales (the Blanknuten Mb.). The formation crops out in Central-Spitsbergen and on the islands of Eastern Svalbard and is easily recognised by the characteristic steep cliffs of the Blanknuten Mb. The Botneheia Fm. is rich in fossil remains of bivalves, ammonoids, fish and marine reptiles, along with thoroughly bioturbated beds. The bioturbated layers occur episodically and are thought to represent oxic episodes in an otherwise dysoxic, anoxic or even euxinic (anoxic and sulphurous) environment. The depositional environment causing these variations is not well understood. This study aims to investigate the distribution of the fossiliferous beds and understand the link between the preservation of fossils and trace fossils, to the sedimentary environment. In this study, new logs have been made of the Botneheia Fm. in both more proximal (Botneheia, Central-Spitsbergen) and distal (western Edgeøya) settings. Additionally, the shallow-shore, time-equivalent Bravaisberget Fm. (Festningen, Central-Spitsbergen) has been studied as a near-shore example. Here we present the most detailed review of the biofacies of the Botneheia Fm. to date and use geochemical proxies to discuss the episodic fluctuations in oxygenation.

Multi-scale lineament interpretation in Southern Finland

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The crystalline bedrock of Southern Finland is increasingly more exploited in various aspects, such as civil engineering projects e.g. road, railroad and underground facility construction and due to increasing interest in geothermal and groundwater resources in the bedrock. Therefore an increased

understanding of faults and fracture networks is needed to enhance and improve the geological modelling of bedrock properties within different projects.

To address these challenges, a research project has been established at the Geological Survey of Finland to study the brittle structures of the bedrock in different scales. With the aid of both field-based and desktop-based studies, brittle structures can be mapped to a certain extent but due to time, resource and data constraints, it is typical that some areas, dimensions and scales have to be overlooked during such studies. In terms of the properties of fracture systems in Finland, relatively few studies are available and there is still quite little understanding of the characteristics of fracture networks and of their variation regionally. This study focuses on the first step: A lineament interpretation in three different scales (1: 500 000, 1:200 000 and infinity scale) on the basis of geophysical and topographic data. The geophysical data utilized in the study is airborne magnetic data and electromagnetic data whereas the topographic data is based on both the latest LiDAR data set, recently updated in Finland, and open source bathymetric data.

Each data set has been interpreted separately in respective scale, and the interpretations have then been integrated into a single lineament data set. The multi-scale data sets produced have then been utilized to study length distributions between different scales and used as input for planning further field-based studies e.g. UAV (Unmanned Aerial Vehicle) photogrammetric data acquisition and detailed-scale outcrop mapping.

High-grade formation of graphite in Vesterålen, northern Norway, and its consequences for petrophysical properties of the lower continental crust

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Field observations and petrography together with modelling of mineral reactions and petrology is used to document graphite formation during granulite facies metamorphism based on data from the Proterozoic orthopyroxene-bearing gneisses of the Lofoten-Vesterålen Complex in northern Norway.

Graphite schist is hosted in sequences of banded gneisses dominated by orthopyroxene-bearing quartzofelspatic gneisses, interlayered with quartzitic and amphibolitic horizons, and lenses of marble and calcsilicate. The graphite schist displays a strong foliation and has a major content of graphite up to a modality of 39%. Quartz and plagioclase ($Ab_{47-93}An_{5-52}$) are additional major phases, together with pyroxenes, biotite (#Mg = 0.67-0.91; Ti < 0.66 a.p.f.u.), and K-feldspar ($Ab_{1-8}Kfs_{92-99}$) or perthite ($Ab_{35-64}An_3Kfs_{50-62}$). Pyroxene is present either as orthopyroxene ($En_{69-74}Fs_{26-29}$; Mg#=0.70-0.74), as clinopyroxene ($En_{33-53}Fs_{1-14}Wo_{44-53}$; Mg#=0.70-0.97), or both. Graphite occur as euhedral "flakes" (i.e. flake graphite) of fine- to medium grain size, with a strong crystal preferred orientation forming the well-developed foliation contributing to the schistosity of the rock together with crystal preferred oriented biotite. Pseudo-section modeling of the graphite- and ortho-pyroxene-bearing gneiss with plagioclase + ortho-pyroxene + biotite + quartz + rutile + ilmenite + graphite-assemblage and Opx-Mg#-ratio = 0.74 constrain the phase stability and estimate the pressure-temperature condition to 810-835 °C at 0.73-0.77 GPa. Although graphite recently is described in quartzitic and metapelitic rocks or as vein deposits in granulite facies crust, we here document graphite in assemblage with metamorphic orthopyroxene. The high #Mg-ratio of biotite and pyroxenes together with a high Cl-content of apatite up to 2 a.p.f.u. indicate the importance of fluids during the high-grade formation of graphite. The metamorphic reactions producing graphite lead to a high electric conductivity, rheological weakening and strain localisation in the lower continental crust.

K-Mg-Fe producing mineral reactions and microfabric development during formation of nodular sillimanite-gneiss (Bamble lithotectonic domain, south Norway)

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The Proterozoic gneisses of the Bamble lithotectonic domain (south Norway) underwent intense scapolitisation caused by K- and Mg-rich fluids and extensive albitisation with formation of numerous ore deposits. By detailed studies of mineral reactions texture we document release of the chemical active Mg, K and Fe-components forming the

metasomatic fluid: Breakdown of biotite to muscovite produces K, larger amounts of Mg, Fe, quartz, and H_2O. Fe is present as tiny Fe-oxide needles in the transforming rock. H_2O is used in the mineral reaction with K-feldspar producing additional amounts of white mica, quartz and K. During a subsequent reaction muscovite is replaced to sillimanite again releasing quartz and K. The reactions form the peculiar sillimanite-nodular quartzite, but also well-foliated sillimanite-mica gneiss. Optical and EBSD microfabric studies reveal a shape preferred orientation for quartz, but despite of a pronounced foliation, quartz does not show a crystallographic preferred orientation. A crystallographic preferred orientation is present for mica and sillimanite. Coarse micas show sutured boundaries to quartz, implying low nucleation rates, no crystallographic or surface-energy control during growth and no obvious crystallographic relationship to quartz. Our study illustrates the transformation of a quartzofeldspatic lithology into sillimanite-bearing quartzite. The microfabric data indicates reaction at non-isostatic stress condition, while the deduced mineral replacement reactions document a source of K- and Mg-metasomatic fluids necessary to cause the pervasive scapolitisation in the area.

Characterisation of pyroxene and olivine in the Tellnes deposit with focus on types, occurrence and physical properties for separation

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The Tellnes deposit is an ilmenite rich norite in the Åna-Sira anorthosite, which is part of the Rogaland anorthosite province, located in the South-Western part of Norway. Today, the ilmenite ore deposit is being mined at Tellnes, in Sokndal by Titania AS. Their main product is an ilmenite rich concentrate ($FeTiO_3$) for the pigment industry. The ilmenite rich norite has chemical and mineralogical variations which can be challenging in relation to the processing of the ore. The mineral processing is based on gravitative and magnetic methods, thus, the specific gravity and magnetic properties are essential criteria for how a mineral behaves through the process and if it ends up in the concentrate or the tailings. Due to their relatively high density and magnetic properties, pyroxenes and olivine can be challenging in the magnetic- and gravity separation process. This might be due to a high concentration of iron and/or poor mineral liberation.

The project intents to define the mineralogical properties of olivine and pyroxene, giving a spatial distribution, by drill core analysis, microscopy and with the use of various analysing tools, such as SEM (Scanning Electron Microscopy), XRD (X-ray Diffraction), XRF (X-ray Fluorescence) and EPMA (Electron Probe Micro-Analyser).
The performance of the different variations of pyroxene and olivine through the gravity- and magnetic separation will be investigated. The set limit for the amount of olivine and pyroxene a charge can contain before it affects the product quality is 15%. This is based on operational experience, and it would be of great interest for Titania AS to test the operational limit to either adjust it or define two separate limits for the given minerals.

The value of the urban sub-surface - how do we plan for the best use of it?

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Oslo is the capital of Norway; a small town by global standards, but still a rapidly growing city. Due to the growth, it will require large investments in communication systems and new dwellings. Underground space is already widely used for transportation, storage, extraction of heat and for foundations of buildings and infrastructure. A rough estimation indicates that the value of the built-up volumes below Oslo is over 30 billion Euros. Due to the rapid growth of the city the use of the sub-surface is expected to continue to develop.
The city of Oslo deals with geological challenges such as subsidence due to deep horizons of clay, quick clays and alum shale's that contains enhanced levels of radium and uranium.
Between 2013-2016 the Oslo Sub -Surface project was carried out. The results from the project are available in the final report and in the action plan "Towards a safe and secure management of the sub-surface in Oslo". Examples from the action plan that is currently under realisation is a municipal sub-surface plan, an increased geological and geotechnical competence in the city administration and increased phocus to data about the sub-surface.
By using the full potential of the Norwegian planning and building act future use of the subsurface in Oslo will be more efficient. The action plan will help us reduce conflicts between individual projects as their boundaries are set at an early planning stage. If information of ground conditions is considered at an early planning level, development of sensitive areas can be avoided or adapted to the known conditions. Costs can be estimated more

accurately, and individual construction projects will be more successful.
An efficient and fact-based management of the subsurface is dependent on the availability and quality of sub-surface information. The action plan will help us provide good quality information generated from sufficient and accurate data. It will also secure that relevant information is available to the public when needed.

Management of geosites used for geotourism in Hedmark and Dalarna (Norway and Sweden)

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This talk is linked to the Interreg project GEARS: Geologisk arv i Indre Skandinavia. GEARS is a transnational project in the Inner Scandinavia region, with emphasis on geological heritage and geological diversity. The Geological Survey of Sweden is the project owner, whereas the Geological Survey of Norway is the lead partner in Norway. The aim is to register, manage and assess values based on the region's shared geological heritage and use this in a geotourism setting. One of the work packages focus on management of sites and areas. A Master thesis at Gothenburg University is included focusing on the international status on geoheritage and geoheritage management and differences and similarities of the management system in the two involved countries.
Geodiversity influences landscape, habitats and species as well as our historical and cultural heritage, education, health and well-being. Geodiversity expressing different kinds of geological (and ecological/cultural) values is an often overlooked natural resource for education, for tourism and for recreation. Geodiversity is a descriptive neutral term. When value are added to geodiversity elements we move into the sphere of geoheritage and when we want to protect geoheritage we start to talk about geoconservation. We have reviewed the integration of geodiversity in nature management policies, and given a historical overview on how geodiversity has been taken into account for in Norway and Sweden
In a geotouristic setting sites that are selected may be of high national and international value, but sites with local value may also be included. The value will naturally have a large affinity towards education and experience potential. The sites may or may not be protected by law. All sites that are used for geotouristic purposes should, however, be manage to secure a sustainable use of the sites. We do not want the sites to deteriorate because of our use. This need of management are independent of the site value and linked to the sensitivity and resilience of the area in question. Its vulnerability may be directly linked to the geological values of the site, but may also be related to general ecological conditions. For geology to become a part of mainstream nature management it is important for both to be considered.

Permafrost in unstable slopes in Norway – results from rock wall temperature monitoring, geophysical surveying and numerical modelling from Mannen and Gammanjunni.

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The warming and degradation of mountain permafrost within alpine areas is an important process influencing the stability of steep slopes and rock faces. In the unstable and monitored rock slopes of Mannen (Møre and Romsdal) and Gammanjunni (Troms) rock wall temperature logger have monitored the thermal regime during the last four years. In 2018 and 2019 we did 3D ERT surveys on the plateau and directly within the rock wall back scarp of the unstable slopes. Laboratory analysis of rock wall samples identified temperature-depending rock strength and resistivity data. Finally, we conducted 2D thermal modelling to evaluate the potential thermal regime along the ERT profiles. All this information strongly indicate, at least locally, the presence of permafrost. The presentation discusses the observations and modelling results with respect to the influence of permafrost on the stability of these sites.

Icelandic permafrost dynamics since the Last Glacial Maximum – model results and geomorphological implications

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Iceland's landscape is notably dynamic due to predominantly young bedrock combined with high geomorphological process/erosion rates. This is particularly so in the periglacial realm and today, permafrost is widespread in Iceland's highlands and mountains over c. 800 m a.s.l. and sporadically in palsa mires in the central highlands. During the late Pleistocene and Holocene, Iceland's periglacial environment varied in time and space, dominated by both glacial and periglacial processes. To evaluate the dynamics of permafrost in Iceland since the last deglaciation, we couple the output of a 3D, time-integrated ice sheet model to a transient permafrost model (CryoGRID 2) applied over the last glacial maximum (LGM) through to the present. Our results demonstrate that permafrost was widespread in the early deglaciated areas of western, northern and eastern Iceland after the LGM. This influenced geomorphological processes and landform generation, as relict rock glaciers were abundant near the coastal areas of Iceland, and their formation was initiated with the early collapse of the marine-based ice sheet in these zones and the aggradation of permafrost. Permafrost degraded rapidly after the Younger Dryas, and as the permafrost that formed during the Little Ice Age now thaws, a consistent increase in slope failure and mass-movement has been observed. Our study demonstrates that large regions of Iceland have been underlain by permafrost for millennia, facilitating landform development and influencing the stability of steeper slopes.

Seismic modelling of faults; viable geometries vs seismic resolution in the subsurface

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Resolution and illumination issues in seismic data curtail identification of fault geometries and fault-initiated rock damage when mapping subsurface faults. Seismic modelling can be utilized to bridge the gap in identifying what can be imaged with certainty in seismic data, with respect to the original geology, especially when also comparing to outcrop data. In this study, we explore how seismic modelling can distinguish between real structures versus seismic artefacts. 2(3)D Point-Spread-Function based convolution modelling is used in a sensitivity study. One input is detailed fault interpretations of high-resolution P-Cable data and comparable conventional 3D seismic data from the Hoop area in the Barents Sea. Another dataset comes from detailed fault geometries observed in outcrops, which were used to build geological models as input to the seismic modelling. In addition to the host-rock lithofacies, parameters of importance for the geological model building include overall fault geometry and the distribution of architectural elements (fault facies) within the fault zone. By varying fault input, lithofacies, a wide range of frequencies, and illumination, we analyse a variety of synthetic seismic images. Finally we compare our modelled outcomes with seismic data from the Hoop area. The scope of the workflow is to increase confidence in seismic interpretations and to identify limitations in the analysis of steep, normal faults in seismic data.

Holocene tephra enhances Svalbard geochronology and improves links between sedimentary archives

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The distal deposition of tephra in far-field locations resulting from explosive volcanism has the potential to geochronologically constrain sedimentary archives and landforms e.g. ice cores and moraines. Tephra as a geochronological method, is unparalleled in spatial and temporal precision, providing the potential to investigate synchronicity or lag-response to climate forcing. However, no

stratigraphic framework for tephra has been developed for the High Arctic. We present preliminary results of distally deposited crypto-tephra found in Holocene lake sediments from Svalbard as well as pumice re-deposited on post-glacial raised beaches. Results suggest there is great potential in extending a tephrochronological framework of distally deposited tephra into the High Arctic based on Holocene lake and raised beach archives in Svalbard. Not only do new results from Svalbard place the distal deposition of tephra on a pan-Arctic scale, but findings bridge gaps relating to the direct comparison of marine, lacustrine, cryosedimentary and landscape archives.

Monitoring subsurface CO_2 storage using seismic and CSEM data – Modelling in Smeaheia area, northern North Sea

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This study deals with the CO_2 plume delineation and saturation estimation using a combination of seismic and controlled-source electromagnetic (CSEM) data. Norway has been evaluating the feasibility of large-scale CO_2 storage sites within the Norwegian Continental Shelf to realise carbon capture and storage (CCS) solutions. One of the potential CO_2 storage sites is the Smeaheia area in the northern North Sea. Smeaheia lies in the Stord Basin, bounded by a fault array separating the Troll oil & gas field in the west and the Basement Complex in the east. The Troll field is approximately 80 km WNW of Bergen. Sognefjord Formation (Upper Jurassic, Oxfordian to Kimmeridgian) sandstone is the potential CO_2 reservoir in the Smeaheia area, capped by the Draupne and Heather Formation (Upper Jurassic) shales.
We modelled a controlled-source electromagnetic (CSEM) survey response and endeavoured to predict the extent and saturation of the CO_2 plume within the Sognefjord Formation reservoir, combining the CSEM with a baseline seismic survey data. This procedure was carried out, assuming a negligible effect of the fluid change on the acoustic impedance. The acoustic impedance normally increases with increasing compaction as a result of a decrease in porosity. If the injected fluid has an identical density as of the in-situ water, the change in acoustic impedance will be insignificant. On the other hand, if the injected fluid has a low density similar to hydrocarbon gases, a noticeable decrease in acoustic impedance is expected. In a saline aquifer the in-situ salt water makes the total resistivity of a reservoir very low; however after injecting CO_2 the overall resistivity of the reservoir increases, making it possible to detect this change using CSEM method. Conversely, the reduction of porosity due to rock compaction also increases total resistivity. We attempted to isolate these different effects.
Our results show a possibility of monitoring the CO_2 plume in terms of extent and saturation using a baseline seismic in combination with a time-lapse CSEM data. These results also have implications on monitoring of oil production - especially with water flooding, hydrocarbon exploration, and freshwater aquifer identification. The CSEM low resolution and depth uncertainties are some limitations that need consideration.

Thought-provoking features in the SW Barents Sea from 3D geophysical modelling - from salt domes to crustal peridotites

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Crustal and sedimentary petrology have been investigated in a study area extending from land to the continent-ocean boundary including prominent crystalline basement highs (Loppa High, Veslemøy High, Senja Ridge), surrounding basins (Hammerfest-, Tromsø-, Sørvestnaget- and Bjørnøy Basin) and platform areas. A new comprehensive 3D subsurface model has been developed from a network of deep seismic lines, expanded into the map plane by gravity and magnetic data utilizing advanced 3D gravity and magnetic modelling (GEOSOFT GM-SYS 3D). The model has further been confined by well data and available geological information. The subsurface model is composed of sedimentary, crustal and mantle layers with assigned density distributions. Sedimentary depth-density functions have been constructed and revealed circular and oval shaped mass deficits on the map plane, which clearly correlate with published salt domes mapped from seismic data in the Tromsø Basin. However, similar mass deficits have also been identified farther west in the Sørvestnaget and Bjørnøy basins, interpreted to indicate far more salt than earlier assumed.
Magnetic attributes have been derived for the crystalline crust. The crustal model indicates rocks of high-density combined with low magnetic susceptibilities in both the Veslemøy High and the Senja Ridge. This make it highly probable that the

petrology can be ascribed to ultramafic rocks. To further analyse the origin of the magnetic anomalies over the area, we combined this conventional layered Earth modelling approach with a voxel-based Magnetization Vector Inversion (MVI) using GEOSOFT's VOXI. This yielded a 3D distribution of the magnetization vectors (i.e. amplitude, declination and inclination). The MVI results provided insight on the magnetic nature of the Veslemøy and Loppa High and allowed a comparison with the Seiland Igneous Province (SIP) on the adjacent mainland, known for its the mafic and ultramafic rocks. The origin of the presumed peridotites in the Veslemøy High and Senja Ridge is discussed; possible options include ophiolitic rocks, mantle rocks exhumed by hyperextension or intrusive rocks. The latter option could indicate a linked magmatic origin for the SIP and offshore highs, possibly related to the Central Iapetus Magmatic Province at Ediacaran-Cambrian times. Finally – could there be a link between the peridotites and the salt deposition?

The sedimentary provenance of Palaeocene – Eocene sandstones from the Svalbard Central Basin and implications for the Palaeocene hydrocarbon plays on the southwest Barents shelf

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The thick mud-dominated Palaeogene Torsk Formation that was deposited on the western margin of the Barents Shelf is an underexplored yet proven play on the Barents Shelf. Despite two gas discoveries, exploration results of these targets have been mixed. A contributing factor to this is due to reduced confidence in regional geological and reservoir prediction models because the sedimentary source for the clastic reservoirs is uncertain.
In the Palaeogene, candidate sedimentary source areas for clastic sediment on the western Barents Shelf include the local basement highs (Stappen / Loppa high), northern Fennoscandia and northeast Greenland. The aim of this sedimentary provenance study was to determine which of these disparate regions was most likely. This was achieved through examining Paleocene and Eocene sandstone samples from well BH10-2008, drilled in the Central Basin on Svalbard. The study included the petrography of 13 samples and 744 detrital mineral chemical, isotopic and geochronological analyses. The signals are compared with similar datasets from the Torsk Formation on the southwest Barents Shelf in order to better constrain Palaeogene sand dispersal.
A major sedimentary provenance change is recorded in the well, consistent with field evidence and other outcrop-based sedimentary provenance studies conducted on the Central Basin. The sedimentary source region changed from one within northeast Svalbard to one from within northeast Greenland in the Early Eocene, as a response to the evolving Eurekan Orogeny. The Eurekan provenance signature is not seen on the western Barents Shelf and the provenance data from these wells suggest sources from Greenland and the developing Eurekan Orogen can be discounted. Instead, the sediment is inferred to have been sourced from local basement highs (Stappen / Loppa high) due to its resemblance with the samples from the Central Basin, which are inferred to have been sourced from northeast Svalbard.
This study provides new constraints on the Paleogene paleogeography and sand dispersal patterns. It suggests that whilst prevalent in Svalbard, sediment from the developing Eurekan Orogen may not have reached the western Barents shelf. Instead, the local topographic highs were the dominant source area throughout the deposition of the Torsk Formation.

The Hopen boreholes and their insight into hydrocarbon prospectivity in the northern Barents Sea

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Hydrocarbon exploration in the Norwegian Barents Sea is currently not permitted north of 74°30'. Despite recent non-commercial work, the hydrocarbon prospectivity in the area referred to as "Barents Sea North" remains rather speculative. However, prior to the present-day restrictions on hydrocarbon exploration in the area, two boreholes were drilled in the early 1970's on the island of Hopen, part of the Svalbard archipelago, in the northern Barents Sea: 7625/7-1 (Hopen-1) and 7625/5-1 (Hopen-2).
The potential insight from these wells is enormous; however, until recently, data from these boreholes has been restricted to mostly confidential reports. Some of the materials from these wells form part of the Harland Collection, held by the Sedgwick

Museum (University of Cambridge) and have been subjected to a renewed phase of analysis.
Sedimentological, palynological and organic geochemical analysis of samples of core and ditch cuttings from the 7625/7-1 (Hopen-1) borehole indicate that it penetrated Late Ladinian to Carnian stratigraphy. A range of facies is encountered, which correspond to four facies associations: deep-marine shelf, prodelta and slope, tide-dominated platform and delta front to delta plain.
This core is interpreted to document the arrival of delta complexes from the east or southeast sourced from the evolving Uralian Orogen. Offshore marine environments in the Ladinian deposited organic-rich mudstones of the Botneheia Formation. Following this, sedimentation became increasing influenced by delta complexes which prograded into the region and gradually in-filled accommodation on the shelf. During the early stages of progradation, a sequence of prodeltaic sediments of the Tchermakfjellet Formation were deposited. Subsequent transgressive events transformed the region into a tide-dominated platform area during which a thick sequence of sandstones and mudstones of the De Geerdalen Formation were deposited.
Organic geochemistry of the well suggests that the Botneheia Formation contains a source rock interval which at peak maturity was oil wet. At a lower maturity it would have been oil and gas prone with excellent organic richness. Similar organic-rich source rocks are found in the Botneheia Formation of Spitsbergen and Edgeøya to the northwest and in the Steinkobbe Formation to the southwest. If these units correlate, it would suggest that the source rock is well developed across the entire western Barents Shelf.

Correlation of Cryogenian diamictites between Svalbard, East Greenland and northern Fennoscandia.

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The global synchroneity of Neoproterozoic diamictites is key to “Snowball Earth” hypothesis, yet correlations between disparate occurrences is often challenging. The most commonly used method from correlating Neoproterozoic deposits is through the magnitude and presence of carbon isotopic anomalies associated with global climatic excursions. Sediment composition, and in particular its provenance can be used to test palaegeographical and palaeoenvironmental models and provide additional constraints on correlation. In addition, provenance can shed light on genesis such as providing evidence for exotic or far-travelled material consistent with a glacigenic origin.
The Polarisbreen Group is a Cryogenian diamictite bearing succession, which forms part of the Eastern Terrane in Svalbard. Its palaeography is poorly constrained and it may have originally formed part of Laurenetia, or may have been an independent microcontinent. In this study, the palaeogeographic position of the Cryogenian succession of eastern Svalbard is evaluated by multi proxy provenance analysis including QEMSCAN, Pb isotopic composition of detrital K feldspar and field-based clast counting. The results are compared with data from the Tillite Group Formation of East Greenland, which is thought to have been deposited in close proximity, with the Eastern Terrane formerly adjacent East Greenland in the vicinity of Ella Ø, Kong Oscar Fjord. These signals are also compared with those obtained from the Smalfjord and Mortensnes formations in northern Fennoscandia. This was done to evaluate the value of the provenance tools as the Fennoscanidan and East Greenland successions were sourced from different continental landmasses.
Pb isotopic patterns from the East Greenland and Svalbard units are strongly overlapping, consistent with a similar provenance and thus their correlation and depositional proximity. Perhaps one of the more striking elements comes from the Fennoscandian successions. The Pb isotopic data from autochthonous Smalfjord and Mortensnes units differ subtly, both have patterns overlapping with Pb isotopic signatures from Fennoscandia. However, the pattern from the Smalfjord Formation within an allocthonous Caledonian nappe is highly exotic for the region. The value of the Pb isotopic data for correlation is of these units within Fennoscandia is underscored, whereby one diamictite assigned to the Smalfjord Formation has a Pb isotopic pattern that is compatible with neither of the autochthonous Mortensnes or Smalfjord diamictites. The provenance data and field observations suggest the stratigraphy in this region may be erroneously correlated.

Sedimentary provenance of Triassic sandstones from southern Spitsbergen

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Uneven palaeotopography is a feature of the western Barents Shelf in the early Triassic. Structural highs either inhibited sediment dispersal or acted as a sediment source. The variable facies of the highs introduce potentially altered sand properties and composition in addition to sand distribution.
The spectacularly exposed Triassic succession around the Sørkapp-Hornsund High in southern Spitsbergen presents an opportunity to investigate these factors in the field, and, possibly reduce exploration risk for analogous submerged systems.
Field and multi-proxy sedimentary provenance data (petrography, QEMSCAN, heavy mineral analysis, garnet geochemistry, K feldspar Pb isotopic data, U-Pb zircon geochronology and combined U-Pb geochronology and trace element geochemistry on apatite and rutile) have helped define four sand types (HST1–4).
The HST1 sand type, which occurs widely in the Early Triassic and intermittently throughout the Triassic to the west of the Sørkapp-Hornsund High, was sourced proximally from regions with a similar geology to the High or from the High itself. The HST2 Sand Type, which includes most of the Middle Triassic strata, was probably sourced from areas affected by the Caledonian orogeny within northeast Greenland. The HST3 Sand Type is confined to Carnian strata to the east of the High. It was sourced from magmatically active and rapidly exhuming regions that was possibly located within the Arctic Uralides near Taimyr. The Snadd Formation of the southern Barents Shelf had a different Uralian source region. The HST4 sand type comprises post-early Norian units across the High and is thickest to the west. Deposited after an inferred drainage reorganisation and basin inversion, it is interpreted to be the result of reworked Palaeozoic-Mesozoic successions located to the north and west.
The distribution of these sand types suggests deposition was strongly influenced by the local Sørkapp-Hornsund structural high. The westward progradation of Carnian Uralian deltaic units appears to have stalled across the high. In addition, the high itself acted as a sediment source, locally delivering lithologically mature sediments. These sandstone relationships may be analogous to the subsurface hydrocarbon-bearing Triassic succession within exploration areas around the Loppa and Stappen highs. This has implications for the occurrence and quality of sandstone reservoir units encountered in these areas, especially since provenance results indicate that the varied depositional environments, introduced by the presence of the high, played a lesser role on the sandstone compositional maturity than provenance.

A sedimentary provenance study of modern river sands from northern Fennoscandia and its insight into the source of Mesozoic successions deposited on the southwest Barents Shelf

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Northern Fennoscandia was periodically a major source of sediment to the Barents Shelf. As the modern exposures may broadly represent lithologies eroded in the past, the analysis of modern river sands can be used to evaluate the extent to which sand deposited on the Barents Shelf was sourced from this area.
Sedimentary provenance techniques were applied to twenty modern sand samples collected from twelve major river catchments in northern Fennoscandia. A highly distinctive provenance signature is recorded in samples from the Tana River, which crosses the Lapland Granulite Belt (LGB). Downstream of exposures of the LGB, modern sands are dominated by rutile with c. 1.9 Ga U-Pb ages and a chemistry indicating crystallization at c. 850 °C from a pelitic protolith.
A detrital rutile signature similar to that in the Tana River is replicated in the Late Triassic – Early Jurassic Realgrunnen Subgroup deposited in the vicinity of the southern Nordkapp Basin, and indicates a common origin from the LGB. The Realgrunnen Subgroup deposited in the southern Hammerfest Basin has a strikingly different proven-

ance pattern. Here, rutiles have mostly 430-515 Ma ages and crystallised at c. 650 °C from a pelitic protolith. The similarity of this pattern to rutile data from the modern Målselva River indicates a source from Caledonian allochthons affected by Palaeozoic amphibolite-facies metamorphism.
Models depicting rejuvenation of a Fennoscandian sedimentary source region in the Late Triassic and early Jurassic are supported by these data. The rutile technique provides one of the clearest mechanisms for tracing the dispersal sediment across the Barents Shelf derived from different parts of northern Fennoscandia.
Despite these contrasting rutile signatures, the Nordkapp Basin and Hammerfest Basin samples yielded similar zircon U-Pb age patterns, dominated by 1.0-1.7 Ga grains. This age range does not correspond with widespread igneous or metamorphic events in northern Fennoscandia and so these zircons were probably recycled from (meta) sedimentary units.
A statistical assessment of the multi-proxy modern sand dataset helps to identify the Barents Sea Group as a source of recycled detrital zircon and hence can account for the mismatch of zircon and rutile patterns in some of the Mesozoic offshore samples. It also shows how readily sedimentary reworking, uneven erosion and fertility can affect and bias the various sedimentary provenance signals.

Differences in sequence stratigraphy and depositional environments of three successive shallow-marine clinothems from the Eocene Central Basin, Spitsbergen

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The Eocene of the Central Basin of Spitsbergen shows a series of eastward building clinothems deposited in a foreland basin. This basin was formed by a westerly active fold and thrust-belt which also acted as provenance area for these shallow-marine sand-wedges. Some of these shallow-marine wedges prograded onto the shelf, whereas some of them reached the shelf-edge and have associated deep-marine sand-lobes.
Three stacked clinothems have been studied interpreted in terms of depositional environment, stacking pattern and sequence stratigraphy. The clinothems consist each of a regressive - seaward building unit followed by a transgressive – landward building unit. The transgressive units of the clinothems consist of estuaries, lagoonal and coastal plain fines, and beach-barrier sand complexes. For the regressive deltaic part, there are clear differences between these three clinothems in terms of the style. The deltaic parts range from a) fluvial and hyperpycnal flow; b) wave reworked delta front; and c) mixed tide and fluvial influenced delta. This variation in deltaic-style is interpreted as a function of the shelf-width of the clinothem below.
These clinothems show a skewed thickness distribution of the regressive vs the transgressive unit within one clinothem in a dip-profile. This gives a good illustration of the concept of sediment partitioning within sequence stratigraphy. This concept dictates that the locus of deposition is forced seaward during regression – towards available accommodation space; whereas during transgression the locus of deposition is moved landward as sediments are trapped here due to added accommodation space in this location. The sediment partitioning concept is a predictive tool and allows differentiation of the internal facies architecture within the sequences, with reservoir implications.

The Role of Caledonian Collapse in the Formation of Norway-Greenland Rifted Margins

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The conjugate plate margins of Norway and Greenland formed along the Silurian Caledonian mountain belt. Orogens are preferred locations for continental rifting because of thermal and structural inheritance within the lithosphere induced by the convergence. Orogeny also leads to a progressively overthickened crust that can collapse when convergence reduces or ceases. In Norway, contraction gave way to extension during the Devonian, leading to re-activation of Caledonian thrusts, crustal thinning, exhumation of high-pressure rocks and denudation of the mountain range. The fast speed of these mechanisms points towards orogenic collapse. But the role of such gravitational flow in the formation of subsequent rifted margins remains unclear, as it is difficult to structurally decipher orogenic collapse from extension applied by far-field tectonic forces.
We use the thermo-mechanical finite element code SULEC to better constrain the dynamics of orogenic collapse and its consequences for the formation of rifted margins. We first built continent-continent collision zones, applying different lithospheric strengths and compression velocities, to dynamically create thrusts faults, sedimentary covers and

crustal thickening. We then use open-boundary conditions to release the potential energy stored during the convergence phase and allow material to flow outside our model box. This stage is dominated by the normal reactivation of inherited crustal-scale thrusts and the former subduction interface. The resulting velocity of extension as well as the surface topography decrease rapidly and the crust gradually returns to its pre-collision thickness preventing longer-term radiogenic heating. Finally, after a certain amount of collapse, we actively extend the continental lithosphere until break-up is reached.
We show that extension following orogenic collapse is accommodated by progressive seaward formation of fault-bounded extensional half-graben basins and core complexes. More mantle is exhumed with lower extension rates. Onshore sedimentary basins form for cases with high amount of convergence prior to collapse.

Ordovician diversification dynamics for hard substrate taxa – a head start for the Great Ordovician Biodiversification Event?

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The evolutionary history of our planet is marked by major events of origination and extinction. One of the greatest increases in biodiversity happened during the Middle Ordovician. It became known as the Great Ordovician Biodiversification Event (GOBE). Previous studies provide evidence that the global increase in taxonomic richness during the GOBE happened during the Darriwilian (c. 467 to 468 Ma). However, there are two components of taxonomic richness: origination and extinction. If we want to understand the mechanisms behind events like the GOBE, we need to get an understanding of the balance between origination and extinction, while considering uneven sampling, which is rampant in the fossil record.
I use data from The Paleobiology Database (PBDB) and capture-recapture models to estimate origination, extinction, and sampling rates simultaneously. My results show that the increase in taxonomic richness during the Darriwilian happened due to a sharp increase in origination rates at the Dapingian/Darriwilian boundary on a global scale. Although it appears that this temporal pattern is common across many different taxonomic groups and in different geographic areas, previous authors have raised the hypothesis that diversification of some taxa on hard substrates started already during the Early Ordovician.
Here, I want to explore the diversification dynamics of taxa that were living on hard substrates during the Ordovician. Do the overall dynamics of origination and extinction differ from the global pattern? Do all taxonomic groups that live on hard substrates show the same patterns of diversification? And finally, what new insights do we gain from these dynamics for understanding one of the greatest biodiversification events on our planet?

Two new niobium cluster minerals from Norway

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In geosciences, niobium (and tantalum) is generally considered to be immobile, by geological processes. Consequently, they are important elements to unravel the rock history. However, Friis & Casey (2018) showed that niobium can indeed be highly mobile when niobium forms polyoxometalate clusters. To date only a handful of niobium cluster minerals have been described, of which Norway is the type locality for the majority.
The current presentation will present data on two new minerals containing niobium clusters. Both minerals have been found by private collector Peter Andresen in the AS Granitt quarry in Tvedalen, Vestfold, Norway within the Larvik Plutonic Complex. The minerals were found at different times in different pegmatites within the quarry, which is mined for the dimension stone larvikite.
The first mineral is a hexaniobate, i.e. contains the Lindqvist ion $[Nb_6O_{19}]^{8-}$, and is the fourth natural hexaniobate to be described. The Lindqvist ions are linked together through Mn^{2+} octahedra forming 1D rods, as in hansesmarkite. The rods are then linked together through two edge-sharing Na-octahedra. This structure has a novel hexaniobate-connectivity, but as it readily dehydration most of the crystal analysed have poor diffraction and the second Na-site seems to be almost vacant. Interestingly, the dehydration results in two slightly different structures, which both will be presented.
The second mineral was discovered in June 2019 and forms bright yellow elongated euhedral crystals in cavities in the pegmatite. The mineral contains the α-Keggin heteropolyion in which four groups of three edge-sharing Nb-octahedra forms a cage around a central Si-tetrahedron forming the ion $[SiNb_{12}O_{40}]^{-16}$. This ion has been synthesised (Nyman et al. 2004), but never found in nature. There are two known heteropolyniobate minerals namely menezesite and aspedamite, but in both cases the Nb cluster consists of six groups of two

edge-sharing Nb-octahedra. The change in cluster geometry means that the known species have large central cations such as Ba and Th. The Keggin clusters of the new mineral are interconnected by disordered Na, Ca and REE sites.

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The Younger Dryas and the Greenland Ice Sheet, a polemic approach

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The Younger Dryas (YD) cold oscillation (12.8 – 11.7 ka BP) happened at a time with increasing summer insolation and rising CO_2 in the atmosphere, and is an outstanding example of dramatic climatic change generated within the earth system. Over the Greenland Ice Sheet (GRIS) temperatures dropped with as much as 10°C, ending with abrupt warming of the same amplitude. How did the ice margin react to these changes? In recent years a large number of studies both from the shelf and from the coastal areas shed light on the ice margin behaviour in this period, raising some problems, and pointing to the urgent need for better dating.

High resolution bathymetric studies have recently yielded a detailed picture of deglacial ice stream behaviour in major transect-troughs on the shelf in all parts of Greenland. Notably, significant GZWs (Grounding Zone Wedges) have, in lack of other methods, been "climatically" dated and referred to cold periods in the ice core temperature record. On the other hand, Cosmogenic dating in coastal areas provides "direct" ages of deglaciation, but only on land; while C14 dating in marine cores also supply "direct dating" of marine changes, which, however, may be offset by possible/likely large scale changes in reservoir effect.

From these two dating approaches, two very different scenarios of YD ice margin behaviour are emerging. "Climatic dating" does, not surprisingly, imply a strong control of temperatures on the ice margin with YD readvance/long-lasting stillstand in mid-shelf troughs. In contrast the "directly" dated records indicate a more complex relation between temperatures and ice margin fluctuations, with no marked effect of neither YD cooling nor late YD warming. In most areas the ice margin retreated throughout YD, but with large variations between troughs, and new dates indicate that large scale moraine systems on the shelf, previously considered to signal distinct periods of cooling, could be metachronous and caused by the interplay between local topography and ice dynamics.

The apparent mismatch between temperatures and ice margin fluctuations may owe to: 1) Unlike other ice sheets GRIS had its entire margin on the shelf at the onset of deglaciation, making it very sensitive to oceanographic change, and 2) The dramatic drop in ice core temperatures was mainly in winter, which would affect Atlantic Meridional Overturning Circulation and sea ice formation, rather than ice margins.

In any case, the relationship between the ice front fluctuations and temperatures has a bearing on the future of GRIS, and there is a strong need for precise dating, and avoidance of habitual thinking.

Description and age of thrust zone separating the Revseggi and Kvitenut nappes of the Hardangervidda-Ryfylke Nappe Complex

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The Revseggi Nappe is the uppermost tectono-stratigraphic unit of the Hardangervidda-Ryfylke Nappe Complex. It is dominated by mica-schists with layers of meta-sandstone and contains kyanite-bearing beds of assumed supracrustal origin. It was intruded by several generations of granite, granodiorite, gabbro and pegmatite, the older ones deformed and metamorphosed. The Revseggi Nappe (previously Revseggi Group) displays a striking lithological and structural contrast compared to the Kvitenut Nappe below it, and it has been speculated that the contact is depositional.

Recent field work has demonstrated beyond doubt that the Revseggi and Kvitenut nappes are separated by a thrust zone, including several tens of metres thick zone of mylonite gneiss, blastomylonite and mylonite and by a zone of thrust-parallel foliation affecting the upper part of the Kvitenut Nappe and the lower part of the Revseggi Nappe. This strongly foliated zone obliterates completely the structure of the older multi-folded layers and internal shear zones in both units.

The thrust history of the Hardangervidda-Ryfylke Nappe Complex is complex, and late Proterozoic to Caledonian (Scandian) thrust events have been reported (see references). The Revseggi Nappe has suffered multistage intrusive and metamorphic events ranging from late Cambrian (495 Ma) to Silurian (428 Ma). Dating of various mylonitic rocks from the Kvitenut-Revseggi thrust contact by use of U-Pb-zircon chronology suggests a multistage Caledonian tectometamorphic thrust history including pre/early Scandian (434 Ma) and Scandian (424Ma) events. The main thrusting of the Revseggi Nappe on top of the Kvitenut Nappe occurred in a pre/early stage of the Scandian thrust phase.

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Stress and deformation analysis in the Barents Sea in relation to Paleogene transpression along the Greenland-Eurasia plate boundary

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Cenozoic contractional structures are widespread in the Norwegian Barents Sea. While the exact dating of the deformation is unclear, it can only be inferred that the contraction is younger than the early Cretaceous. One likely contractional mechanism is related to Greenland plate kinematics at Paleogene times. We use a thin sheet viscous finite element modelling approach to compute stresses and deformation within the Barents Sea in response to the Greenland-Eurasia relative motions at Paleogene times. The analytical solution for the 3-D folding of sediments above basement faults is used to assess possibilities for folding. Two existing Greenland plate kinematic models, differing slightly in the timing, magnitude and direction of motion, are tested. Results show that the Greenland plate's general northward motion promotes growing anticlines in the entire Barents shelf. Folding is more likely in the northern Barents Sea than in the south. Folding is correlated with the Greenland plate kinematics through time: model M1 predicts a main phase of contraction at early Eocene while model M2 predicts contraction later in the Eocene. Both models successfully explain folding above NNE-SSW Caledonian trended faults east of Svalbard and above NW-SW Timanian trended faults in the southern Barents Sea. We conclude that Paleogene Greenland plate kinematics are a likely candidate to explain contractional structures in the Norwegian Barents Sea.

Structure, emplacement mechanism and magma-flow significance of igneous fingers – Implications for sill emplacement in sedimentary basins

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Field and seismic observations show that numerous sills exhibit lobate morphologies. Such observations are in clear contradiction with established models of sill emplacement, which assume that sills are simple planar sheets propagating as tensile fracture in a purely elastic host. Robust understanding of the emplacement mechanisms of finger-shaped sills, and direct observations supporting finger orientation as magma-flow indicator are lacking. In this paper, we present the results of detailed structural mapping on an exceptional, easily accessible 1-km long outcrop in the Neuquén Basin, Argentina, that exhibits a sill, its contacts and the structures in the finely layered sedimentary host rock. We show that the sill is made of distinct segments that grew, inflated or coalesced. We also demonstrate that the fingers were emplaced according to the viscoelastic fingering or viscous indenter models, i.e. the magma pushes its host rock ahead, with no field evidence of tensile elastic fracture mechanism. We identified new structural criteria at the intrusion's contacts for inferring magma flow direction during the magma emplacement. Our small-scale structural observations carried out on a seismic-scale outcrop have

the potential to considerably aid the structural interpretation of seismic data imaging igneous sill.

To better constrain the emplacement mechanism of magmatic fingers, we performed 2D quantitative laboratory experiments of magma emplacement in the brittle crust. The model magma is Golden Syrup and the model crust is a fine grained, Mohr-Coulomb dry granular material of variable cohesion. The syrup was injected at constant flow rate in a 2D Hele-Shaw cell, and its propagation and displacements of the granular material were monitored from the side of the cell. Our experiments show that when the model crust was of high to moderate cohesion, the syrup intrusion dominantly propagated by pushing the host laterally. Conversely, when the model crust was of low cohesion, the syrup intrusion exhibited finger shape and it propagated by pushing the host ahead, triggering local compression in front of the intrusion tip. The results of these latter experiments are in very good agreement with the structural signature of the viscous indenter mechanism, as described in the field. Our field observations and experiments strongly suggest that the viscous indenter mechanism is highly relevant for revealing magma emplacement in weak host rocks, such as shale formations, poorly consolidated sediments, evaporites and the ductile crust.

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Introducing digital mapping in undergraduate field courses: how and when?

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Learning to collect high-quality data in the field is an integral part of Earth Science education. Traditionally, geological fieldwork has been taught in undergraduate mapping courses using paper map, notebook and compass. However, an increasing variety of digital tools has become available over the past decade, and is increasingly used by professionals in the field.

We present a case study where we introduced digital tools in an undergraduate mapping exercise, which is part of the second-year 10 ETCS Structural Geology and Tectonics course at HVL Sogndal. 18 students spent 5 days in the field, whereof 3 days were spent with independent bedrock mapping in groups of 3 students. The students rotated between the following tasks each day: (1) taking notes and sketches with a notebook, (2) taking structural measurements with a traditional compass, and (3) using a Samsung Galaxy Tab3 tablet and FieldMove to take notes, structural measurements, photographs and sketches. After the course, the students evaluated the digital tools, comparing them with the traditional methods.

The following advantages of the digital tools emerged: (1) easier to work in bad weather, (2) easier to orient themselves in the mapping area and to get an overview over the geology, (3) all observations, measurements, photos and sketches are collected together, which helps during post-field-work interpretation. The following main disadvantage emerged: the structural measurements with the tablets were often unprecise, and it took long time for the devices to equilibrate.

Interestingly, 80% of the students rated the influence of the digital tools on the quality of the conducted work as mainly positive to very positive – an impression not supported by the teacher (the quality of the reports was similar to previous years without digital mapping). 87% of the students would like to continue using digital tools during subsequent field work, but also 100% of the students agreed that traditional methods should be learnt *before* using digital tools.

We conclude that introducing digital tools had several positive effects, but also raised several questions: How can we introduce digital tools without loosing solid training in traditional field methods? And how can we make sure that the learning outcome and the quality of delivered products is similar or better than with only traditional methods? We also conclude that combining analogue and digital methods for taking structural measurements was a great opportunity to teach students critical evaluation of their measurements, suggesting that depending on the hardware, digital methods should not be used uncritically on their own.

Acid mine drainage from Folldal mine tailings: Geochemical characterization and simulation

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The mining of certain minerals, such as copper and zinc is commonly connected with acid mine drainage (AMD) problems that can have serious impact on human health and cause ecological destruction. The Folldal mining area was intensively mined for copper, sulphur and zinc for about 200 years from 1747 to 1968. The main objectives of this research work were to predict the acid producing capacity

of Folldal mine tailings by using static and kinetic tests and to develop geochemical models to quantify leachate composition. The static tests were carried out for 19 topsoil samples collected from different parts of the mining area. Humidity cell (small column) tests (kinetic tests) and large column test were performed to assess the sulphate and heavy metals leaching rates from the soil samples. Inverse geochemical modelling using PHREEQC codes was applied to explain possible mass transfer processes between column leachates of mine tailings and rainwater. The net neutralization potential (NNP) and the neutralization potential ratio (NPR) calculated based on total concentration of sulphur and total inorganic carbon, TIC (static test), varied from -159 to 3.3 t CaCO3 /1000 t and 0.01 to 11.5 respectively. The NNP in most samples were in an uncertainty zone (-20 to +20 t CaCO3 /1000 t) and the NPR <1 which indicating that the Folldal mine tailings have a potential to produce acid. The pH values in the leachate samples from humidity cell (small column) test varied from pH 3 to 8. The sulphate production rate in nearly all the leachate samples of the topsoil from the Folldal mining area was >10mg/kg/week, even after 20 weeks of rinsing/leaching, indicating that the tailing material on the surface will release acid over a long time.

Inverse geochemical modelling indicated that dissolution of pyrite, chalcopyrite, schwertmannite and sphalerite accounted for the high concentrations of sulphate, Cu and Zn observed in the study area. However the geochemical model for kinetic oxidation rate of pyrite, did not describe the observed large column test data sufficiently, probably because the PHREEQC model does not take dissolution of ultra-fine particles into account, as well as the impact of microbial activity.

A new nomenclature map of the mid-Norwegian margin: status update

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Since the last official NPD nomenclature map of the mid-Norwegian margin (MNM) was published in 1995 (Blystad et al., 1995), a great amount of data including new 2D and 3D seismic surveys, refraction data, potential field data, seabed sampling, exploration wells, revised biolithostratigraphic schemes have been acquired. This has resulted in improved mapping of the volcanic rifted margin, especially in its deepest part and in the outer (volcanic) province. Within different scientific projects we perform a comprehensive interpretation of this new regional geological and geophysical dataset. This led to the compilation of new nomenclature map of the mid-Norwegian margin, where we unified our structural observations. In order to avoid map visualization complexities and to reflect basin configuration at different stages of the MNM development, we present two separate map sheets showing: 1) the pre-breakup structural elements and 2) syn- to post-breakup elements. The pre-breakup map sheet documents the first order rift architecture of the MNM before the onset of volcanism and includes new and revised structural elements on the platform, terraces and deep Møre and Vøring basin province and related fault systems. The syn- and post-breakup map sheet provides the most up-to-date regional mapping of the different volcanic facies recognized in the outer province. The second map sheet also includes sills and associated hydrothermal vent complexes, magnetic anomaly chrons and oceanic fractures zones, basin inversion structures, slides and glacial depocentres. After the publication, the digital version of the map will be freely available at NGU and VBPR websites and will include different layers in standard GIS formats (e.g. shapefiles) and a ready-to-use GIS project including embedded files, specific color codes, templates and detailed attribute tables. We believe that our new regional map brings a great addition and update to Blystad's landmark map and will help both academic and exploration communities to be introduced to the up-to-date regional framework of the MNM.

Combining the Øygarden Fault Zone and past seismicity to develop a Probabilistic Seismic Hazard Study for U-864 submarine wreck location, west of Fedje Island (Norway)

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On the way from Germany to Japan via Norway, on February 9th of 1945, the German submarine U-864 was sunk by the British submarine Venturer, approximately 2 nautical miles west of Fedje Island

in Hordaland, Norway. Since the submarine was loaded with hazardous mercury, Kystverket is working on alternatives to protect the submarine wreck and the contained mercury for leakage. One option is to cover and fill the area, and the seismic hazard values are important to calibrate the structural requirements for the cap. In this work, we investigated the likelihood for potential ground shaking as excited through earthquakes, in order to provide a basis for geotechnical work estimating the stability of the cover material. Earlier work on that matter was based on the national earthquake hazard map from 1998, which is regarded as not sufficient in local detail and outdated with respect to data and methodology applied.

To estimate the probability of ground shaking from earthquakes, we applied a site-specific Probabilistic Seismic Hazard Analysis methodology. A common approach for hazard evaluation is to use simple area source zones. This approach potentially underestimates the predicted ground motion level, due to well-known smearing effects of the source zones on the distribution of the activity rates. To compensate for this limitation, potentially seismogenic structures defined by structural geological data are used in combination with the past seismicity. This approach combines two different types of earthquake source models: homogeneous area source zones (a Poissonian earthquake distribution until 2019 in southwest Norway) and the Øygarden Fault Zone.

Calculations are performed at Peak Ground Acceleration and several Spectral Acceleration periods for 100, 475 and 10 000 years return periods, i.e. average recurrence time of exceeding a certain expected ground shaking. All results are evaluated at bedrock conditions and are presented in terms of 5% critically damped response values (i.e. the response of a single degree of freedom oscillator). The results are presented with a series of hazard curves and Uniform Hazard Spectra for the U-864 submarine wreck location. Such results are to consider particularly important for local risk assessment and other disaster mitigation-related studies. The estimates of potential future ground shaking are important input parameters to the conduct save dimensioning of the capping and the counter fill that can withstand probable future shaking.

Small impact craters on Mars studied by numerical models and observations at the NASA InSight landing site

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Impact craters are one of the most common geological features in the Solar System and can be found on a variety of different planetary bodies. Due to its widespread nature, crater statistics can be used in remote age determination of planetary surfaces, and is currently the only tool available for such purposes (Öpik, 1960; Shoemaker, 1961). However, target properties such as porosity, strength, cohesion and friction play a major role on the final crater diameter of small craters (e.g. Collins et al., 2011; Wünnemann et al., 2011; Prieur et al., 2017). Since these physical properties vary significantly both horizontally and vertically on a planetary surface, the age estimation when using small crater diameters in crater statistics might lead to errors. We here study the effects of target properties on small impact craters (D < 100 m) near the InSight landing site on Mars, by a combination of numerical modelling and crater statistics. The numerical simulations, 128 in total, were conducted using the shock physics code iSALE (Collins et al., 2004; Wünnemann et al., 2006) for four different velocities and two different target materials, sand and rock, both basaltic in composition. We found that for the different combinations of impact velocities and projectile diameters, but with equal kinetic energy, the derived crater scaling laws were different which contrasts with traditional crater scaling laws. While, for the two different materials the difference was unexpectedly small and revision of the model setup is needed. In addition, cratering statistics and derivation of crater size-frequency distributions (SFD) were performed for two areas with different target properties (sand and rock) for the study area. The crater SFD show that the areas have the same age within the uncertainty, but that they differ in the SFD slope, which could be a result of geological processes. While, the coupling of the crater SFD with power-laws derived from the numerical models show that the change in slope of the two crater SFDs can possibly be explained by difference in target properties between the areas.

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Fe-Mn crusts in the Norwegian-Greenland Sea

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Ferromanganese crusts are regarded as a potential future deep sea mineral resource for elements such as Co, Ti, Mn, Ni, Pt, Zr, Nb, Bi, Mo, W, Th and rare earth elements (Hein and Koschinsky, 2014). From 2010 to 2019 The University of Bergen have collected ferromanganese crusts in the Norwegian-Greenland Sea. Here we present chemical data from several of these Fe-Mn crusts (including crusts collected from the Jan Mayen Frature Zone in 2013 by the Norwegian Petroleum Directorate). The crusts have been analyzed with ICP-MS, ICP-OES and XRF. These hydrogenetic deposits show a unique composition, different from other oceanic regions. The crusts show relatively elevated concentrations of Al, Li, Sc, Nb, Ti and several of the REEs whereas elements such as Co and Bi show relatively low concentrations. Furthermore, from Scanning Electron Electron microscopy we identified sedimentary minerals and we show that internal change in internal chemistry and texture of crusts separated over 300km (Southern Jan Mayen Through and Aegir Ridge) display several similarities.

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Sedimentation rates in the Greater Barents Sea throughout the Triassic

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The largest delta plain in the history of Earth existed in the Barents Sea during the Triassic and caused the deposition of a ca. 3 km thick package in the Greater Barents Sea Basin. This sedimentary package shows thickness variations between different stratigraphically defined intervals, indicating that the sedimentation rates varied immensely through time. These diversities have not yet been studied, and the geodynamic reasons for changes in sedimentation rate are not yet understood. Here, we investigate these variations during the Triassic across the entire Greater Barents Sea Basin (Norwegian and Russian Barents Sea; North Kara Sea, Timan-Pechora Basin, Svalbard, Franz Josef land), compare the sediment thickness to the subsidence in the basin, and discuss the source-to-sink and geodynamic controls that could have caused the variations in sedimentation rates.
Traditionally, it has been assumed that the clastic sediments that filled this basin were sourced from the Uralian Orogeny. Recent studies indicate that the source-areas are more diverse, with sources located in the Southern Urals, the northern Uralides/Novaya Zemlya/Kara Sea, Northern Fennoscandia and in Northern Greenland. The contributions from these sources varied through time, and the total amount of sediment supplied from each source also changed greatly throughout the Triassic.
During Induan times (Early Triassic), the thickest clinoformal unit prograded into the basin. Sedimentation rates were extremely high, and the mass transport exceeded the highest modern mass transport rates from a river (Amazon River) by 2.5 times. During the Olenekian (early Triassic) and middle Triassic, mass transport rates decreased to about a tenth compared to the Induan. Furthermore, a prominent shift of depocenter has been observed: the lower Triassic depocenter was in the Eastern Barents Sea, whereas the late Triassic depocenter was located in the Western Barents Sea. During the late Triassic (early Carnian) sediment rates noticeably increase but were not as high as during the early Triassic. A Carnian peak in sedimentation rates coincides with the depocenter shift in the late Triassic. Tectonic mechanisms (basin subsidence and uplift of source areas) responsible for both creating accommodation space and high sedimentation rates were active in Induan and Carnian time.
Our results show variation in sedimentation rates, clinoform geometries and shelf-edge-trajectories. This variation was caused by different forcing factors operating in the source and sink (e.g. Siberian Traps, Wrangellia LIP magmatism). This information increases our understanding of reservoir type and distribution, source rock potential in the basin, and the geodynamic evolution of the Greater Barents Sea and adjacent regions.

Volcanic geohazards of Jan Mayen

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Jan Mayen is a volcanic island located at 71 degrees north, between Greenland, Iceland and Norway. The island is home to the world's northernmost active surface volcano, and since it was discovered in the early 17th century, there has been at least five volcanic eruptions on the island.
During the Holocene, the volcanism on Jan Mayen has been mostly in the form of Hawaiian to Strombolian eruptions with a smaller number of Surtseyan and dome-forming eruptions. Prior to this study the geohazards of Jan Mayen have not been studied in detail and we present here the first hazard assessment of Jan Mayen volcanism, with emphasis on Sør-Jan and the flanks of Beerenberg.
In this study, we present a volcanic hazard assessment, which evaluates the volcanic susceptibility, estimates recurrence rates, simulates different eruptive scenarios and produces hazard maps for the different scenarios. The susceptibility and hazard maps show how the main hazards, ash fall and lava flows, could affect the infrastructure on Jan Mayen Island. The results of this study will be useful for hazard mitigation, emergency planning and future area use.

Geothermobarometry of recent Jan Mayen tephra

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Jan Mayen is a volcanic island located in the Arctic North-Atlantic Ocean, just south of the junction between the Jan Mayen fracture zone (transform fault) and the Mohn's ridge (mid ocean ridge). The northern part of Jan Mayen island consists of the Beerenberg volcano which has erupted at least four times during the last 400 years.
In this study we investigate the shallow magma storage conditions of the Beerenberg volcano on Jan Mayen by investigating equilibrium glass-mineral pairs. Tephra from several recent volcanic eruptions was collected on the flanks of Beerenberg. Glasses and minerals from these samples have been analyzed with EPMA and results of the EPMA analysis are presented here. These results have been used to conduct preliminary geothermometry and geobarometry calculations to infer shallow magma storage conditions under Beerenberg.
Most of the erupted magmas are of trachybasaltic to basanitic composition, but one of studied the eruptions is of basaltic composition and has a higher Mg content than the other eruptions. Most of the trachybasaltic eruptions contain phenocrysts of olivine, pyroxene and feldspar, while the basaltic eruption contains pyroxene and only minor amounts of olivine and feldspar. The preliminary temperature reconstructions show eruptive temperatures around 1150 °C for the trachybasaltic eruptions with pressures around 6 kbar, and 1170 ° C temperature and pressure of around 2 kbar for the basaltic eruption. The geobarometric calculations show that at least two levels of magma storage have existed underneath Beerenberg in recent times.

Glacier changes in interior northern Svalbard since 1923, based on repeated photography and Structure-from-Motion DEMs

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In 1923 a sledge party from University of Oxford came to northeastern Spitsbergen and performed the first east-west crossing of this section of the island. They gathered unique photographic material from the interior of Svalbard. 93 years later (2016) a reconnaissance expedition from Oxford University was able to repeat the journey and retake photographs from the same locations. The 2016 expedition also acquired image data from small unmanned aircraft systems (sUAS) to produce 3D models of the glacier surface with Structure-from-Motion (SfM) photogrammetry. Several sections across Chydeniusbreen were flown at different altitudes along the glacier length, primarily in the same regions as transects of ICESat laser altimetry. The DEM results were compared to DEMs from the Norwegian Polar Institute and will be compared to the ICESat data as well as to the more recent ArcticDEM. A retreat and thinning of the terminus between 2011 and 2016 was detected,

whereas the other transects were harder to interpret due to a large offset between the datasets. Comparison of the historical and recent photos of glacier state along the route, showed minor differences in glacier size along the coast, but the appearance of new snowfields in the interior in 2016. This is in large contrast to the glacier change for the rest of Svalbard. During the spring of 2018 and 2019 additional sUAS data in the vicinity of the sledge route were compiled, this time from steep icefalls in the Atomfjella area, providing SfM DEMs of glacier terrain previously unstudied. The steep nature of these glaciers challenge high-resolution satellite monitoring, hence the SfM DEMS offers valuable insight in the state and dynamics of some of the steepest and fastest cold-based glaciers on Svalbard.

Diffusive and advective transport of methane in the martian subsurface

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During the whole geological history of Mars, methane formation mechanisms could have taken place in the deep subsurface and could still be active nowadays. After its generation, methane would migrate upwards and be either directly released at the surface or trapped in subsurface reservoirs (clathrates, zeolites or sealed traps) where it could eventually accumulate over long time periods before to be episodically liberated during destabilizing events.
In this work, methane transport through the martian subsurface is studied using a one-dimensional numerical model considering adsorption onto, advection and diffusion through the regolith. The total CH_4 flux is given by the sum of the advective flux calculated via Darcy's law and the flux resulting from molecular and Knudsen diffusion. The latter is determined using the mean transport pore model. Surface diffusion is generally not significant and is thus not taken into account in this study. Pressure diffusion and thermal diffusion are also neglected as their contribution is rather small compared to molecular diffusion (concentration gradients) and Knudsen diffusion, which are normally considered to be the most important diffusive processes in soils. Finally, adsorption is modelled similarly to Meslin et al. (2011). Experimental methane fluxes from clathrate dissociation are imposed at the base of the model to describe the lower boundary condition. The CH_4 subsurface reservoirs are assumed to be located several meters to several tens of meters below the surface following the clathrate stability zone.

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Geomechanical and geophysical evaluations for safe CO_2 storage in the North Sea

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Norway is planning to launch large-scale CO_2 storage projects in the North Sea. The first full-scale project "Northern Lights" is on its way to realization, where Equinor is teaming up with Total and Shell. For such offshore CO_2 storage projects, geomechanical and geophysical evaluations are essential to ensure safe operation and avoid unwanted leakage of CO_2 to the seabed, i.e. storage conformance and containment. In this study, we evaluate the feasibility of microseismic monitoring for CO_2 injection within potential storage sites in the North Sea. Microseismic monitoring is based on measuring seismic signals resulting from abrupt movement, deformation, and re-activation or creation of fractures and faults within the subsurface. For this, we performed advanced laboratory tests in combination with numerical simulations at the field scale, including fracture/fault (re-)activation. The laboratory work includes acoustic emission (AE) monitoring of laboratory-scale microseismicity. This presentation focuses on the geomechanical characterization of the relevant lithologies, based on tested cores and analysis of well log data. Examples of local- and field-scale geomechanical modelings are shown, with focus on the expected geomechanical behavior of CO_2 reservoirs in the North Sea. The tested cores are sandstones and mudstones of potential CO_2 storage reservoir and cap rocks that are representative of the North Sea lithologies (e.g., Draupne and Sognefjord formations). Insight from our laboratory tests was scaled up and applied to field scale through numerical geomechanics analysis. The interpretation of such monitoring data requires a quantitative understanding of subsurface concerning geology, geomechanics, and geophysics. The work is performed under the project IGCCS (Induced-seismicity geomechanics for controlled CO_2 storage in the North Sea, # 268520/E20) supported

by the NFR-CLIMIT program and two industry partners Equinor and Total.

Thermo-tectonic development of the Wandel Sea Basin, North Greenland

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The Carboniferous to Palaeogene Wandel Sea Basin of North Greenland is an important piece in the puzzle of Arctic geology, particularly for understanding how the Paleocene–Eocene movement of the Greenland Plate relates to the compressional tectonics in Canada and on Svalbard during the Eurekan Orogeny.

Our study reveals a long history of episodic burial and exhumation since the collapse of the Palaeozoic fold belts along the east and north coasts of Greenland. Our results provide evidence for pre-Cenozoic phases of uplift and erosion in Early Permian, Late Triassic, Late Jurassic and mid-Cretaceous times, all of which involved removal of thick sedimentary covers.

Paleocene exhumation affected the major fault zones of the Wandel Sea Basin. The Paleocene episode defines the timing of the compressional event that caused folding and thrusting of Upper Cretaceous and older sediments along these fault zones. We suggest that the inversion reflects the onset of the Eurekan Orogeny caused by the movement of the Greenland Plate after the onset of seafloor spreading in the Labrador Sea.

Regional end-Eocene uplift and erosion affected the Wandel Sea Basin after the deposition of the Thyra Ø Formation, when a Palaeogene cover of about 2.5 km was present across a wide area. Northern Peary Land, north of the Harder Fjord Fault Zone, was uplifted about 1 km more than the area south of the fault zone during this episode. The end-Eocene regional denudation and reverse faulting coincides with the end of seafloor spreading in the Labrador Sea and hence with the end of the Eurekan Orogeny. The significance of this is not clear as these events also coincide with a major plate reorganisation in the North-East Atlantic as well as with regional exhumation of West and East Greenland and adjacent Arctic regions.

Mid–late Miocene cooling reflects removal of a sedimentary cover of about 1.5 km across most of the study area.

The preserved sedimentary sequences of the Wandel Sea Basin represent remnants of thicker strata, much of which was subsequently removed during multiple episodes of uplift and erosion. The thickness of these sedimentary covers implies that they must have extended substantially beyond the present-day outline of the basin, and thus that the Wandel Sea Basin at times was coherent with sedimentary basins in North-East Greenland, Arctic Canada and Svalbard, as has been suggested from stratigraphic correlations.

Bed controls on the retreat dynamics of marine-based ice sheets

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Basal topography and substrate geology are widely considered to exert a control on the flow and retreat behaviour of ice sheets. Theory dictates that, for example, negative relief topography such as troughs and fjords should facilitate ice streaming, that beds that deepen towards the interior (i.e. 'reverse slopes') will undergo uncontrolled grounding line retreat, and that an unconsolidated substrate will drive streaming via bed deformation while high-friction beds will stabilise both flow and retreat. Crucially, these relationships imply that the first-order evolution of marine-based ice sheets may be predicted based on their topographic and geological setting. High-quality and high-resolution bathymetric data from glaciated continental shelves allow us to document the style of ice flow and retreat in diverse subglacial settings. Here we analyse glacial landform assemblages from 101 locations peripheral to the Antarctic, Greenland, Laurentide, NW European, Icelandic and Patagonian ice sheets and ask whether, and to what degree, palaeo-ice flow and retreat styles correspond systematically to their catchment-scale basal settings. We find that topographic setting broadly determines ice flow style. Troughs indeed favour ice streaming, but banks are not a universal impediment to streaming flow: given a large catchment and a low amplitude bank, sensitivity to topographic steering is overcome. We find that the faster the flow, the less sensitive it is to the underlying bed slope, and we suggest that, once initiated, a stream can be maintained in settings that might otherwise be considered less favourable. The broad topographic setting is a poor indicator of the style of grounding line retreat. As expected, reverse sloping beds favour inconsistent or

unimpeded grounding line retreat, although when supply is high and lateral pinning is effective, steady, regular retreat occurs. Surprisingly, both the speed of ice flow and the style of grounding line retreat are insensitive to the type of substrate.

Assessing the potential of microseismic monitoring of North Sea geological CO_2 storage sites through laboratory testing

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Carbon capture and storage is necessary if we are to reach net-zero global CO_2 emissions. Currently, North Sea saline aquifers are targets for large-scale geological storage of CO_2. At such storage sites, geophysical monitoring is needed to follow changes within the reservoir sandstone and the sealing caprock above and avoid leakage of CO_2 to the seabed. In particular, pressure changes due to CO_2 injection may cause slip on faults within and around the reservoir, resulting in detectable microseismic activity. Microseismic monitoring can inform on deformation within the reservoir, the location and geometry of faults (including sub-seismic faults), and the in-situ stresses.

To assess the effectiveness of microseismics as a monitoring tool, we must first characterise the potential for microseismicity within North Sea lithologies. We carried out triaxial tests on samples of potential North Sea reservoir rocks (sandstones of Sognefjord and Utsira formations) and cap rocks (shales of Draupne and Nordland formations). In each test, the sample was coupled with an array of piezo-transducers to measure ultrasonic wave velocities and monitor acoustic emissions (AE)—sample-scale microseismic activity generated by microcracking. Each sample was first consolidated by axial and radial loading to the relevant effective horizontal and vertical stresses, before a through-going shear failure was created by axial loading. Following failure, the fracture planes were then reactivated multiple times by axial loading at different effective horizontal stresses, i.e. at different simulated depths.

We detected several thousand AE events while testing the sandstones, for which we calculated the AE rate, analogue seismic b-values and AE source parameters (including magnitude and frequency content), localised AE events, and inferred AE focal mechanisms and moment tensors from P-wave first motion polarities and amplitudes, as well as their fault plane directions. Where available, fault plane directions were used to infer the in situ stress field local to AE events.

The deformation of the shales, however, was aseismic within the observable frequency range. The clay content of these shales (~50-70 %) also points to aseismic deformation. For all samples, we quantified the stress conditions required for fracture propagation and fracture reactivation within these materials, and determined the frictional properties of the fracture planes.

We compared our laboratory results with data on relevant lithologies at different scales, which together suggest that because of CO_2 injection, we may expect little microseismic activity to originate from the caprock, although microseismics may provide insight into fault locations, and deformation and stress changes within the reservoir itself.

Surface water conditions and vegetation changes in the marginal Arctic Ocean (ODP Hole 910C, Yermak Plateau) during the mid-Piacenzian Warmth Period, derived from palynomorphs

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The marine palynomorphs in twenty-four samples from a 41-39 m thick late Pliocene (3.53 to 2.98 Ma) sedimentary sequence in Ocean Drilling Program (ODP) Hole 910C at the Yermak Plateau in the marginal Arctic Ocean, eastern Fram Strait, have been investigated. Twelve of the samples are from sediments deposited during the mid-Piacenzian Warm Period (mPWP) (3.264–3.025 Ma) with a temporal sample resolution of 15 to 22 ka. The other samples are from the time period before this phase, including the Marine Isotope Stage M2 (3.312–3.264 Ma) and the periods succeeding the mPWP. Terrestrial pollen and spores have been further investigated in sixty samples from the same interval (3.4-2.98). This study is focusing on comparing the impact of vegetation-based climate changes against the occurrence of marine palynomorphs. The dinoflagellate cysts (dinocysts) reveal that although the site was influenced by warm

Atlantic water, as reflected by Cyst of *Protoceratium reticulatum*, polar water masses dominated (domination of *Brigantedinim* spp.). The dinocyst data from the mPWP suggest that surface water temperatures during summer reached values above those at present in the region (e.g. the dinocysts *Barssidinium pliocenicum*, *Oligosphaeridium israelianum*). During the mPWP, the water column may have been vertically mixed, at least during spring/early summer. Taxa like the dinocyst *Islandinium minutum*, indicating a stratified water column and Arctic surface waters during spring/early summer, are lacking. The relative frequency of marine and terrestrial palynomorphs have been evaluated using multivariate analysis. Palynomorphs were analysed irrespective of climatic phases derived from pollen datasets in the ecological perspective. Therefore, the relative dominance of temperate pollen taxon like *Pinus-Abies-Podocarpus* and *Betula-Juglans* types assemblage suggest climatic fluctuations from cold and wet to warm and humid, respectively, during 3.4-3.01 Ma. A sharp increase in *Pinus-Abies* during the M2 glacial phase is correlated with a decline in *Operculodinium israelianum*, which suggests a weak thermohaline circulation. During early mPWP, most of the warm temperate plant taxa correlate with *O. israelianum,* and *P*. *reticulatum* prevalence. However, the occasional and rare presence of dinocyst *Lingulodinium machaerophorum* indicates sporadic supply of freshwater and stratified waters. It correlates with the occurrences of *Picea*, *Podocarpus*, *Juglans* and herbs showing frost-free summers during the late mPWP. Although sea ice may have existed, its presence cannot be confirmed by the dinocysts recovered from the sampled sediments.

Marine palynomorphs reveal a Miocene age for the Molo Formation, Norwegian Sea shelf off Vestfjorden

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Marine palynomorphs have been re-analysed from seven side-wall cores from the lower part of the Molo Formation in exploration well 6610/3-1 off Vestfjorden/Lofoten. Taking advantage of the description of new species from other studies, and access to reference successions from nearby sites with an independent chronostratigraphy, we have obtained an improved and more reliable depositional age constraint for the Molo Formation in its northern distribution area. Taken together, the new data provide incontrovertible evidence for a Miocene age for the Molo Formation in well 6610/3-1. This age is supported by e.g., the lowest occurrence of the dinoflagellate cysts *Barssidinium graminosum* and *Barssidinium pliocenicum,* and the highest occurrence of the dinoflagellate cysts *Minisphaeridium latirictum* and *Operculodinium piaseckii*. The deposition of the Molo Formation in well 6610/3-1 was initiated subsequent to a time period of erosional activity which, according to our data, took place between the late middle Miocene and the late Miocene. The dinocyst data suggest that the Molo Formation in well 6610/3-1 started to accumulate at around 8.8/8.7 Ma. Support for this interpretation is provided by the presence of the dinoflagellate cyst *A. andalouisiensis andalousiensis,* the co-occurrence of the dinoflagellate cysts *Barssidinium evangelineae* and *M. latirictum,* and the presence of the acritarch *L. lucifer*. The conditions during deposition of the sediments were characterized by a warm temperate, high-energy environment influenced by river discharge. Extensive erosion and recycling of older sediments, particularly from the Paleogene, provided a significant/important source for the sediments in well 6610/3-1. The combined effects of eustatic sea-level fall and uplift/updoming of the hinterland/coastal zone exerted a strong influence on the erosion and rapid accumulation of the investigated sequence.

The nordite-group from the Ilímaussaq Alkaline Complex, South Greenland

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The nordite-group is a complex rare-earth silicate with the ideal formula Na_3Sr*REEMe*Si_6O_{17}, where *Me* can be Zn, Fe, Mn, while REE site is most prominently occupied by Ce or La in addition to traces other REE.
The nordite-group consists of five approved species all of which have first been described from the alkaline complexes of the Kola Peninsula, Russia. From the Ilímaussaq Alkaline Complex, nordite has been described from a trachytic dike on the island of Igdlutalik, which is known as the type, and only, locality of emelusite and is also rich in narsarsukite (Upton et al. 1976). In addition to the Igdlutalik

occurrence, we have discovered a locality rich in nordite at the Taseq slope in the northern part of the complex.

At Taseq the nordite is associated with ussingite, i.e. highly agpaitic conditions, as it is the case from most of the Kola occurrences. Whereas nordite at Igdlutalik is associated with a more Si-rich environment, that even has some quartz. The current presentation will provide the first chemical and crystal structural characterisation of nordite from the Ilímaussaq alkaline complex. We have confirmed that the nordite from Igdlutalik is nordite-(Ce) with the empirical formula $Na_{3.07}(Sr_{0.75}Ca_{0.21}Ba_{0.05})_{Ó=1.01}(Ce_{0.53}La_{0.44}Nd_{0.05}Pr_{0,03})_{Ó=1.05}(Zn_{0.84}Fe_{0.02}Mg_{0.02}Mn_{0.01})_{Ó=0.90}Si_{5.99}O_{17}$.

The analysis of the nordites from Taseq has proven to be because they contain the highest Ba content of any published nordites. In several analyses the Ba content surpasses the Sr content and would qualify as a new species. The dominant REE of the Ba-rich nordite is Ce and Fe dominates the *Me*-site. Single-crystal structure refinements show that the Na-sites are still dominated and almost solely occupied by Na, whereas the site scatter of the Sr-site shows it to be dominated by Ba. Because the *Me*-site is dominated by Fe the investigated mineral is the Ba equivalent of ferronordite-(Ce) and has the ideal formula $Na_3BaCeFeSi_6O_{17}$.

Adding to the species complexity is the presence of sector zoning in the minerals from Tasseq, while the ones from Igdlutalik are more homogeneous. This is a structure not described in nordites before, supporting the notion of a new species.

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Nordic groundwater quality monitoring; status, trends and future

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Nordic countries have monitored groundwater quality for several decades. Effects of acid deposition were a key motivation during earlier programs (from ~1970-ties), but new sets of groundwater related challenges have risen through the years and decades. Pesticides, fertilizers and road salts have been of concert for long, whereas new substances such as pharmaceuticals, microplastic and PFAS will present themselves, expected or not, in our groundwater resources as well as in many other parts of our environment.

Today the EU Water framework directive (WFD) and its groundwater daughter directive (GWFD) is leading the way for an appropriate set of groundwater monitoring programs in EU and other WFD-associated states. National level authorities as well as regional and local water authorities all need to apply to legislation derived from the WFD and organize an adequate monitoring regime based on assessments of aquifer vulnerability and human activities potentially affecting the groundwater resources.

WFD was made to protect European water resources through at common frame of rules, restraining member states from prioritizing national business competitiveness at the expense of the qualitative or quantitative state of their own water resources. But still all states applying to the WFD need to address their monitoring needs in their own way, locally adapted to geology and polluting activities, as well as to the experience and the data they acquire along the road. How often to sample, how densely to sample, which areas to prioritize, which parameters to measure, how to group groundwater bodies and so on; will therefore need individual adjustments and continuous updating in each state.

With that in mind, Nordic countries were invited to contribute with a brief overview on how *they* have decided to monitor and publish national groundwater quality data; for WFD or other uses. The speech will summon and compare the contributions; presenting some general status and trends on Nordic groundwater quality, as well as the tedious and thorough monitoring programs that were necessary to get the numbers.

Structural control of selected sulphide deposits in Mofjellet, Nordland

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The Caledonian orogenic-metallogenic belt is known to host abundant sulphide deposits with varying grades and volumes of base metals, many of which were exploited economically. The deposits are related to mid-ocean ridges, island arc and back-arc spreading ridges, and are classified as volcanogenic massive sulphide (VMS) deposits (Grenne et al., 1999). The formation resulted from

Rodinia rifting and subsequent opening of the Iapetus ocean during Neoproterozoic to Devonian, i.e. pre-Caledonian, age. The Rana area in Nordland, Norway, is known to host several sulphide deposits, some of which were mined mainly in the last century. The largest mine was the Mofjellet mine, which, in the period 1928-1987, produced 4.35 Mt of ore with the grades of 3.6% Zn, 0.7% Pb and 0.3% Cu.

This master thesis focuses on the geology and structures related to two different ore zones, hosting sulphide deposits, the Hesjelia- and the Hellerfjellet ore zones, both of which are located within the Mofjell Group of the Rödingsfjäll Nappe Complex in the Uppermost Allochthon of the Scandinavian Caledonides. Earlier work focused on geological and geophysical mapping and geochemical characterisation of the host rocks and deposits, in order to approach the geological environment and a possible genetic connection between the different deposits. One drill hole has implied a connection of two outcropping deposits in the Hesjelia ore zone, the Hesjelia and Hammertjønna deposits. A drill hole in the Hellerfjellet zone has confirmed that the Hellerfjell deposit has a minimum length of 250m down dip, while geophysics indicate a strike length of 1.5 km. One important task is to understand the structures controlling the geometry of the deposits, and thus the main ore axis, and further to create a 3D model based on surface observations and drill hole data. Another task is to constrain the nature, origin and sequence of the host rocks, based on whole-rock geochemistry and zircon dating. The practical aim of this thesis is to provide data to the mining company Sotkamo Silver Oy, which will be used in their future core drilling campaigns.

Results to be presented at the conference include a 3D model and geochemistry plots.

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Teaching and learning Plate tectonics in school science – a research design

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This paper presents an ongoing PhD-project focusing on lower secondary school students learning plate tectonics. In the new national science curriculum, *Kunnskapsløftet 2020,* plate tectonics is emphasized, and has the potential to facilitate deep learning. However, research on teaching and learning about plate tectonics is scarce, and more research is needed on instructional approaches on the subject (Mills, 2016). Additional research presents students' misconceptions on important geological processes such as earthquakes, rock formation and volcanoes (Francek, 2013).

Therefore, this PhD-project builds on the aforementioned research as well as theoretical perspectives on science learning. Together with teachers, a 12 hours teaching design has been developed and tried out with a class of 30 students (aged 13). The teaching activities aim to engage students in scientific practices across classroom and the local environment to learn about plate boundaries and consequential formation of major rock groups. Preliminary research questions are: a) How do students develop understanding of plate tectonic processes? b) How can teachers support students' meaning making processes through a dialogic approach? c) In what way does learning activities in the teaching design contribute to students' exploratory talk?

Data comprise interviews with students and teacher(s), video data recorded through class- and field sessions, as well as students' written material such as diagrams. In this presentation, we focus on the teaching design and preliminary results and implications for teaching plate tectonics in lower secondary school.

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Comparing classic mineral analysis using optical microscope, XRD-XRF with modern automated mineral detection such as QemScan

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7120/12-2, Alke discovery, was drilled by Norske Hydro in 1981. Six cores were cut inclusive the Basement at TD. An extensive mineral analysis was done by IKU including optical microscope, electron microscope and XRD at 62 core samples. In 2017, 257 core chips were sampled and sent to Rock Type in Oxford to run QemScan analysis (Ayling et

al., 2012) for comparison. Optical microscopy, scanning electron microscope with EDS, X-ray diffraction (XRD) and XRF represents the key methods used to characterize material properties in the past. These techniques still play a crucial role in mineralogy, petrology and geology. Last two decades have seen the widespread use of SEM-based Automated Mineralogy (AM) systems to help identifying minerals by their composition and to quantify their proportions, size and textural relations.

AM instruments such as QEMSCAN were initially designed for use in mineral processing to determine particle mineral liberation from plant products. Quantitative Evaluation of Minerals by Scanning Electron Microscopy is a fully automated micro-analysis system that enables quantitative chemical analysis of materials and generation of high-resolution mineral maps as well as structure (Sandemann, 2015). Although the combination of SEM and EDS is not new, it is from year 2000 and onwards the proportion of elements of each mineral was stored in databases and large mineral libraries were generated. This led to the fast-automatic mineral analysis. Today, automatic mineral analysis is regarded as objective versus the optical microscopic method that is very subjective.

A sample in Stø formation at about 1962 meters, the rock matrix contains 21% of Halite in addition to 47% Quartz, 12% clay minerals and a porosity of about 10%.

Mineral studies form the 80's typically includes correct quantity of quartz, feldspars and pyrite, but then includes a considerable number of elements called; rock fragments, clastics, cement, matrix and organic matter, all in reality unidentified minerals.

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The Last Glacial and Holocene proglacial deposits of Lake Bolshoye Shchuchye, Polar Ural, Arctic Russia

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Seismostratigraphic studies of the 11.8 km^2 and ~140 m deep Lake Bolshoye Shchuchye, Polar Urals, reveal that the lake basin contains up to 160 m thick acoustically laminated sediments. The spatial and temporal distribution of the lake sediments have been mapped with the aid of 100 seismic profiles and 2 well-dated long sediment cores retrieved from the lake basin. Time slice maps constructed from the seismic reflection data allows the sediment volume and sediment flux to be quantified through four periods. Hemipelagic processes dominated the sedimentation in Lake Bolshoye Shchuchye during at least the last 24 cal. ka BP, with only local variations from delta progradation and slope gravity processes. The sedimentation rate during Last Glacial Maximum was high and characterized by varved deposits. A major shift in the sediment accumulation, dated to *c.*18.7 cal. ka BP, is interpreted to mark the end of the local glacial maximum and the initiation of glacial retreat in the area. Around this period, the sedimentation flux was greatly reduced, indicating fast retreat and possible disappearance of the glaciers. The shift at the Younger Dryas - Holocene boundary is very pronounced in the seismic signature, marked by a further reduction in sedimentation rate. The denudation rate in the accumulation area during the Holocene is only the eighth part of the LGM denudation rate. The age of the oldest stratified sediments in Lake Bolshoye Shchuchye is not well constrained, but estimated to *c.* 50-60 ka.

Mapping of chemical, physical and geological conditions in the upper parts of river Risas watershed due to episodes of fish deaths

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In the spring of 2007, 2015 and 2016 brown trout in the upper parts of the river Risa, Ullensaker municipality, Norway, was observed to behave strange and several were already dead, not witnessed earlier. During all three episodes a large number of either dying or dead trout were collected and some of the fish where analyzed. Results from the analyzes showed that many of the trout had high concentrations of iron, manganese and aluminum on their gills. It was concluded that metals precipitated on the gills which caused insufficient oxygen uptake, and that this was the

likely cause of the fish deaths on all the occasions (Teien et al., 2008).

To this day there has not been any success in finding the cause for the metal-rich water that caused the fish deaths. Whether natural episodic events or human activities are the reason is still unknown. One theory is that anoxic groundwater is the source of the metal-rich water, other natural sources that have been discussed are bogs and waterbodies in the watershed with possible low pH and high concentration of metals (Hongve, 2016). Human activities in the relevant time periods have to be explored. Within the watershed there are several anthropogenic activities; the Oslo airport, military activities, an infiltration system for landfill leachate, agriculture, gravel pits and a motorway (E6), all of them in need to be considered as possible sources of contamination to this river. Due to high pH and circulation of the Risa river, a previous master thesis found it unlikely that the groundwater would cause episodic releases of metals enough to kill the fish and suggested instead an alternative hypothesis of ammonia contamination (Frogner & Almhjell, 2019). This Master thesis is a contribution to further research on possible causes of the fish deaths in Risa. The hydrogeology downstream the leachate infiltration facility will be important in this case as it drains to Risa. To explore potential sources of metals, chemical analyses of water and soil will be performed and deposits within the watershed will be mapped in detailed. The latter will be used in a MODFLOW model to reconstruct groundwater flow and potential contaminant transport.

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Compositional and isotopic micro-analysis by LA-ICP-MS at the Norwegian Laboratory for Mineral and Materials Characterisation (MiMaC, NGU-node)

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The newly established Norwegian Laboratory for Mineral and Materials Characterisation (MiMaC) comprises state-of-the-art instrumentation intended to study samples along the value chain from raw mineral resources to advanced processed materials. The MiMaC node at the Geological Survey of Norway (NGU) includes a new Cetac 193-nm excimer laser, Agilent 8900 triple-quadrupole ICP-MS, and Nu Plasma 3 high-resolution multi-collector ICP-MS. The laser enables high-spatial-resolution microanalysis, with beam diameters of 1 -155 mm and excavation of 10's-100's of nm per pulse. The triple-quadrupole ICP-MS rapidly measures across the mass spectrum from Li to U and permits energy filtering and chemical separation in a collision-reaction cell situated between two quadrupoles. The multi-collector ICP-MS is capable of high-precision isotope ratio measurements with ~100 ppm reproducibility (2 relative standard deviation) in minerals sampled by laser-ablation. Together, the instruments enable a plethora of compositional and isotopic analyses of many different geologic and synthetic materials. In this presentation, I will give an overview of the capabilities and future plans of the MiMaC LA-ICP-MS lab at NGU, including radiogenic isotope (Sr, Nd, Hf, Pb) analyses of minerals, U-Th-Pb accessory (zircon, titanite, apatite, monazite) and rock-forming (calcite) mineral dating, 2-D trace element mapping, and laser-ablation split-stream measurements (coupling the laser to both ICP-MS instruments simultaneously), among others. The MiMaC node at NGU is accessible to users across Norway and abroad with the aim of facilitating high-level mineral and materials research.

Lower Cretaceous source rocks in the SW Barents Sea – Aptian and Cenomanian potential

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Due to a complex geological history with deep burial and subsequent uplift, exploration on the SW Barents Shelf has been difficult, resulting in few commercial discoveries. A major risk factor is the presence and maturity of potential source rock (SR) units. Traditionally, the Upper Jurassic black shales has been given most attention as it represent the main SR unit for most of the large producing oil and gas fields across the Norwegian Continental Shelf. Despite its wide distribution on SW Barents Shelf, the Upper Jurassic Hekkingen Formation is typically only oil-mature in a narrow belt along the western margin of the Hammerfest Basin and the Loppa High. In the marginal basins further

to the west, the Upper Jurassic is deeply buried and over-mature. The presence of alternative SR units is therefore crucial for exploration success.
By combining seismic and well data, this study investigate the Lower Cretaceous succession in the deep marginal basins of the SW Barents Sea focusing on the presence and distribution of intra-Cretaceous organic-rich units that may act as alternative SR units.
Our findings suggest that lower Aptian SR units may be viable in the Fingerdjupet Subbasin and the Hammerfest Basin. However, several factors limit their lateral extent and accumulation potential. Among these are the structural delimitation as these units accumulated in active rift basins. Periods of anoxia and relative high sedimentation rates are key processes in these restricted basins in order for accumulation and preservation to take place. The Bjørnøya and Tromsø basins underwent significant subsidence during the Late Jurassic–Early Cretaceous rift phase. The lower Aptian SR unit is consequently over-mature and difficult to interpret. Instead, a Cenomanian SR unit could provide an alternative source for hydrocarbon generation in these deep basins.

A new process of glacial erosion: geomorphological evidence from Sweden

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Traditionally, two main processes of glacial erosion are recognised: abrasion and plucking. We present field observations that indicate operation of a third, highly effective process of glacial erosion which we term *glacial ripping*. Geomorphological evidence for glacial ripping comes from low relief Precambrian gneiss terrain in eastern Sweden. Boulder spreads are extensive, 0.5-4 m deep covers of large, angular boulders, many with glacial transport distances of 1-100 m. Boulder spreads are distributed in ice-flow parallel belts up to 10 km wide in Uppland and extend over a distance of >500 km in Sweden on the former bed of the last Fennoscandian Ice Sheet (FIS). Boulder spreads occur alongside partly disintegrated, large roches moutonnées, typically with displaced blocks, caves and lee- and flank-side block trains. Both features are closely associated with disrupted bedrock, where rock masses show extensive fracture dilation in the near surface, locally with sediment fills in sub-horizontal fractures. Our hypothesis is that these features derive from a subglacial process sequence of (1) hydraulic jacking and bedrock disruption, (2) ripping and (3) transport and final deposition of boulders. Soft sediment fills in fractures in quarries and excavations indicate jacking and dilation of pre-existing joints under conditions of groundwater overpressure to depths of 1-10 m below the former ice sheet bed. Overpressure reduces frictional resistance along basal fractures. Where ice traction overcomes this resistance, the rock mass strength of the near-surface rock, including knobs, is exceeded, resulting in disintegration into blocks. Further ice sliding transports the fragmented blocks, creating boulder spreads and locally piling boulders on moraines. Short boulder transport distances, the small (<0.5 km^2) extent of many discrete boulder patches and boulder covers on moraines indicate that the processes involved in ripping developed late in the last deglaciation. North of Stockholm, glacial ripping operated during the rapid retreat and downwasting of the FIS from its Younger Dryas limits. The depths of rock mobilised to form boulder spreads are estimated as 1-4 m. This compares with mid-range estimates of 1.6-3.5 m depths of erosion over the last 100 ka derived from cosmogenic nuclide inventories of samples from non-disrupted bedrock surfaces in Uppland. Glacially disrupted and ripped bedrock is also made ready for removal by future ice sheets. Hence the newly recognised ripping process set is a highly effective mechanism for glacial erosion.

Late Cenozoic depositional patterns and basin configuration, Northern North Sea (60-62°N): The Utsira Formation

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The Northern North Sea is one of the most studied basins in the world, but there has been less emphasis on the Late Cenozoic successions. A new 35 000 km^2 3D seismic survey from 60-62°N facilitates regional analysis for increased understanding of these successions and their supply areas. In this study, focus is placed on the Miocene to Early Pliocene Utsira Fm. The Utsira Fm. was primarily sourced from the East Shetland Platform to the west, but we also suggest a larger component of easterly supply from Scandinavia than what has been previously described.
Previous depositional models of the Utsira Fm. have argued for a marine shelf/narrow strait origin (Galloway, 2002; Rundberg and Eidvin, 2005) and a

primarily turbiditic/submarine fan origin (Gregersen et al., 1997; Gregersen, 1998). To deduce and illustrate the link between margin evolution and depositional systems, RGB frequency-blended images are generated and analysed alongside traditional depth-structure, thickness and RMS amplitude maps. When combined, they provide information on geomorphologies, depositional patterns and basin configuration.
Characteristic shelf-slope-basin floor systems suggest that transport and deposition by mass-gravity processes were important in forming the westerly supplied part of the Utsira Fm. Recognition of depositional and erosive elements such as shelf edge incision, distinct sinuous slope features and lobate-shaped basin floor fans lead us to favour a turbiditic/submarine fan origin. Very similar depositional patterns are also visualised for the easterly supplied part of the Utsira Fm. Based on the observed and interpreted similarities, we propose a depositional model that argues for a relatively similar Late Miocene to Early Pleistocene evolution along the western and eastern basin margins. Deposition of the Utsira Fm. mainly occured under regressive conditions and falling relative sea level.
A key implication of this research is that a shelf-slope-basin floor basin configuration with sufficient relieff for mass-gravity processes to occur must have existed during deposition of the Utsira Fm.

Building on knowledge from the petroleum industry, we can make a new value chain and a business model for Carbon Capture and Storage (CCS) in the North Sea Basin

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CO_2 capture, transport, and storage (CCS) is a process where carbon dioxide (CO_2) is captured from energy production or industrial plants, transported in pipelines or by ships, and deposited so it will not enter the atmosphere. Deep underground storage is the only current means of disposing of large amounts of CO_2, safely and permanently.
CCS does have strong ties with the oil and gas industry. What we know about the offshore geology, and its potential to store CO_2, builds on decades of research in and experience from the oil and gas activity. The skills and expertise in the North Sea workforce are exactly what are needed to get CCS going.
The world first offshore CCS project started in 1996, with the Sleipner Field development, which give us more than 20 years of experience with storage of CO_2 in geological formations offshore Norway. A lot of work has been done to map, characterize and evaluate potential storage sites.
The Norwegian Petroleum Directorate (NPD) presented a CO_2 Storage Atlas for the Norwegian Continental Shelf (NCS) in 2014. The main objective with this Atlas was to identify safe and effective areas for long-term storage of CO_2.
A new regulation for CO_2 transport and storage was also published in 2014.
Depending on their specific geological properties, several types of geological formations can be used to store CO_2. In the North Sea Basin, the greatest potential capacity for CO_2 storage will be in deep saline-water saturated formations or in depleted gas fields and in oil fields.
The government issued feasibility studies on CCS solutions in 2016 with the ambition to develop a full-scale CCS value chain in Norway by 2024. This project includes capture of CO_2 from industrial capture sources in the Oslo-fiord region (cement and waste-to-energy) and shipping of liquid CO_2 to an onshore terminal at Kollsnes, the Norwegian west coast. From there, the liquified CO_2 will be piped and injected into the Johansen Formation south of the Troll Field area for permanent storage. This full-scale CCS project in Norway is the first industrial CCS projects to develop an open access infrastructure with the intent and the capacity to store significant volumes of CO_2 from across the European continent.
A breakthrough was reached when we awarded the first CO_2 exploitation license on NCS, EL001, to Equinor in January 2019. Together with their partners, Shell and Total, they are responsible for the transport and storage part of the governments initiated full-scale CCS project.

Tracking the timing of climatic variation from the Cambrian into the Early Silurian: Re-Os isotope geochemistry of the Lower Paleozoic section in Sweden

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Climatic variations that significantly impact weathering rates are reflected directly in the Os isotopic composition of seawater, either locally or globally. Thus, $^{187}Os/^{188}Os$ ratios preserved in organic-rich sedimentary rocks archive climatic variations in the geologic record. The lower Paleozoic has relatively few age constraints despite its importance in the

explosion and diversification of multicellular life. Here we report Re-Os isochron ages and initial $^{187}Os/^{188}Os$ ratios (Os_i) based on samples of organic -rich shales taken from drill core, providing robust geochronology tied directly to chemical environmental indicators. The Alum Shale was sampled from the Tomten-1 drill core at a depth corresponding to the middle of Cambrian Stage 10. A Model 1 isochron yields an age of 488.4 ± 5.1 Ma (2-sigma; MSWD = 1.5; n = 25), with an Os_i of 0.82 ± 0.04. The Tøyen Shale was sampled from the Lerhamn drill core at the Floian-Dapingian stage boundary, and yields a Model 1 isochron age of 469.8 ± 1.4 Ma (2-sigma; MSWD = 1.5; n = 10) with an Os_i of 0.801 ± 0.002. These isochrons provide radiometric ages for two significant points in the Early Paleozoic, and record a decrease in Os_I from ratios above 1.0 in the Ediacaran to a relatively constant ratio near 0.8 throughout the Cambrian and early Ordovician [1]. Re-Os isochrons for Katian (Upper Ordovician) and Telychian (Llandovery, lower Silurian) shale sections from drill core in the Siljan region, central Sweden [2], provide two reliable points for the Os seawater curve. The first, the Fjäcka Shale from the Stumsnås 1 core, yields an age of 454.0 ± 6.1 Ma (Os_i = 0.563 ± 0.036, MSWD = 1.08, n = 5). The second, a previously unknown Llandovery shale from the Mora 001 core [2], yields an age of 435.1 ± 1.5 Ma (Os_i = 0.553 ± 0.007, MSWD = 1.3, n = 10). Together, these isochrons document a significant decrease in Os_i through the Ordovician, consistent with reduced chemical weathering and seawater temperatures leading up to the Hirnantian glaciation [3].

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Morphological trends in the Smithian (Early Triassic) ammonoid *Arctoceras blomstrandi*

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Arctoceras blomstrandi is the most abundant ammonoid in the Smithian (Olenekian, Lower Triassic) of Svalbard, Arctic Norway. It is a key species for biostratigraphy across the Arctic region where it is often more abundant than the type species of the *Euflemingites romunderi* Zone. *A. blomstrandi* is also a useful species in examining the adaptive radiation in Boreal ammonoids following the end-Permian mass extinction. New, extensive collection with precise stratigraphic control has been carried out in localities in Sassendalen, central Spitsbergen. The new data support the grouping of *A. blomstrandi* into a single morphospecies, but also demonstrate considerable intraspecific variation. Systematic variation is seen in both shell shape, allometric coefficients and ornamentation through the stratigraphy. The new data allow for a more precise systematic description and definition of *A. blomstrandi* that include these temporal morphological changes. Through the studied sections there are clear, consistent changes in both size and morphology trending towards smaller, wider and more evolute individuals. The stratigraphic trends in ornamentation can to some extent be explained by covariation with coiling parameters (Buckman's law). The morphological trends coincide with the earliest phase of the positive carbon isotope excursion which marks the Smithian/Spathian boundary, and may possibly be explained as adaptive responses to environmental change through the latest part of the middle Smithian.

Geochemical volcanostratigraphy defines the tectonic evolution of the Karasjok Greenstone Belt, Finnmark

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The Karasjok Greenstone Belt is a Paleoproterozoic supracrustal belt that forms the westernmost and structurally lowermost tectonic unit in the Lapland-Kola Orogenic Belt in the northern Fennoscandian Shield, and which continues into Finland and Russia as the Central Lapland Greenstone Belt. Davidsen (1994) divided the stratigraphy of the northern part of Karasjok Greenstone Belt into four formations (from base to top): The 50-150 m thick *Lavttevárri formation*, which lies unconformable on top of the Archaean Jergul Gneiss complex. The lower part of the formation consists of clastic metasedimentary rocks. Tholeiitic metavolcanites dominate the upper part of the formation and contain interlayered komatiite units, rhyolitic metavolcanites (Leptite) and mica-schists. *The Corgašávzi Formation,* 250-700 m thick, is mostly composed of meta-psammitic rocks with the upper part of the formation also consisting of tholeiitic metavolcanites, mica-schists and some layers of marble. Mafic layered intrusions are commonly found in this formation. Banded amphibolites with

a tholeiitic composition make up most of the 300-700 m thick *Briittágielas Formation*. In addition, the formation consists of several intercalated metakomatiites, schists and sulphide horizons. Layered intrusions are also abundant. *The Fossestrand Formation,* more than 300 m thick, consists of metakomatiitic and coarse-grained gabbroic rocks. We have sampled all main units of the Karasjok Greenstone Belt with the purpose to establish a geochemical stratigraphy and to obtain better control on the age relationships between the different formations. The analysed samples from the Jergul gneiss complex show enrichment in LILE and LREE relative to primitive mantle and chondrite values. The geochemical signature is similar to other TTG units in the region. The ultramafic and rhyolitic volcanites from the Lavttevárri formation show similar trace element patterns as the underlying Jergul gneiss complex. This suggests that: i) the volcanites of this formation originated from the same mantle source as the gneisses and therefore are part of the same Archean magmatic system, or ii) the parental magmas for the volcanites are derived from similar magmatic source during a later event. The samples from the Briittágielas formation all show strong enrichment in LREE and LILE with a pattern commonly found in subduction-related settings. The layered intrusions found in the Briittágielas and Corgašávzi formations share the same patterns. This magmatic event could represent an early Sveco-Karelian subduction related back arc setting. The komatiites and intrusions of the Fossestrand formation show a flat REE and trace element pattern when normalised to primitive mantle values. This is interpreted to be due to deep-seated mantle plume magmatism. A tentative conclusion of the established geochemical volcanostratigraphy of the Karasjok Greenstone Belt is that the region underwent continental rifting, subduction related (back-arc?) magmatism, and then deep mantle plume magmatism before the Svecokarelian and Svecofennian orogeny.

Clay coating preserving high porosities in deeply buried intervals of the Stø Formation, southwestern Barents Sea

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The mature and homogenous sandstones of the Stø Formation contain some of the most promising reservoir intervals in the Norwegian Barents Sea. However, the reservoir quality is highly variable due to detrimental effects of quartz cement resulting from deep post depositional burial. Core plug data from well 7219/8-2 situated in the Southwestern Barents Sea show that certain intervals of the Stø Formation have abnormally high porosity and permeability values compared to surrounding low porosity- and permeability intervals of the formation. Petrographic analysis indicate that the high porosity intervals have the same mineralogical- and textural characteristics as the low porosity units. The only difference observed is the presence of illitic clay coating covering the majority of the detrital quartz grains in the high porosity intervals. The amount of quartz cement is limited in intervals with good coating coverage and make up 5-11% of these samples. In intervals with negligible grain coating coverage, the quartz cement volume exceeds easily 20% and hence is severely detrimental to porosity. The illitic clay coating inhibits quartz cementation by limiting the available area for nucleation on detrital grains. Lower intragranular volume (IGV) in coated intervals show that the illitic clay coating aid quartz dissolution at clay-quartz interfaces indicating that silica availability is not the limiting factor with regard to low quartz cement volumes. The study illustrates the potential for preserving excellent reservoir quality in deeply buried zones of the Stø Formation and similar lithologies.

Cap rock characteristics of Upper Jurassic organic-rich shales in the Norwegian North Sea and the Barents Sea

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The Norwegian Petroleum Directorate (NPD) states that the presence of a cap rock with sufficient sealing capacity, coupled with Cenozoic uplift and associated erosion, gas expansion and possible fault reactivation are critical factors for the Jurassic plays in the Barents Sea (NPD, 2019). The primary objective of the current study was to evaluate the effect of clay-silt-sand proportions, organic content, maximum burial depth and upliftment on the elastic and geological (sealing) properties of important cap rock formations on the NCS. We utilize petrophysical well log data and rock physics crossplots to compare a wide variety of cap rock formations within and across the two studied regions to show that the obtained trends are not local features, but general for the Upper Jurassic shale succession.

Leakage processes are complex, can relate to faults, fractures or migration though the cap rock pore volume, and are not inherently negative, e.g. in the case of gas leakage and oil retention. As an example, seismic data indicates a certain amount of gas leakage over part of the Goliat structure, seemingly through the cap rock sequence dispersed across the reservoir compartment (i.e., diffusive or Darcy flow mechanisms) rather than localized at fault intersections (point source type leakage; Løseth et al., 2009). The Central North Sea Jurassic reservoirs rely on the time-equivalent primary cap rock formations as the Barents Sea, with the added consideration of limited and localized source rock maturation due to shallow burial in the proximal regions. A functioning cap rock with minimal leakage could consequently be important to compensate for small generated hydrocarbon volumes, as upliftment is suspected of having de-activated the petroleum system relatively quickly after the onset of oil generation (Ritter et al, 1987; Hermanrud et al., 1989). Similarly when considering reservoirs for CO_2 storage, the difference between a cap rock that will retain hydrocarbon/CO_2 gas and one that is only capable of trapping oil/supercritical CO_2 is of absolute importance.

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Outburst flood-generated sand dunes in south eastern Norway - beyond the aeolian paradigm

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A major glacial-lake outburst flood (GLOF) in the Glomma valley, south eastern Norway, took place during the final decay of the Scandinavian Ice Sheet. A combined morphological, geophysical and sedimentological study of a mid-reach area provides new insight into the variety of processes and deposits of the flood. The succession, some tens of metres in thickness, comprises the infill of a major flood basin that developed during hydraulic ponding. Large-scale sand dunes, or dune ridges, accumulated downstream of a topographical constriction hosting a high velocity flow. Flow expansion at the outlet generated intense turbulence and scouring. The sand-loaded eddies helped feeding the semi-stationary dune ridges that grew vertically and downflow under high aggradation rates. Internal structures vary but reflect an overall shift in sedimentation from prevailing supercritical flow to overall subcritical flow conditions during rising flood levels. A subsequent fast-falling flood level gave rise to a significant drop in hydrostatic pressure which triggered a release of excess pore pressure through massive dewatering and fluidisation. Water-escape structures include numerous (sub)vertical pipes. The present study shows that outburst flood-generated large-scale dunes are not necessarily coarse grained, but can develop in well-sorted, fine sand and are thereby easily confused with aeolian deposits. Accordingly, several dune fields in SE Norway are here reinterpreted as the product of major flood events. Sandy dune fields with similar characteristics in other parts of Scandinavia and possibly elsewhere could likely also be reinterpreted, and the role of outburst floods during final deglaciation of the Scandinavian Ice Sheet has seemingly been underestimated.

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Sediment Production: Lithological and Subglacial Hydrogeological controls (SPLASH)

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Sediments originally formed underneath glaciers (*till*) underlie the ground we live on; understanding how they form is thus highly relevant to society. In Scandinavia, ice sheets have left behind large bodies of thick and variable successions of sediments that were formed underneath the ice (e.g. Ehlers et al., 2018). These sediments contain many of the known water resources. In order to protect them from percolating of pollutants, and to ensure building and infrastructure stability, it is crucial to know the properties of these sediments. The latter are directly determined by the depositional environment and the processes of deposition (Evans, 2017). Yet, nearly all we know is by indirect inference from sediment formed during the last ice age since the subglacial environment is

a highly inaccessible area. In this study, we use a recently-discovered, unprecedented access to a glacier bed (Blåisen, Norway) to gain new direct insights into **till** formation. For this, we will develop new methods of studying these crucial sediments and prepare them for analyses using state-of-the-art engineering geological methods. Furthermore, the quantity and mechanical properties of the sediment underlying glaciers have an important control on ice flow and are likely to influence the rate of glacier retreat (Burki et al., 2009). Therefore, to improve models of ice dynamics in response to climate change, sliding parameters needs to be constrained using knowledge about sediment properties underneath modern glaciers such as Blåisen (Åkesson et al., 2017).

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Prospecting for geothermal energy from groundwater at Økern Portal, Oslo

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Low enthalpy aquifer technology (LEAT) is an open system based on circulation of groundwater through fractures, which delivers heating and/or cooling of buildings in a cost-efficient manner. An open system with suitable geology may reduce the required number of wells significantly, compared to a closed system solution. This solution is chosen at Økern Portal in Oslo to comply with the contractor's goal of 90% of heating energy coming from energy wells.

18 wells, with varying depth and deviation, have been subjected to a comprehensive geophysical logging program and hydrological pump testing. Fractures and fracture systems are interpreted from geophysical data. Values for specific capacities are obtained from step tests with controlled pump rates. The logging program includes impeller flowmeter and heat-pulse flowmeter, while pumping simultaneously, allowing detailed assessment of flow contribution from individual fractures. Hydraulic fracturing is implemented in low-capacity wells to expand existing fractures and, thus, improve permeability and specific capacity.

The energy is produced from heat pumps fed with water from a set of pumping wells and water is returned to the aquifer through a number of injection wells. Hydrological considerations include balance between pumping wells and injection wells and injecting warm/cold water away from the pumping wells. Several scenarios are presented, where different constellations of wells are chosen for pumping/injection. This open circulation system solution is balanced, which means the same amount of water is injected as pumped up. All scenarios are therefore balanced using the specific capacity of each well and a fixed, linear limited drawdown. Optimal utilization of the wells is achieved by pumping from 5 wells with relatively high specific capacities, located in the western part of the site, and injecting into 13 wells with relatively low specific capacity, located in the eastern part. Inherent challenges of the system include its sustainability over time. However, such systems involve large volumes of rock and water and projects with similar size and geology indicate high stability.

Climate in the Arctic towards 2100: Focus on the European sector

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A new Arctic is emerging due to climate change. Over the past 50 years, the temperature in the Arctic has risen twice as fast as the global average. The increase of air temperature in Svalbard is even faster, and makes this region one of the fastest-warming areas in the world. Recent winters have been characterised by periods of extraordinarily warm weather in combination with intense rainfall, causing ecological disturbance and new challenges for societies and infrastructure. Permafrost is warming, and especially coastal areas are exposed for erosion. Climate models project a continued warming, even under moderate greenhouse gas emissions. This presentation will explore the effects of global warming on the Arctic. The emphasis will be on the Svalbard area. The presentation is to a large degree based on two recent assessments; "Snow, Water, Ice and Permafrost in the Arctic" (SWIPA; AMAP 2017) and "Climate in Svalbard 2100" by the Norwegian Centre for Climate Services (Hanssen-Bauer et al. 2019). Both assessments highlight the need for new monitoring efforts coordinated across disciplines, to give access to reliable and up-to-date information.

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Synchronous ice-sheet retreat from the Ra-moraine across southern Norway

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We present new AMS ^{14}C dates of terrestrial macrofossils obtained from proglacial lake records constraining the age of the classical Ra-moraine in southern Norway to the very end of the Younger Dryas. The prevailing view has been that the Ra-moraine was deposited during the early to mid-Younger Dryas, with subsequent retreat from the moraine around 12.5 cal. ka BP. These conclusions were, however, relying solely on radiocarbon dates from marine shells. In this study, we targeted palaeo-lake basins (now mires) above the local marine limit in order to obtain terrestrial macrofossils and thus a more accurate age of the Ra-moraine. Two localities were cored: Blokkemosen in Østfold, southeastern Norway - and Nupedalen mire in Vest Agder, southern Norway. Both located distal to the Ra-moraine. The coring at Blokkemosen revealed glacial silt and sands before coming to a stop in coarser sediments. The core from Nupedalen revealed an undisturbed lateglacial-Holocene sequence with Younger Dryas glacial silt in between Allerød gyttja and Holocene gyttja. AMS ^{14}C-dates of terrestrial macrofossils found in the glacial silts suggests that the ice-sheet remained at the Ra-position to as late as the Younger Dryas-Holocene transition, c. 11.6 cal. ca BP). These results hence suggest a synchronous ice-sheet retreat from Younger Dryas maximum positions in southeastern, southern and western Norway. Consequently, the Ås- and Ski-moraines, north of the Ra in southeastern Norway, must be of early Holocene age. Further, this suggests that the ice sheet retreat rate in the Oslofjord area was faster than previously thought, reaching c. 200 ma^{-1} for the time period 11.5 - 10.5 cal. ka BP, i.e. the early Holocene. This retreat rate is of the same order as early Holocene retreat rates from western Norway.

Paleolakes and evaporite deposits across Mars

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The long-lasting debate on Mars of *warm and wet* versus *cold and icy* is no longer about the presence of liquid water or the existence of rain during early Mars but more about the persistence of the wet conditions through a long geologic period [1]. Clays and evaporitic minerals, like chloride salts, are widely distributed across Mars, providing evidence of past water-rock interactions and represent our best chance to determine past water chemistry [2,3].
One would expect to find evaporitic minerals in paleolake deposits. Over 435 lakes have been catalogued on Mars, divided into “open-basin”, which show evidence of breaching and drainage and “closed-basin”, having inlet channels but no evidence of outflow [4,5]. Previous studies of closed-basin lakes have found little evidence of evaporite precipitation in their inlet deltas [4], but these studies have not maximized use of spectral imagery for identifying evaporites. Further, the present catalogue only references impact craters with incised rims, whereas on Earth at least some lakes are fed by groundwater only. Thus, there may be more closed basin paleolakes on Mars than previously estimated.
Here we suggest extending the paleolake database and spectral analysis over both open- and closed-basin paleolakes. Building upon the existing literature, we will provide a more in-depth analysis of available CRISM and OMEGA data over Mars’ basins. By constraining water chemistry through evaporite mineralogy, we provide insight into pH, temperature, and solute composition, which can help resolve whether these lakes formed through groundwater aquifers or surface runoff – an outstanding question in Mars’ past.

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Assessing chemical compositions of Cr-spinel as a tool for provenance based on a regional comparison of Upper Triassic sandstones from the Barents Shelf

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The mineral chromian spinel (Cr-spinel) varies in its chemical composition according to petrogenesis and metamorphic alteration, as well as being the only common mafic-ultramafic mineral considered stable in sediments. These qualities make the mineral interesting in order to identify and differentiate potential contributions from mafic-ultramafic source rocks in sandstone provenance studies. Studies of detrital Cr-spinel have previously focused on major and minor element compositions. The addition of Cr-spinel trace element analysis seems to add significant source-sensitive information. In this study, we have performed major-, minor- and trace element analysis of detrital Cr-spinel from the Triassic Snadd and De Geerdalen formations from selected locations in the Barents Sea (shallow cores) and Svalbard (outcrops). Notably, the Cr-spinel major element compositions show remarkably similar variations across the large regional area, favouring an ophiolite-associated Cr-spinel origin. An ophiolite related source interpretation fits well with an ultimate source in the Uralide Orogeny, as suggested in other provenance studies of these formations. Trace element compositions do, however, reveal a more complex evolution in the Cr-spinel source. A relative enrichment of Zn, Co, Mn seen together with a relative depletion of Ga, Ni indicate a metamorphic modification of the Cr-spinel chemistry. As detrital trace element compositions of Cr-spinel is a relatively novel field of study, there are several challenges concerning data interpretation. Assessments of the impact of erosion, sedimentary sorting, diagenetic stability and metamorphic alterations, are all challenges that can provide new information to future Cr-spinel provenance studies.

Anatomy of the evaporite accumulation and salt wall evolution in the Tiddlybanken Basin, southeastern Norwegian Barents Sea

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Reprocessed 2D seismic reflection profiles and well data are utilized to study the Tiddlybanken Basin and Signalhorn Dome in the southeastern Norwegian Barents Sea. Interpretation of selected seismic profiles, time-thickness maps and conceptual models are presented to highlight the control of pre-salt graben architecture on the facies distribution within the layered evaporitic sequences, passive diapirism along strike of the salt wall, and the link between reactive diapirism and pre-salt structures.

The Carboniferous graben architecture is subdivided into three half-graben units that are separated by a NW-SE trending horst and an overlapping transfer zone. The arcuate geometry of the horst is believed to be the effect of the pre-existing Timanian basement grain. The overlapping transfer zone created a barrier that affected the facies distribution and thickness within the layered evaporitic sequences. During the early Triassic to earliest Cretaceous, the northwestern part of the Tiddlybanken Basin was developed due to passive diapirism caused by the halite lithology within the layered evaporitic sequences. The central and southeastern part of the salt wall was not recovered from the pillow stage due to lack of halite lithology in the deepest evaporitic sequence. In the late Triassic, far-field stresses from the Novaya-Zemlya fold-and-thrust belt reactivated the half-graben structures and formed the Signalhorn Dome, rejuvenated the NW part of the salt wall and affected the sedimentation rates in the southeastern broad basin. The salt wall, the Signalhorn Dome and the underlying Carboniferous graben structures were again reactivated in post-Early Cretaceous time, likely in response to regional compressional stresses related to the early Cenozoic transpressional Eurekan/Spitsbergen orogeny. During this phase, the NW and SE parts of the salt wall evolved due to reactive diapirism; however, salt reactivation was minimized towards the transfer zone beneath the center of the salt wall.

Description and crystal structure of three new barium beryllophosphates

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Three new Ba-bearing beryllophosphates were recently described in pegmatitic geological contexts, showing exciting crystal structures. Minjiangite, $BaBe_2P_2O_8$, was discovered in the Nanping No. 31 pegmatite, Fujian Province, China. It crystallizes in space group *P*6/*mmm* (*a* = 5.028(1) and *b* = 7.466 (1) Å), and shows a phyllophosphate structure consisting of double layers of tetrahedra, which contain both Be and P in a 1:1 ratio. Inside the layers, the $(Be,P)O_4$ tetrahedra form six-membered rings by sharing corners. The Ba atoms are located in very regular 12-coordinated polyhedra and connect two successive double layers (Rao et al., 2015; Dal Bo et al., 2014).

Wilancookite, $(Ba,K,Na)_8(Ba,Li,[])_6Be_{24}P_{24}O_{96}.32H_2O$, forms tiny rhombododecahedral crystals in the Lavra Ponte do Piauí pegmatite, Minas Gerais, Brazil. Its crystal structure (*I*23, *a* = 13.5398(2) Å) is identical to those of pahasapaite and of synthetic zeolite RHO (Hatert et al., 2017); the framework is based on corner-sharing BeO_4 and PO_4 tetrahedra forming a large cavity in which occur Ba atoms and water molecules. Three different types of rings are building the cavity: eight-membered rings parallel to (100), six-membered rings parallel to (111), and four-membered rings parallel to (110).

More recently, limousinite, $BaCa[Be_4P_4O_{16}]\cdot 6H_2O$, was discovered in the Vilatte-Haute pegmatite, Limousin, France. This beryllophosphate, which crystallizes in space group $P2_1/c$ (*a* = 9.4958(4), *b* = 13.6758(4), *c* = 13.4696(4) Å, β = 90.398(3)º), shows a zeolite framework identical to that of phillipsite, based on corner-sharing BeO_4 and PO_4 tetrahedra forming inter-connected 4-membered and 8-membered rings. Large cages within this zeolite framework contain Ba, Ca and water molecules; calcium is distributed over the two Ca1 and Ca2 positions, with occupancies reaching 0.648(9) and 0.345(11), respectively. Ba occurs at a very large crystallographic site, with a complex morphology and a (11 + 1) coordination; the Ca1 site shows a (7 + 1) coordination, with a morphology corresponding to a very distorted cube; the Ca2 site shows a 7 coordination with a morphology of very distorted pentagonal bipyramid. This mineral species is the third known zeolite-type phosphate.

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Modeling the effects of carbon release from the Central Atlantic Magmatic Province (CAMP)

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The Central Atlantic Magmatic Province (CAMP), the end-Triassic mass extinction (ETE), and major carbon cycle disruptions occurred synchronously around the Triassic-Jurassic (T-J) boundary (~ 201 Ma). The carbon cycle perturbations include significant increases in atmospheric CO_2 concentrations (pCO_2) and negative carbon isotope excursions (CIEs), the latter attesting to input of isotopically depleted carbon into the ocean-atmosphere system. Parts of the plumbing system of CAMP intruded into volatile-rich sedimentary basins in northern Brazil, likely leading to significant generation of thermogenic carbon. Here we use carbon cycle modeling to explore the effects of carbon release from CAMP on atmospheric pCO_2 and oceanic $d^{13}C$. While mantle-derived carbon alone cannot account for the negative CIEs, an extremely isotopically depleted carbon source (e.g. methane clathrates) is not required. We propose a new model for the T-J boundary carbon cycle perturbations, based on realistic scenarios for the evolution of CAMP, including the newest U-Pb geochronology from both the flood basalts and the sub-volcanics. We find that organic-rich shale affected by contact metamorphism around CAMP sills represents a likely source for ^{13}C-depleted carbon, and that the release of mixed mantle- and sediment-derived carbon can explain the observed T-J boundary proxy data. Our results strengthen the case for an active involvement of CAMP in the end-Triassic crisis, and that the sub-volcanic part of a LIP represents a key driver for global carbon cycle perturbations.

Metamorphic P-T paths of Eastern Finnmark: Towards a better understanding of the tectono-metamorphic evolution of the Kalak Nappe Complex

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Garnet in rocks of low to medium metamorphic grade may record important information about the pressure – temperature (P-T) conditions experienced during its growth. In the case of the Kalak

Nappe Complex (KNC) of Finnmark, such P-T paths could help answer long-standing questions related to the provenance of the KNC and its tectono-metamorphic history (e.g., Kirkland et al., 2007; Zhang et al., 2016). Rocks investigated in this study are part of the Kolvik Nappe as well as undifferentiated (semi-)pelites forming the basal part of the KNC in Eastern Finnmark (Svaerholt Terrane of Kirkland et al., 2008). They were collected at Bekkarfjord, on southern Nordkinnhalvøya, and along the west coast of Laksefjord. The paragenesis quartz + white mica + biotite + plagioclase + garnet ± chlorite is present in all studied samples. In order to infer the tectono-metamorphic history of these samples, phase equilibrium and garnet crystallization modelling using Theriak-Domino and Theria_G software has been integrated with detailed petrographic, microstructural and geochemical results obtained from X-ray µCT and EPMA analyses. Garnet exhibits characteristic growth zoning in central parts of the crystal, with bell-shaped Xsps and Xgrs contents from core to rim and concomitant increases of Xalm and Xprp. The outermost rim of garnet varies in thickness between <15 µm and 50 µm, and is marked by a steep increase in Xgrs and drop in Xalm contents at constant or decreasing Xprp values. This translates into a Barrovian event with a P-T slope of ca. 20 bar/°C early in the garnet crystallization history and a P-increase at constant or decreasing temperature during garnet rim growth. Microstructural evidence indicates differences in the relative timing of garnet growth and deformation for the samples studies. Radiometric age dating of garnet, using the Lu-Hf and Sm-Nd isotopic systems (in progress), will connect these results to the long and protracted history of the KNC.

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Why does not lithology correlate with gamma-ray spikes in the shaley source rocks of the Upper Jurassic Alge Member (southwestern Barents Sea)?

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Prominent high-value gamma-ray spikes in maximum flooding surfaces of the Upper Jurassic Alge Member of the Hekkingen Formation display an uncommon stratigraphic and geographic variation in the southwestern Barents Sea. This variation normally would indicate a compositional change in the Alge Member, thus, at the same time challenging the common perception that the Upper Jurassic source rock is a homogenous succession of black shale. The aim of this study is to identify the compositional variation in the source rock that causes the regional variation in the gamma-ray readings, and to develop an improved understanding of the depositional environment and the paleogeography during deposition. The organic composition of the member is determined by geochemical analysis and maceral analysis, whereas mineral analysis and X-ray diffraction of the clay fraction reveals the inorganic composition. In addition, seismic reflection data, well logs and sedimentary core logs are used to compare compositional and depositional variation of the Alge Member.

The studied compositional elements of the Alge Member show no correlation to the high-value gamma-ray spike. Instead, seismic data and the sedimentary core logs reveals a correlation with the depositional conditions. The area with low-value gamma-ray readings, west and northwest of the Loppa High, contain wedge-shaped geometries in the seismic data and the presence of gravity flow deposits in the core interpretation. These observations reveal that the ongoing rifting and uplift of the western Loppa High influenced the deposition of the member. In the Hammerfest Basin and in the area eastward toward and surrounding the Nordkapp Basin, high-value gamma-ray readings are observed as the Alge Member experienced a low energy deposition in hypoxic to anoxic bottom conditions.

The study shows that there is a correlation between the high-value gamma-ray spikes and the uranium content of the black shale. Uranium precipitation takes place in hypoxic to anoxic conditions, thus, these conditions are required to deposit a high-value gamma-ray spike. Thus, the distribution of the high-value spikes can be used to reconstruct the development of the anoxic zone during the deposition of the source rock.

Architecture of a Triassic distributary fluvial system: The Skagerrak Fm. of the Ula field, Norwegian Central Graben

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The study and understanding of the Triassic Skagerrak Fm. in the Norwegian Central Graben is less mature compared to the equivalent formation in the UK sector. Recent work focused on the UK Central Graben indicates that sedimentary systems sourced from Scandinavia proliferated during the Middle Triassic. As such, Ula data could play a key

role in corroborating findings from the UK sector whilst benefitting from a detailed regional evaluation of provenance and distributary character.
Detailed analysis of 200 meters of core from the Skagerrak Fm. of the Ula field allows for a comprehensive, hierarchical approach to study depositional architecture. Lithofacies are organized in facies associations that represent 3D elements such as braided fluvial channel-fills, sheetflood elements, distributary channel-fills, lacustrine mouthbars, lacustrine pro-delta elements and paleosols. These elements occur in sets (1-10m) that represent fluvial channel-belts, overbank sand sheets and lacustrine deltas. At an even larger scale the fluvial element sets stack in repetitive patterns (10-20m) that record an upward transition from confined to progressively more unconfined elements. These stacks are interpreted to represent channel-belt avulsion cycles. Finally, at the largest scale observable in core, it is documented how three to five such avulsion cycles are stacked (40m) to represent a distributary fluvial system (DFS). This DFS is bounded above and below by lacustrine element sets (5-20m).
The observed 10-20-meter-thick channel-belt avulsion cycles at Ula compare well with similar nodal avulsion cycles observed in the 'medial fan' setting of the Permian Organ Rock Fm. in Utah. Also, the stacking of several such avulsion cycles together representing a DFS is broadly similar between both formations. A striking difference between these ancient DFS's is the expression of their distal part: The Organ Rock DFS terminates into a series of terminal splay lobes deposited in a playa setting, whereas the distal expression of the Skagerrak DFS at Ula is that of stacked ephemeral deltas.
We conclude that the lake margin setting was an integral part of the DFS at Ula. Rather than the DFS terminating into a series of extensive terminal splays as seen in the Organ Rock Fm., it terminated rather abruptly in an ephemeral lake. This difference could have implications in improved understanding of scale and extent of depositional elements in a salt-controlled topography, which can fundamentally change/improve the reservoir model facies distribution of this kind of distributary system.

Unstable rock slopes in the far North of Norway: a larger challenge than expected

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Based upon an analysis of historic rock avalanche and large rock slope collapses with consequences to society, the northernmost province of Norway, Finnmark, was ranked as low priority in the national mapping plan for unstable slopes (Devoli et al., 2011). In fact, only eight historic rock slope collapses have been documented. Is this because historic archives are poorer in the far north than in the south or that settlements are scarcer or indeed there have been less events in the past centuries?
A systematic analysis of deformation data derived from Sentinel InSAR data that became available in autumn 2018 (www.insar.ngu.no) reveal that slopes in northern Norway are not stable but rather active. A total of 88 unstable rock slopes were identified using InSAR data, several of those with deformation rates above 1 cm/year in the 2-3 years observation window of Sentinel data. Other rock slopes with important post glacial deformation have been recognized on orthophotos but they do not show any detectable deformation in the past years. This could be linked to a dormant state, a deformation behaviour that is not easy to detect based on slide kinematics (toppling) or orientation of the vector of displacement and the line of sight of the satellite. About 50% of the deforming rock slopes lie above a fjord, a lake or a dammed magazine so that the potential area of impact is much larger than the run-out area of a potential failure.
One of the unstable rock slopes above a fjord is Reinbenken (Kruvnnut), which lies on the western slope of Porsangenfjord in front of of Honningsvåg. This unstable slope covers an area of ca. 0.5km2 and has slid downslope from the 350-m-high plateau by 80 m as a semi-coherent block. Analyses of InSAR data suggest a displacement rate of ~1cm/yr with a maximum displacement along the NW tip of 1.5 cm/yr (which might be only surficial material) and a minimum velocity of ~0.7 cm/yr along the southern flank. The northern flank is fully developed and here the coastline is displaced by about 30 m. The southern flank is less developed, and the block is dissected in several blocks that step up to the undeformed surface to the south. Several tens-of-meter-long open cracks run parallel to the backscarp within the landslide block. Within the front of the slide several secondary scarps with young surficial landslides occur indicating strong deformation in the front. However, they do not line up at one altitude suggesting that no thoroughgoing daylighting sliding surface exists above the water line. Bathymetric data show large boulders at the fjord bottom, these are also visible on fjord bottom videos. These observations support that the rock-slide front is collapsing in superficial landslides.

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A tetrapod trackway from the Late Carboniferous on Bjørnøya, Svalbard

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The Late Carboniferous was a crucial interval for the establishment of terrestrial ecosystems. A dramatic change in tetrapod distribution and ecology is coupled with an ongoing transition from amphibian to amniote domination. In 2017, a new set of tetrapod footprints were discovered from a single slab discovered on the Arctic island of Bjørnøya which appear to preserve the transition from swimming to walking. The slab was analysed through the creation of a three-dimensional photogrammetric model, and palaeoenvironmental observations were taken to provide context to the ichnological determinations.
The trackway occurs within the Late Carboniferous Kapp Hanna Formation, consisting of interbedded sandstone, conglomerate and subordinate mudstones, interpreted to have been deposited within a fluvial floodplain setting with palaeoflow to the northwest. Impressions were made on top of a metre-thick mud interval. Soon after formation, these were infilled by sand forming an intricate cast on the underside of the overlying sandstone unit. Photogrammetric analysis of the surface reveals at least two separate and crosscutting trackways. The first comprises 36 prints and a tail trace and the second shows 24 prints.
The pes is pentadactyl (66 mm long, 51 mm wide) and impressed closely behind but not overlapping the manus. Digit length increases from I-IV with digit IV the longest, and II is the same length as digit V. The sole is oval-shaped, short, broad and deeply impressed. The manus (60 mm long, 39 mm wide) is tetradactyl. Digit length increases I-II and digit II is the longest, though digit III is almost as long. Digit IV is approximately 85 % shorter than digit III. The tracemaker is interpreted to be *Limnopus*, an eryopoid temnospondyl amphibian.
The trackways also preserves irregular, scratch-like markings that are interpreted as swimming traces and therefore also swim-walk transitions. Locomotion analysis reveals that on moving from submerged walking and swimming to terrestrial walking, large Late Carboniferous temnospondyls increased their pace angulation and lengthened the stride. This shows that the shift from walking to swimming behaviour in early tetrapods represented a balance of locomotive dynamics rather than a discrete change.
These tracks may be the farthest north *Limnopus* trackways yet found in terms of palaeolatitude, showing that the eryopoids inhabited northern reaches of the palaeotropics. They are the first Carboniferous tetrapod traces recovered from Svalbard and the Fennoscandian region, and are probably among the oldest examples of *Limnopus* yet found.

Impact of aquaculture activity on the benthic environment - A stratigraphic study from Hardangerfjorden (SW Norway)

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Fjords are coastal marine areas with high sediment accumulation rates, which serve as pollution traps and sediment sinks for organic material. Meanwhile, intensified human-induced activities may lead to blooms of phytoplankton that substantially contribute to the organic carbon flux to the sea floor. This elevated flux may increase organic carbon storage in the marine sediments, and may affect the benthic community.
This study presents results from surface samples and sediment cores taken near active aquaculture installations in Hardangerfjorden. Living (stained) benthic foraminifera from 2 fish farms, one in shallow (120m) and one in deeper (470m) waters, and from sites in different distances (100m and 500m) to them were analysed. Foraminiferal abundance was higher at the shallow than at the deeper sites, while species diversity showed the opposite trend. Diversity was reduced closer to the farms, while abundance patterns were variable. In addition, benthic foraminifera, geochemical (metal concentration, total organic carbon and nitrogen, $d^{13}C$ of specific foraminiferal species and the bulk sediment) and sedimentological (grain size) parameters in dated sediment cores from the shallow fish farm were investigated to get information about the environmental development from pre-industrial to present day times. Here the focus was put on organic carbon accumulation and benthic foraminiferal assemblages to assess eventual changes in the ecological quality status (EcoQS) of the benthic environment, which might be coupled to aquaculture activity. Organic carbon accumulation rate increased closer to the fish farm after its establishment and was higher compared to the

values observed in the core from further away. Foraminiferal diversity was relatively stable, indicating 'good' EcoQS at both sites, according to the Norwegian ecological classification system. Benthic foraminiferal accumulation rates showed an increase in the core located further away from the fish farm after its establishment. The foraminiferal assemblages in both cores showed a significant increase in relative abundance of *Brizalina skagerrakensis* during the last 70-80 years (since approx. 1940), which corresponds to a shift to slightly lighter $d^{13}C$ values in the same period. Both records might indicate a general increase in primary productivity triggered by increased nutrients in the area.

Ductile to brittle structural framework of the Nordfjord area, Western Norway

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The Nordfjord region represents a key area in the Caledonian Western Gneiss Region of SW Norway, situated between the NE-SW-trending Møre-Trøndelag Fault Complex and the west-dipping Nordfjord-Sogn Detachment Zone. The Nordfjord runs along a steep E-W-trending shear-zone/fault complex that juxtaposes ultra-high pressure rocks with the Hornelen supradetachment basin. Across this deformation zone, we observe an abrupt change in peak metamorphic conditions (Hacker et al. 2010) and a major step in mineral ages related to Devonian post-orogenic collapse of the Caledonian orogen (older in the south and younger in the north). Steeply dipping ductile fabrics are generally associated with sinistral kinematics, but are progressively overprinted by dextral kinematics and top-to-W shearing in the footwall of the Nordfjord-Sogn detachment (Labrousse et al. 2004, Young 2018). A similar subvertical sinistral shear zone, cut by extensional E-dipping low-angle shear zones and faults, was recently discovered at the eastern boundary of the Western Gneiss Region (Lom area). A correlation based on foliation trace maps suggests that these two sinistral shear zones form parts of the same crustal-scale shear zone that cuts across the central portion of the Western Gneiss Region and significantly influenced the geometry of the post-orogenic detachment system. Based on a remote sensing lineament analysis and field observations, four main sets of brittle faults systems have been identified; (1) a foliation-parallel and steeply dipping E-W trending set, (2) a NE-SW trending set subparallel to the foliation, (3) a N-S trending set with steep dip crosscutting the foliation, and (4) a NW-SE trending fault set found throughout the area. In order to constrain the absolute timing of the different fault sets, fault-related calcite-mineralizations as well as fault gouges were sampled for U-Pb calcite dating and K/Ar fault gouge dating. In addition, Apatite Fission Track Analysis and (U-Th)/He dating of Apatites will be performed from samples across major faults. A geomorphological study will complement the structural and thermochronological data with the final aim to contribute to the understanding of the landscape evolution of the region.

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Introducing the four GeoERA groundwater projects and their contributions to sustainable management of groundwater and subsurface resources in a changing climate

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The four GeoERA groundwater projects study aspects of groundwater quantity and quality issues related to natural processes and human activities to improve our basis for informed decision making e.g. for climate change mitigation and adaptation, taking into account competing uses of the subsurface and other subsurface resources. The projects provide new and important data for further development of the European Geological Data Infrastructure (EGDI) as a leading information platform for groundwater data in Europe and one of the leading platforms, globally. The four projects will deliver "FAIR" (Findable, Accessible, Interoperable and Reusable) data and information via EGDI

easily accessible for all relevant end users. This will improve our understanding of the subsurface and support common efforts to meet the UN sustainable development goals and develop efficient tools for climate change impact assessment, mitigation and adaptation. Here we briefly present the main objectives and deliverables of the four groundwater projects: **HOVER** – "Hydrogeological processes and geological settings over Europe controlling dissolved geogenic and anthropogenic elements in groundwater of relevance to human health and the status of dependent ecosystems"; **RESOURCE** – "Resources of groundwater, harmonized at cross-border and Pan-European Scale"; **TACTIC** – "Tools for assessment of climate change impact on groundwater and adaptation strategies" and **VoGERA** – "Vulnerability of shallow groundwater resources to deep sub-surface energy-related activities".

The Troll Grounding Zone Wedge – architecture, sediments and rates of formation

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Grounding Zone Wedges (GZWs) are prominent glacial-morphological features, which may reflect ice stream responses to factors such as changes in sea level, atmospheric and oceanic temperatures and substrate conditions. Here we report data from three published shallow borings that penetrate the Troll GZW in the Norwegian Channel, as well as high-resolution bathymetric data, TOPAS high-resolution seismic profiles, and 3D seismic surveys. The GZW is located about 200 km south of the present day shelf edge, and was formed during the retreat of the Last Glacial Maximum (LGM) ice sheet. It is up to 65 m thick, about 20 km long in the along-flow direction, around 20 km wide, and is the largest of the GZWs identified in the Norwegian Channel. The Troll GZW sediments are relatively uniform with 35-40% sand, of which 2-4% represent grain sizes >1mm. A slightly decrease in water content with depth, from 25% to 20%, is observed. Shear strength measurements show higher values within the GZW, compared to those values found in both younger and older glacimarine units. The Troll GZW has the same lithological characteristics as LGM Glacigenic Debris Flows deposited on the North Sea Fan, at the outlet of the Norwegian Channel. The Troll GZW has an acoustically layered seismic pattern. Identification of Mega-Scale Glacial Lineations and iceberg plough marks indicate that the Norwegian Channel Ice Stream was streaming over parts of the GZW during its formation. Previous studies have shown that LGM sediments were delivered to the North Sea Fan by a rate of 8000 m3/yr per meter ice stream front. If anticipating the same rates during formation of the Troll GZW, which has a sediment volume of at least 14 x 109 m3, it was formed in minimum 85 yrs.

University-Industry cooperation in the teacher-training program -The Water-project-

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In 2018, the University of Southeastern Norway (USN) and Ramboll signed a three-year R&D contract creating an opportunity for students to learn science in the real word, working alongside with experts. The Waterproject is a Pilot project aiming to become a part of the regular teacher-training program at the USN. The project design builds on the research work after Remmen and Frøyland (2017) «extended classroom», where one of the main goals is to achieve in-depth learning. The Students at USN joined the Pilot 1 spring 2019. An ongoing sampling program, led by Ramboll, as a part of a larger project, building railway in the Moss area, gave an excellent opportunity for the students to work in a real world project. The students worked alongside Ramboll, using sampling-methods that held the standard demanded by EUs water framework directive. In addition, the work linked to the UNs sustainable goal; Clean water. University-Industry Cooperation is a well-known teaching strategy. The industry has, for decades, collaborated with classical University science- and engineer-courses. For universities, the aim has mostly been learning in professional environments. The industry, on the other hand, has classically aimed for recruitment and research. A University-Industry cooperation in the teacher-training program is a new cooperation type inspired by the demands of the new green economy. In February 2020, the pilot project enters its second year. We ask ourselves several questions at this stage of the project. Do the students achieve learning outcomes in science as well as relevant competences reflecting in-depth learning? What are the challenges? Are there any surprises? In November 2019, the Norwegian directorate for education and training presented a new curriculum for Norwegian Schools, leading to increased focus on the educational sector. Discussions regarding

learning strategies are relevant. Educational research and media are hitting us with buzzwords like 21 century skills, lifelong learning, in depth learning and sustainability. By researching, communication and sharing project experiences, the educational sector can grow and meet new challenges in the years to come. The Waterproject represents one way of working in an Industry-University project for science learning. If successful, we hope our project can act as a small contribution to a large research area.

Magmatic and metamorphic ages of the host rocks to iron oxide deposits in the Grängesberg-Blötberget area, Bergslagen, Sweden

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The Bergslagen ore province in south central Sweden is extensively mineralised, above all in the form of different types of iron oxide deposits. These as well as most sulphide ores are hosted by metamorphosed Palaeoproterozoic volcano-sedimentary units. Despite the abundance of iron oxide mineralisations in the province, apatite-iron oxide (AIO) deposits only occur in its northwestern part. The largest of these are those at Grängesberg and Blötberget. They are characterised by steeply dipping magnetite-dominated ore lenses, surrounded by localised breccia and alteration zones, and further outwards also skarn deposits. They are also spatially associated with banded iron formations (BIF). The mineralised zone is overlain by a porphyritic, felsic metavolcanic sequence and clastic metasedimentary rocks, representing the upper part of the volcano-sedimentary succession in this part of Bergslagen. These rocks have locally been intruded by a coarse-grained 1.89 Ga granodiorite, subsequently thrusted onto the ore zone (Högdahl et al. 2013), as well by a fine-grained leucogranite with associated dykes.

It has been proposed that the AIO ores belong to the lower part of the volcano-sedimentary succession in Bergslagen (Magnusson 1973, Allen et al. 1996). In order to test this and better constrain the timing of peak regional metamorphism in the area together with the emplacement of the leucogranite, U-Pb zircon SIMS analyses were conducted on key lithologies. The host rocks to mineralisation at Grängesberg and Blötberget as well as a magnetite-bearing feldspar-porphyritic dacite located between them gave similar ages, around c. 1.9 Ga (1903±4 Ma, 1897±2 Ma and 1901±3 Ma, respectively), whereas the fine-grained granite yielded an age of 1859±2 Ma. The latter coincides with zircon rim ages of 1.86 Ga at Blötberget and in the BIF at Håksberg, which reflect the timing of peak metamorphism. Apparently, the orthomagmatic and epigenetic AIO mineralised system (e.g. Jonsson et al. 2013) formed near the c. 1.9 Ga host rock age prior to the emplacement of the 1.89 Ga granodiorite and its overthrusting at peak metamophic conditions at 1.86 Ga. The potential interrelation between AIO and BIF deposits is still open for interpretation; yet, considering the ages of their host rocks, they formed within a relatively limited time-span.

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Documenting trace fossils: revisiting Banks´s 1970 *Dimorphichnus* on the Digermulen Peninsula, Finnmark

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The Digermulen Peninsula on the western side of Tanafjord, Finnmark, Arctic Norway, exhibits one of the best and most complete early Cambrian trace fossil records in the world. The complete succession spans the late Ediacaran to the Early Ordovician. But especially the Cambrian record of faunal colonization and the agronomic revolution is well documented. Larger trace fossil assemblages or larger individual trace fossils may be impossible to collect physically, and their documentation needs to be secured with other methods such as photographs, scanning or casting. The Digermulen Early Life Research Group has during several field seasons cast important trace fossil-bearing sur-

faces that would be impossible to collect, or where such attempts most likely would lead to the destruction of the surfaces. Over time such fossils may be lost, which makes scientific documentation crucial.

Here we present a case study on the long-term fate of a trace fossil left *in situ* and its possible documentation. A large arthropod "raking trace", *Dimorphichnus*, was described and photographed in situ by Banks (1970) from a quartzitic sandstone from the Cambrian Series 2, Lower Duolbagáisá Formation from a section north of Breidvika valley, on the eastern side of the Digermulen Peninsula. Some 40 years later during our first field season the trace was easily located and seemingly unaffected by time and appears stable where it is exposed on the rock face. However, the outcrop is affected heavily by running water and overgrowth which will have long-term detrimental effects. The surface was thoroughly cleaned and a silicon mold of the trace was made in the field. Later in the lab, a durable Jesmonite composite was used to produce a highly detailed cast. A number of fine details, otherwise not seen in the field, have been observed and the trace is currently undergoing scientific description. The first cast of the trace will become the registered reference specimen in the museum collection at the Arctic University Museum in Tromsø. The procedure outlined here allows, 1) a copy of the specimen to be available for research, 2) a physical record of the specimen to be preserved in case the fossil completely deteriorates in the field, 3) the weathering of the specimen to be monitored more closely by comparing cast with previous and future photographs of the *in situ* specimen, and 4) the trace to be shared with other museums either through subsequent casts or 3D scanning.

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DATED-2: An updated chronology and time-slice reconstruction of the last Eurasian ice sheets

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DATED-1 comprised a fully-documented empirical reconstruction of the changing extent of the last Eurasian ice sheets 40-10 ka (at 1000-year resolution after 25 ka) based on an assessment of all relevant chronological data (Hughes et al. 2016). All uncertainties within the underlying data are synthesised and expressed in terms of distance; deviation between maximum and minimum limits, and their relative proximity to the extent considered 'most-credible', indicates the degree of uncertainty along the ice margin at each time-slice. Explicitly reporting all uncertainties in this way provides a straightforward means to compare geological data with results from numerical modelling of past ice extent. A by-product of the process was creation of an archive of all published dates (and associated data necessary for their interpretation, quality, and recalculation) relating to the build-up and retreat of the Eurasian ice sheets. Both the time-slice reconstructions and underlying chronological dataset are available via the online data repository PANGAEA in GIS and Google Earth compatible formats, and the reconstruction in NetCDF format on request.

DATED-1 runs the risk of being frozen-in-time and losing its relevance if not maintained and updated to reflect the latest observations. Six years on from the DATED-1 census, the volume of data, from dates and also geomorphological mapping, has grown significantly. We present the second-generation Eurasian ice sheets' synthesis, DATED-2, which brings the chronological dataset and reconstructions up-to-date by including all information published before 1 January 2019 (1 January 2018 for the British-Irish Ice Sheet). Despite a 40% increase in the number of dates, including a near doubling of dates derived from terrestrial cosmogenic nuclide methods, and over 2000 new dating-sites, the overall spatial and temporal distribution of chronological information is largely unchanged. We find it disappointing that we cannot improve the precision (i.e. narrow the distance between maximum and minimum lines) more. The time-slice reconstructions continue to rest on relatively few dates and the largest uncertainties remain, e.g. the timing of coalescence and separation of the ice sheets, and the nature of deglaciation of the eastern Barents Sea. We highlight the main changes in DATED-2, present a new calculation of the evolution of ice sheet volume in terms of sea level contributions, and discuss implications for, and obstacles to, understanding the build-up and deglaciation of the last Eurasian ice sheets.

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On the origin and evolution of topography in Norway

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Substantial controversy surrounds the origin and evolution of high topography along passive continental margins. I will focus on the well-documented elevated passive margin in southwestern Scandinavia and address the origin and evolution of topography in Norway using three complementary quantitative analyses.

1) In order to assess the origin of the present day topography we quantify the relative contributions of crustal isostasy and dynamic topography. We find that majority of the topography is compensated by the crustal structure, strongly suggesting a topographic age that is in accord with the 400 Myr old Caledonian orogenesis. In addition, we propose that dynamic uplift of ~300 m has rejuvenated existing topography locally in the coastal region over the last 10 Myr. This uplift, combined with a general sea level fall, can explain observations that have traditionally been interpreted in favor of a peneplain uplift model. The isostatic analysis demonstrates that the high topography along the Scandinavian margin cannot represent remnants of a peneplain uplifted within the last 20 Myr. The topography must have been high since the Caledonian orogeny.

2) We analyze the age of the high elevation low relief surfaces often interpreted as the old paleic peneplain surface, by comparing the budget of erosion onshore with the erosion reflected by offshore sedimentation in western Scandinavia during the late Pliocene and Quaternary glaciations (0–2.8 million years ago). We find that the sediments generated by fjord erosion over the entire western Scandinavia accounts for only 35–55% of the total sediment volume deposited off the coast of Norway. This large mismatch implies that during this period, significant erosion must have also taken place away from the fjords at high elevation and indicates a bimodal distribution of glacial erosion and conclude that glacial and periglacial processes have a substantial impact on the formation of low-relief surfaces observed in glaciated mountain belts and high-latitude continental margins. Our results provide strong support for a Plio-Quaternary glacial origin for the high-elevation low-relief surfaces in western Scandinavia and are not consistent with a Mesozoic or Cenozoic peneplain origin. The volume balance between offshore sediment deposition and onshore inferred erosion shows that most of the fjord topography was formed during the Plio-Quaternary glaciations, leaving only little room for the prevailing older ideas of fluvial erosion in response to Cenozoic uplift(s).

3) Lastly we analyze Eocene to mid-Pliocene (54-4 Ma) landscape evolution in the Scandinavian region using inverse modeling of landscape evolution. We combine a highly efficient forward-in-time landscape evolution model (FastScape) with an optimization scheme suitable for non-linear inverse problems. The inverse model is optimized using 1) sediment fluxes based on decompacted offshore sediment volumes and 2) maximum pre-glacial topography from a mid-Pliocene landscape reconstructed using geophysical relief and offshore sediment volumes from the mid-Pliocene-Quaternary. The inverse modeling shows several scenarios consistent with the offshore sediment record and the maximum elevation for our reconstructed mid-Pliocene landscape reconstruction. Our preferred model for Eocene to mid-Pliocene landscape evolution in Scandinavia is one where high topography (~2 km) has existed throughout the time interval from 54-4 Ma. We do not find several phases of peneplain uplift necessary in order to explain offshore sediment volumes and large-scale topographic patterns. On the contrary, extensive peneplain dissection is inconsistent with the low rates of erosion we infer based on the offshore sediment volumes.

In summary, these three complementary quantitative approaches show no support for the peneplain uplift model and indicate that most of the topography in Norway most like originates from the 400 Myr Caledonian orogeny, with the exception of Western Norway where local moderate uplift may be required.

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15 years with the Spitsbergen Mesozoic Research Group

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When dinosaurs ruled on land the apex predators in the ocean were marine reptiles. From the Arctic archipelago of Svalbard, the Spitsbergen Mesozoic Research Group has excavated numerous well preserved marine reptile skeletons in order to understand the biology of these animals and the environment they lived in. The work of twelve field seasons since 2004 has made this one of the largest and most productive paleontological research projects in the high Arctic world-wide. The initial eight seasons focused on one of the richest occurrences of Late Jurassic—earliest Cretaceous (c. 150–139 Ma) marine reptiles in the world, and nearly sixty specimens have been collected, together with a diverse assemblage of invertebrates. The last four seasons were spent investigating events further back in time, as Spitsbergen preserves the remains from some of the first marine reptile radiations in the wake of the most devastating extinction in the history of the Earth, at the Permian–Triassic boundary (c. 252 Ma). The international research group published their first scientific results in 2012, followed by a steady stream of publications in the years since. Collectively, it has contributed significantly to the understanding of marine ecosystems at the Jurassic–Cretaceous boundary and is starting to yield results about life's recovery in the first millions of years after the Permian–Triassic extinction. Outreach has been a major part of the project from the very beginning, both because it is important to share these scientific results with the public, but also because it attracts funding. Alternative financial support and a lot of determination have been crucial components for the success of this long term research project. This has been made possible through cooperation with a local tourist agency and the petroleum industry, grants from the National Geographic Society, income from public lectures and personal sponsors.

Submarine landform records and seismic stratigraphy of Younger Dryas ice-marginal zones along the Helgeland coast, northern Norway

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The Younger Dryas (YD) climatic deterioration caused a vast expansion of the Scandinavian Ice Sheet; a final glacial spasm leading to the deposition of large ice-marginal features along the entire ice sheet's fringe. In the fjord-incised terrain of Helgeland, northern Norway, Quaternary geology mapping has unmasked the presence of large end moraines onshore that is assumed related to the YD ice sheet culmination. Subsequently, cruises conducted in 2016-2018 with our research vessel Seisma collected high-resolution, EM-2040 multibeam bathymetric data with the aim of locating the submarine continuation of the YD ice margin. The cruises in 2017 and 2018 also conducted seismic profiling of the ice-marginal zones.
The YD ice margin is defined by terminal moraines and grounding-zone wedges (GZW). Distal to the grounding line, we have mapped thick deposits of glacigenic debris flows, some extending several km from the glacier terminus. Elongated crag-and-tails and drift landforms occupy the fjord bottom inside of the grounding line, pointing to rapidly flowing YD ice-streams. Terminal moraines are typically found in the high-relief fjords where glacial flow was constricted by topography. Seismic data suggest aggradation (and progradation) of the moraines due to upward stacking of till and extensive glacigenic debris flow activity on the distal side. This architectural build-up was critical for grounding line stability, as glacial advance took place in fjords with palaeodepths as much as 800 m. GZWs are seen deposited where glacial flow was allowed to expand, e.g. on the strandflat beyond the overdeepened fjords. As there merely was a seasonal sea ice cover along the Norwegian coast during YD, we find no evidence for the GZWs being formed due to the presence of an ice shelf. Small-scale sediment wedges just inside of the YD maximum position mark short-lived stillstands during initial grounding line retreat.

Age and maximum flood height of the Nedre Glomsjø outburst flood, southeastern Norway

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The large ice-dammed lake Nedre Glomsjø was drained catastrophically at least once at the end of the last Ice Age. Conspicuous outburst flood gene-

rated erosive ledges in the upper reach of the flood path show that the (largest) flood was up to several km wide and 95 meters deep. Such upper flood level indicators are present in the more topographically constrained reaches, but in the wider valley segments, morphological traces of flood high stand are sparse or lacking. Here, sediment coring of several basins (bogs or swampy edges of lakes) around the purported flood high stand now provide new details on run-up height, as well as the event's age. Preliminary interpretations of the data suggest a 10-15 m higher flood run-up than previously reconstructed through morphological traces. 19 organic samples submitted for AMS radiocarbon dating will (hopefully) yield temporal constraints on the outburst flood event. Based on XRF analysis conducted on the sediment cores, we also provide a geochemical profile of the conspicuous flood silt bed, allowing a non-destructive and time-efficient tool to identify and trace the regional stratigraphic marker elsewhere.

PFAS transport in unsaturated soils - a column study

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The contaminant situation at several Norwegian firefighting training facility (FTF) has been investigated several years after the use of perfluorooctanesulfonic acid (PFOS) based aqueous film forming foams (AFFF) products has ceased. Detailed mapping of the soil and groundwater reveal high concentrations of per- and polyfluoroalkyl substances (PFAS). PFOS accounts for most of the total PFAS concentration at several sites. At some FTF sites the groundwater has been contaminated from the AFFF use.

To get a better understanding of the historic fate of AFFF used at the site, unsaturated column studies were performed with pristine soil with a similar texture and mineralogy as found at the FTF. Transport and attenuation processes governing PFAS behavior were studied with focus on cold climate conditions and infiltration during snow melting, the main groundwater recharge process at the FTF. Low and high water infiltration rates of respectively 4.9 and 9.7 mm/day were applied for 14 and 7 weeks, thereby applying the same amount of water, but changing the aqueous saturation of the soil columns. The low infiltration rate represented 2 years of snow melting, while the high infiltration rate can be considered to mimic the extra water added in the areas with intensive firefighting training. In the low infiltration experiment PFOS was not detected in the column leachate over the complete 14 weeks. With high infiltration PFOS was detected after 14 days and concentrations increased from 20 ng/l to 2200 ng/l at the end of the experiment (49 days).

Soil was extracted from the columns in 5 cm layers and showed PFOS concentrations in the range <0.21-1700 µg/kg in the low infiltration column. A clear maximum was observed at a soil depth of 30 cm. No PFOS was detected below 60 cm depth. In the high infiltration column PFOS concentration ranged from 7.4 to 1000 µg/kg, with highest concentrations found at 22-32 cm depth. In this case PFOS was detected down to the deepest sample (~90 cm).

The estimated retardation factors for the column experiments were much lower at 6.5 and 5.8 for low and high infiltration, respectively. This study showed that PFOS is strongly attenuated in the unsaturated zone and mobility is dependent on infiltration rate.

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Oxygen isotope characteristics of Karoo picrites with a primitive mantle affinity

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Continental flood basalts (CFB) in the Karoo large igneous province have been divided into the North and South Karoo groups. Picrites from the Luenha river, Mozambique, have been shown to represent the primitive mantle-like end-member required to explain the geochemical characteristics of the North Karoo CFBs, which have elevated DNb compared to the South Karoo CFBs. These picrites exhibit a narrow range of bulk-rock Nd isotope compositions (eNd_{180Ma} -2.0 to +1.4) but a wide range of bulk-rock, plagioclase and groundmass Sr isotope compositions (full range $^{87}Sr/^{86}Sr_{180Ma}$ 0.704096-0.71061), extending to high values suggestive of crustal contamination in the origin of these rocks. Despite this, preliminary O isotope data for olivine from one sample with elevated

$^{87}Sr/^{86}Sr$ show uniform, mantle-like $d^{18}O$ values (4.68±0.38‰ to 5.53±0.37‰). New O isotope data acquired on the NordSIM Cameca IMS 1280 ion microprobe will determine the O isotope composition of a sample inferred to most closely represent the parental magma as well as test the intra- and inter-sample O-isotopic variability of these picrites. Combined with the available bulk-rock and plagioclase phenocryst compositions, these data allow us to constrain the progress of crustal contamination and evaluate the homogeneity of the parental magmas. Most importantly, we aim to distinguish between the effects upon the samples of crustal contamination versus mantle source heterogeneity.

Monitoring the Effect of Geothermal Effluent from Powerplants on Groundwater in the Lake Mývatn Area and Theistarreykir area, NE-Iceland

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The chemical composition of the inflow into Lake Mývatns and the lake itself is stable due to the fact that almost all the inflow is supplied through groundwater by artesian springs. Geothermal and volcanic activity affects the groundwater system and thus the chemistry and biological activity of the lake which is unique especially at this high latitude. Landsvirkjun, the National Power Company of Iceland, owns and operates the power stations and high temperature wells in Bjarnarflag, Krafla and Theistareykir. In order to study the possible influence of the geothermal water from separation stations and wells (effluent water), Landsvirkjun has undertaken an extensive programme to monitor the chemistry of the groundwater, and also to study the origin of the thermal part of the groundwater flowing to Lake Mývatn. Regular chemical monitoring of the groundwater in the Mývatn area began in 2003 and in Theistareykir and Kelduhverfi in 2007. The main emphasis has been placed on monitoring the concentration of arsenic (As) and aluminum (Al) as these elements are in relatively high concentrations in the effluent water from the power stations in Bjarnarflag, Krafla and Theistareykir, but in very low concentrations (often below the detection limits) in the cold and warm springs in the area The main purpose of monitoring the chemical composition of groundwater in Kelduhverfi, north of Theistareykir, is to collect basic information in order to estimate possible influence on groundwater from geothermal utilization at Theistareykir field as the powerplant there began operating in late 2017. The data collected so far show the chemical composition of groundwater in its natural state. The concentration of arsenic is in all cases below Environmental limit I (0.0004 mg/L). The results of the monitoring of the chemical composition of water in springs at Lake Mývatn and of groundwater west of Námafjall during the last decades does not show any influence from the geothermal water from the power stations in Bjarnarflag and Krafla with respect to arsenic (As) and aluminium (Al). Higher concentration of arsenic and aluminium is observed in two monitoring wells in Búrfellshraun lava field, east of Námafjall and close to where the effluent water from the Krafla power station disappears into the lava.

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UNFC as a tool for sustainable sourcing of raw materials for the green transition

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According to the UN and its economic commission to Europe, we wont be able to reach a single one of the global goals, nor the Paris agreement, without sustainable access to raw materials and energy. For now and for the foreseeable future, recycling will not be enough to meet the huge demands of raw materials needed for the energy transition, huge efforts must be put to improve the entire ecosystem of reuse and recycling, and still it will be necessary to source primary raw materials.
Europe is strongly import dependent, and the situation is getting worse every year. The list of critical raw materials for Europe is just getting longer each time it is reviewed. This is crucial for the European economy and Europe's possibilities to contribute to climate mitigation, especially in the geopolitic context we find ourselves today.
Concurrently, the resistance against exploration and mining in Europe is growing, especially in areas lacking modern experiences with this industry, but also in mining areas, the NIMBY perspective is growing stronger. This happens in regions where the environmental regulation is strong, where the industry is running the best environmental performance in the world, and has a genuine will to interact with the local society in order to meet demands on social sustainability. And simultaneously be economically sustainable to be able to

afford those standards and survive and be competitive over time. It's a matter of conflict between local environment and global climate mitigation.
In this context, UNFC, UNs framework for classification of raw materials (including secondary raw materials and other commodities), and its resource management system (UNRMS) can provide a powerful tool for communicating the level of sustainability for a project or a region, to different stakeholders, such as governments, financers, landowners, local communities and other interests.

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Recognition of Svecofennian serpentinized ultramafic bodies at Tjusterby in the Pernå region, SE Finland

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Two highly magnetic Svecofennian serpentinized ultramafic bodies were discovered under sea water in the Pernåviken bay, southeastern Finland, as part of an international course in Ore Prospecting, conducted by the University of Turku in 2015-2016. The discovery was made through systematic onshore search for metal anomalies in till, boulder tracing and magnetometry, the latter also conducted off shore.
The magnetic survey identified two ellipse-shaped total field magnetic offshore anomalies. The SW-NE-elongated western anomaly is about 800 m long and 400 m wide, and includes two peaks with maximum amplitudes of 2800 and 3100 nT, located 300 m apart. The "saddle" between the two anomalies has a magnetic field value of about 2100 nT. The smaller, ESE-WNW-elongated eastern anomaly, has a maximum amplitude of about 2200 nT, is 600 m long and 300 m wide. Both positive anomalies are bordered in the north by negative, several hundreds of nT in amplitude, side anomalies.
The anomaly data were used to model two ellipsoidal bodies with magnetic susceptibility ($31{,}888\times10^{-6}$ SI), similar to the susceptibility of the adjacent onshore serpentinite boulders. The magnetic remanence was set to 3.86 and 3.34 A/m for the western and eastern ellipsoid, respectively. Expressed in Koenigsberger value (Q), these correspond to 2.9 and 2.5. The direction of the remanence is fairly close to the palaeomagnetic direction for 1.88 Ga (declination = 326°, inclination = 30°). Considering the vertical extents, both ellipsoids extend to the shallow subsurface and the magnetic bodies are thus exposed to the bedrock surface and were accessible to erosion during the latest glacial event.
In this way, rock fragments of all grain sizes were glacially transported 100-200 m SE-wards from the magnetic bodies, which created magnetic soil and boulders in the onshore areas. The soil turned out to be Cr-Ni-Fe-enriched while the boulders were shown to be truly ultramafic rocks with serpentine, phlogopite, plagioclase, magnetite (and other opaque phases) as well as occasional brucite, chlorite and garnet. The unserpentinized protolith was probably a dunite. These serpentinites are first of their kind in the Pernå region, but similar bodies probably also occur elsewhere in the Svecofennian Häme Belt in southern Finland.
Based on comparisons of the Tjusterby ultramafic bodies with serpentinites elsewhere in the world, it is suggested that the serpentinization of the Tjusterby dunites was linked to a subduction zone, as opposed to abyssal (mid-ocean ridge) or mantle wedge environments.

Snow avalanches on Svalbard

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Avalanches have long been regarded as an insignificant geodynamical process on Svalbard. Maybe, avalanches had little interference with the human activities of mining in limited areas and hunting in coastal zones. Processes not considered relevant for the mining and hunting activities were not studied or not even noted. Nevertheless, avalanches have always been a part of the natural slope processes and slope mass transport. They are a common process in all slopes steep enough to start avalanches. Traces and depositions contribute to the typical geomorphology on Svalbard. Avalanches as a hazard for the settlement of Longyearbyen were first studied in the mid 1980s. But first the increased use of the terrain by free time activities in the early 2000 brought avalanches into the mind of research and society. Several fatal accidents raised the avalanche awareness, introduced efforts in society and research to be better prepared and to study the process from a scientific point of view. The major avalanche event in 2015, foreseen by experts already 25 years earlier, put avalanches on top of the agenda in the small communities in Svalbard. Several settlements were mapped for

avalanche hazard, avalanche forecasting and evacuation routines were implemented and structural mitigation measures are currently under construction. During these short period, when avalanches were recognised as an important process, intensive change of the climatological conditions are taking place. Changes in temperature, precipitation, circulations patterns and the open Isfjord alter the snow climate from winter to winter such that the value of the little knowledge that was collected during the last 20 years is of limited use for the design of future mitigation.

Glacial dynamics and retreat pattern in the Fingerdjupet Trough (Spitsbergenbanken, western Barents Sea) during the last deglaciation

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Fingerdjupet is a trough on the south-eastern side of the shallow bank Spitsbergenbanken, W-Barents Sea, and a tributary to the much larger Bjørnøyrenna trough (Bear Island Trough). In this study, new high-resolution multibeam bathymetry and sub-bottom profiler datasets from Fingerdjupet are used as a basis for detailed geomorphological mapping of the seafloor. The mapped features, e.g. mega-scale glacial lineations, provide evidence for a palaeo-ice stream in Fingerdjupet, that drained ice southwards from Spitsbergenbanken. The onset zone of ice streaming shows evidence of drainage of grounded ice from the west and northwest in a southerly direction into Bjørnøyrenna. The combined landform records and acoustic stratigraphy allow a detailed reconstruction of the glacial dynamics during the last deglaciation. The withdrawal of the Fingerdjupet ice stream from Bjørnøyrenna was characterised by rapid retreat that was punctuated by longer periods of slower retreat. At least five or six major ice margin stillstands and/or readvances are identified in the landform record and/or acoustic stratigraphy. During these events, large grounding zone wedges were deposited at the ice stream margin. As the ice stream retreated out of the trough and onto the shallower bank, a significant change in retreat rates and associated processes is registered in the seabed geomorphology. Here, numerous retreat moraines indicate a slowly retreating grounded ice margin, punctuated by several minor stillstands. Several controls and/or drivers on the style of retreat have been identified, including bedrock topography, sea level rise, catchment size, and drawdown of bank ice and/or migration of the main ice divide over the bank. The findings of this study confirm earlier assumptions that an ice stream operated in Fingerdjupet and that it drained from an ice divide located along the crest of Spitsbergenbanken.

Mountains of southernmost Norway: uplifted Miocene peneplains and re-exposed Mesozoic surfaces

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The origin of the Norwegian mountains (the Scandes) is a key controversy in modern geoscience. Are they remnants from the Caledonian Orogeny, modified shoulders of late Mesozoic rifts, or are they evidence of Neogene uplifts? Our synthesis of geological data, landscape analysis and new thermochronological data from Norway south of ~60Ṅ, combined with previously published data from southern Sweden, reveals a four-stage history:
(1) Middle Triassic and Middle Jurassic exhumation produced a weathered basement surface with a hilly relief.
(2) After late Mesozoic rifting, Upper Jurassic – Oligocene sediments accumulated across most of the area.
(3) Early Miocene uplift and erosion to the base level of the adjacent ocean led to formation of a peneplain that extended across sedimentary basins and Caledonian rocks; the sub-horizontal Hardangervidda plateau represents this peneplain.
(4) Early Pliocene uplift raised Hardangervidda to its present elevation of ~1200 m above sea level and led to re-exposure of the tilted, Mesozoic surface at lower elevations.
The Southern Scandes are thus, like other elevated passive continental margins around the world, the product of post-breakup uplift and erosion. Identification of the mechanisms driving these uplifts awaits geodynamic modeling constrained by observations such as those presented in this study.

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Japsen, P., Green, P.F., Chalmers, J.A. & Bonow, J.M. 2018: Mountains of southernmost Norway: uplifted Miocene peneplains and re-exposed Mesozoic surfaces. Journal of the Geological Society, London 157, 721-741.

The 30 June 2017 North Sea earthquake: Location, characteristics and context

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On 30 June 2017 at 13.33 UTC a magnitude 4.5 earthquake occurred in The Viking Graben of the North Sea. When recorded, the event was the largest in the area for several decades, and was reported felt in north-east Scotland, Orkney, Stavanger in Norway, the Shetland Islands, and on the Sleipner A oil platform. This is an area with numerous offshore platforms related to oil and gas production. Estimating the event depth, location, and focal mechanism is therefore important for risk assessment.
The earthquake was recorded by stations at both regional and teleseismic distances, where depth phases were observed at a large number of global stations. The location algorithm used to locate this event was extended to accommodate the use of a local velocity models for the source region. This local model included a sedimentary layer with seismic velocities taken from a 5 km deep well-log at the closest hydrocarbon field. The inclusion of the local model resulted in a depth estimate of 7 km, indicating a hypocenter in the Baltica basement.
This depth estimate is also supported by depth phase modelling of seismograms at teleseismic distances. Regional moment tensor analysis results in a reverse thrust faulting focal mechanism. Previously, no focal mechanisms have been calculated for the region surrounding this event. The new focal mechanism therefore helped in further inferring a stress direction in the Viking Graben, and showed high consistency with the ridge-push force from the Mid-Atlantic seafloor spreading.
Correlation detectors were run on 30 years of data searching for repeating signals, using the 30 June 2017 event as a template. Four events were found to match the signal template. Three aftershocks; one magnitude 1.9 event which occurred only 33 minutes after the main event and two smaller magnitude ~1 events the following days. Additionally, a magnitude 2.5 earthquake on the 13 November 2016 was found to match the 30 June 2017 event well. We also present a multiple event relocation of events in this region which resulted in a more consistent and clustered seismicity pattern.

Understanding the transitions from subaqueous to subaerial volcanic environments; inferences from exceptional exposures along the coast of Angola

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Transitions between subaqueous to subaerial volcanic environments, and vice versa, are a common factor along volcanic margins, in emergent volcanic systems, and where continental volcanics encounter lake, river and ice systems. In volcanic margins and at the basal sections of flood basalt sequences, these transitions can provide important information about the existing environment prior to volcanism, preserve key sedimentological data, and provide palaeo-sea level and shoreline indicators which can be used to map out this transition. Along the Angolan coast, Africa, remarkable outcrops which highlight these transitions are preserved in a number of locations. Here, we report on five such examples where; shallow submarine pillow and hyaloclastites are interbedded with shelf sediments (Sumbe section), an emergent volcanic centre marks the transition from marine into subaerial eruptions (Ponta Negra section); lava flows enter a soft sediments shoreline to produce peperites (Uah section); lavas transition into a coastal area feeding invasive flows (Canico section); and an extensive section which displays many aspects of shallow intrusion and both submarine and subaerial eruption settings (Baia dos Elefantes section). Such extensive and well preserved examples can help us understand how to interpret similar geology in less well preserved areas and in subsurface data sets, where there is a need to better constrain the onset of volcanism and its manifestation within a changing palaeo-environment during its evolution.

Marine faunas of the Preboreal stage in the Oslo area

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The early Holocene marine faunas of the Oslo area were studied in classical works by Brøgger (1901) and others, but there has been relatively little

research in this field in recent decades. We want to look at these faunas again, with new methods and in the light of new knowledge about the dramatic environmental changes after the Younger Dryas/ Holocene transition, including the Preboreal Oscillation. Classical fossil localities near the marine limit at ca. 220 m above sea level around Oslo are now difficult to localize, overgrown or completely lost and it is difficult to collect new material. However, the material of Brøgger, Øyen and others can be studied in the extensive Quaternary collections of the Natural History Museum in Oslo. In addition to reviewing present knowledge and documenting the present state of classical localities, we apply new methods to shells in museum collections. These include new 14C datings, LA-ICPMS and oxygen isotope profiling along *Mytilus* shells to study annual cycles in temperature and salinity, CT and SEM imaging. The aim is to produce new information on the environmental conditions and stratigraphic correlations during this critical phase in the deglaciation of southeast Norway.

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Mapping the subglacial landscape at the Folgefonna ice caps, investigating future drainage patterns caused by shrinking glacier size

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The Sørfonna icecap is the 3rd largest glacier in Norway (157 km^2 in 2013), and largest of the three glaciers constituting Folgefonna. Sørfonna is important for the society. Hydropower stations are placed both south and northwest of the icecap, and hydropower companies worry about future possibilities for hydropower in a warming climate. Sørfonna is also a large part of the tourism in the area and is the centre of the Folgefonna national park. In order to improve predictions of future glacier coverage and contributions of meltwater to existing hydropower stations, we have constructed a subglacial topography map of this icecap. The map will also be used to model the development of the icecap during two climate scenarios 100 years forward into the future.

To find the glacial depth we used a Blue System Integration radar set up (2.5 MHz antenna) over four field seasons (2015-2018). GIS-software was used to interpolate a subglacial topography map from the depth measurements. The map shows an undulating landscape and a thicker glacier than anticipated (maximum depth 570 m) and a total volume estimates of 28 km^3. Analysis of the subglacial topography show that if the current retreat of Sørfonna continues, the ice cap will eventually disintegrate into small mountain glaciers, dead ice bodies and new lakes, consequently affecting water drainage into established hydropower stations. During the retreat, the environment will potentially give rise to trapped glacial lakes followed by glacial outburst floods, floods and mass wasting events.

This study suggests that increased monitoring of the glacier is required in order to ensure safety of local communities. Nearby infrastructure will most likely be affected by the glacier retreat and related hazards that are predicted to occur more frequently the years ahead. The result will in turn enable the development of solid regional research-based adaptation strategies.

Igneous and metamorphic evolution of continental basement in the collisional root zone of the Scandinavian Caledonides – records from a tectonic lens in Roan, Vestranden, west-central Norway

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A tectonic lens at Roneset in Roan, Vestranden, displays uniquely preserved primary intrusive relationships, structures, and textures which record the Proterozoic pre-metamorphic history as well as the Caledonian metamorphism of the Baltica continental margin. A discrete mylonite zone, active through upper and lower amphibolite-facies conditions, served to protect the Roneset tectonic lens from Caledonian deformation. The exposed area of the Roneset lens is c. 22000 m^2 outcrop at the sea shore.

Gabbro and charnockite in the tectonic lens represent, together with 1.65 Ga quartz-monzodioritic, quartz-monzonitic and granitic intrusions within the Roan peninsula, the north-westernmost extension of the Transscandinavian Igneous Belt. A body of structurally older hornblendite has been intruded by gabbro, forming an intrusion breccia. Up to 10 cm wide dry zones dominated by two pyroxenes and plagioclase occur as a network in the brecciated hornblendite. All these intrusive rocks are cross-cut by younger dolerite dykes that preserve fine-grained chilled margins towards their host rocks, despite overprinting granulite-facies metamorphism.

The Caledonian metamorphism of the Proterozoic rock complex in Roan reached high-pressure granulite-facies conditions. The metamorphic assemblage of the youngest pre-Caledonian intrusions - the metadolerite dykes - consists of clinopyroxene + garnet + plagioclase + orthopyroxene + hornblende + biotite + FeTi-oxide + quartz. The metamorphic assemblages of the older rocks are also characteristic of the high-pressure granulite-facies. Notably, although metamorphosed at considerable depth (30-40 km), the rocks in the Proterozoic rock complex do not record eclogite-facies conditions. This is in contrast to an allochthonous eclogite complex of Iapetus origin also situated within the Roan peninsula (cp. Möller et al., 2020, this abstract volume).

Late-orogenic retrograde amphibolitization was associated with the intrusion of late Caledonian pegmatite dykes and veins and, outside of the tectonic lens, open to tight folding about NNE-SSW axial surfaces.

The structural relationships inside the Roneset lens illustrate that unique information can be gained from well-preserved tectonic lenses even in the deep root zone of collisional orogens. Further detailed investigations, including metamorphic petrology, geochronology, and geochemistry, are in progress.

Reference:

Möller et al., 2020: Eclogite- and upper amphibolite-facies metamorphosed Iapetus units within Precambrian basement, Roan, Vestranden, Norway. Abstract NGWM.

The Hedesunda granitoid complex, east-central Sweden

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The Hedesunda granitoid complex covers an area of ca 40 x 20 km within the Svecofennian province in east-central Sweden. Because of its dominantly pinkish colour, coarse porphyritic texture and largely undeformed nature, it stands out from the surrounding early-orogenic orthogneisses, and its position within the Svecofennian orogenic evolution has been highly disputed. New U-Pb zircon SIMS dating confirms previous TIMS dating, showing that the Hedesunda massif is a composite intrusion, with an older phase at 1.86 – 1.87 Ga, and a much younger phase at 1.79 Ga. The geographical distribution of these superficially very similar granite generations, as outlined on recent SGU maps, is largely confirmed by their geochemical characteristics.

The older Hedesunda I intrusion ranges from dioritic through tonalitic and granodioritic to granitic in composition, while the Hedesunda II rocks are purely granitic. The Hedesunda I rocks are dominantly calc-alkalic and magnesian, they range from metaluminous to peraluminous, and fall in the volcanic arc field. The Hedesunda II rocks are calc-alkalic to alkali-calcic, ferroan and peraluminous, and mostly fall in the within-plate field. The Hedesunda II rocks show stronger enrichment in most incompatible elements than the Hedesunda I rocks, and follow separate fractionation trends. Initial $å_{Nd}$ fall between 0 and +2 for both granite generations.

The Hedesunda I intrusion presumably formed during an extensional phase towards the end of the subduction-related Svecofennian magmatism, shortly after the regional deformation and metamorphism affecting the surrounding orthogneisses, possibly as a result of basaltic underplating. The Hedesunda II granite intruded some 80 million years later, penecontemporaneous with other late- to post-orogenic granitoids within the Svecofennian province and the TIB-1 phase within the Transscandinavian Igneous Belt further west.

Analogue modelling of an organic-rich shale utilizing a smectite-based gelatin

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In-situ for shales, the process of diagenesis and hydrocarbon creation in organic-rich shales results in failure throughout the rock as the conversion of kerogen into hydrocarbon creates tensile failure. The relationship between shale and its TOC (total organic carbon) content defines when, where, how, and the degree to which the host rock fractures. Within this framework, there are a variety of factors that influence the failure of shale and the creation of the fracture network. At a baseline, it is important to understand the competence of the medium prior to failure. Once the shale is at depth, this could vary for a broad range of reasons influenced by everything from deposition to diagenetic trends to date. As the fracture process begins, how TOC rich the host rock is, will have a strong determination on the number of fractures. The temperature the medium has exposure to during the fracture process influences failure.

Analogue modelling provides an opportunity to understand how microfractures occur in-situ from a first-principles perspective. Laponite, a smectite

based gelatin, is the ideal representation of shale as the background medium. A combination of sugar and yeast are utilized to model the reaction between kerogen lenses and temperature, wherein sugar represents the kerogen lenses and yeast represents temperature. Similar to how an increase in temperature results in kerogen converting states resulting in tensile fractures, the reaction between sugar and yeast creates CO2 resulting in tensile fractures within the laponite. Finally, the combination of all of the above is placed into a Hele-Shaw cell ideal for representing any 2D plane in-situ. Once the slurry is within the Hele-Shaw cell it is cured for a fixed length of time. Variations in cure time result in different background competence levels prior to running the analogue experiment.
The analogue experiment allows one to investigate how variations in TOC content, background competence prior to fracturing, and increasing temperature influence the failure process from a qualitative perspective. In turn this knowledge can be applied to better understand how and the degree to which organic rich shales fracture in-situ.

Subglacial seasonal meltwater deposits from a thick Weichselian till sequence, Dösebacka Sweden

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Seasonal changes in subglacial hydrology, which affect ice-flow rates, have been inferred from the Greenland ice sheet. The sediment record of this type of event is not known because of the inaccessibility of the bed. Here, we report on a serendipitous sequence of diamicton and sorted sediments in a rock-cored drumlin at Dösebacka, Sweden, which we interpret as being produced by seasonal development of subglacial meltwater delivered from the surface of the Scandinavian ice sheet during the last glaciation. The sequence consists of 30 m of diamicton with interbeds of sorted material. Though there is some variation, sorted sequences are 5-30 cm thick and are coarsening upward starting with 1-3 cm of clay, followed by silt, sand and pebbly sand. Deformation in the sorted sediment is present but not extensive. Diamicton beds are 1-5 m thick between the sorted layers. Five to seven sorted layers are identified and can be correlated across the outcrop. Hillefors found pollen and *Pediastrum* in clay, and he dated the bulk organic matter to around 28,000 cal 14C YBP. The diamicton is massive and contains an ice-flow-parallel fabric, and we interpret the diamicton as subglacial traction till. We interpret the sorted sediment as a sequence deposited by subglacial meltwater and created during increased water pressure at the bed. Initially, increased water pressure reaches flotation and produces patches of bed separation that are not connected laterally. In this standing water, clays are deposited. With time, these pockets become better connected, and water velocity increases as indicated by the coarser sediment. We hypothesize that these sequences represent seasonal delivery of meltwater from the surface. Thus, each sorted bed represents a summer and indicates seasonal subglacial drainage evolution. The coarsening upward indicates the evolution of bed-hydrology integration from standing pools to connected systems. The radiocarbon date suggests organic material derived from the surface of the ice sheet or from eroded interstadial sediment.

Cobalt mineralisation in the Bergslagen ore province, Sweden: an overview

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Today the uncommon transition metal cobalt is a much sought-after raw material, not least due to increasing global demand for battery applications at the core of today´s transition to “fossil-free” electromobility. Cobalt mineralisation has been known and periodically exploited for a long time from deposits in the classic Bergslagen ore province, south central Sweden. It was also here that Georg Brandt first isolated the metal cobalt from Riddarhyttan ore in the 1730s (e.g. Tegengren 1924).
The main periods of cobalt ore production in Bergslagen were during the 18th and 19th centuries and were dominated by the mines at Tunaberg and Vena. Primary cobalt production from Håkansboda, Riddarhyttan and Åtvidaberg was more modest, while it was also extracted as a by-product from the Falu mine (e.g. Tegengren 1924). Smaller and lesser known Co mineralisations occur fairly widespread in the province, with concentrations such as in the Filipstad district (e.g. at Getön, Gruvåsen, Finnshyttebergsfältet, Nordmark, Långban; Zakrzewski et al. 1980, Nysten et al. 1999). More recently, locally abundant Co mineralisation was discovered in the Burkland copper ore of the active Zinkgruvan mine (e.g. Bjärnborg 2009). Major hosts of Co in Bergslagen include cobaltite, cobaltoan arsenopyrite, glaucodot, linnaeite-carrollite solid solutions and safflorite. Notably, in older times

many Co minerals were described under names such as “speiskobolt” or “smaltite” (e.g. Flink 1908), leading to ambiguities as to their modern interpretation. In most mineralisations, the Co minerals, commonly cobaltite, occur as often coarse, euhedral to subhedral crystals (sometimes reaching spectacular formats and degrees of crystallographic development) and grains, while less commonly as anhedral grains or aggregates. To a large degree, these are porphyroblasts or metablasts, i.e. they formed during regional metamorphic recrystallisation of pre-existing, syn-volcanic, c. 1.90-1.88 Ga (Svecofennian) hydrothermal mineralisations. The association between Co mineralisation and Cu sulphide ores is characteristic (e.g. Tunaberg, Håkansboda, Burkland), while in some areas, there is (also) a direct relation to Au-Bi-(Mo)-enrichment (e.g. Finnshyttebergsfältet, Nordmark, Riddarhyttan).

Overall, the Bergslagen ore province exhibits a diverse suite of Co mineralisations of which several remain unstudied with modern methods, warranting further investigation on different scales.

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Sphalerite deformation highlighted by chemical etching and reflected polarised light darkfield and differential interference contrast microscopy

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The metamorphism, deformation and, in part, remobilisation of sulphides and sulphosalts are abundant, yet often overlooked features in sulphidic ore deposits in older geological terrains (e.g. Marshall & Gilligan 1987). With regards to deposits in the Fennoscandian shield, the absolute majority of Proterozoic examples known to us have been affected by such processes to a varying extent.

Chemical etching of ore minerals, particularly isotropic sulphides such as sphalerite, has been utilised over time to reveal grain boundaries, twinning and other patterns of growth, intergrowth and deformation (e.g. Ramdohr 1980; Cugerone et al. 2018). The resulting textural patterns can then be studied in detail with different types of light and electron microscopy. Here, we have chiefly studied sphalerite from the purportedly deformed ore in the Lovisa Zn-Pb deposit in the Bergslagen ore province, Sweden (cf. Andersson et al., this volume). Sphalerite is known to primarily deform through twinning by translation gliding along {111} planes in its structure (e.g. Clark & Kelly 1973). To observe such otherwise invisible deformation features, polished sections with sphalerite were etched with hypochlorite solution and subsequently investigated by means of reflected polarised light microscopy complemented with reflected light darkfield and differential interference contrast microscopy. The sphalerite from Lovisa exhibits abundant intra-granular twinning of several types and on different scales, including growth and deformation twinning as well as kinking and folding of earlier-formed twin lamellae. Additionally, more elongated and parallel to subparallel twin sets occur but are less common. Successive annealing of earlier-deformed sphalerites is suggested, which led to the local disappearance of deformational twinning, new formation of growth twins, and disruption of preferred orientations. The progression of deformation in these assemblages is galena (least competent) -> sphalerite -> quartz/pyrite (most competent). The observed features record extensive modification of this ore, from peak to advanced retrograde regional metamorphic conditions, thus corroborating current interpretations of its textural evolution.

Part of the study presented here was performed on samples from the Lovisa deposit within the ongoing X-Mine project. This is funded by the European Union’s Horizon 2020 research and innovation programme under grant agreement No 73027.

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Towards a unified fluid model for vein-hosted polymetallic (Cu-Pb-Zn-Ag-Au-Bi-Sb-Te-Se-Ge) mineralisations in south-western Sweden

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In order to better understand the process(es) behind the mineralogically diverse and polymetallic,

mainly quartz-hosted vein mineralisations present in SW Sweden (chiefly in parts of Dalsland and W Värmland), fluid inclusion (FI) studies were undertaken. Previous FI studies of Värmland veins were presented by Johansson (1985), Andersson (1990) and Alm et al. (2003). In order to characterise, compare and potentially link these spatially isolated datasets - following the hypothesis that these mineralisations formed from a major, regional-scale process - we sampled and investigated mineralised quartz veins in the Glava field (Värmland) and the Knollegruvan, Slädekärr and Vassvik mines (Dalsland) for FI. Three main types of FI were recognized, from earliest to latest: 1, aqueous-carbonic inclusions; 2, aqueous inclusions, and 3, hydrocarbon inclusions. Total homogenization (T_H) of the aqueous CO_2-bearing FI occurred, depending on the amount of CO_2 present, between 213° and 379°C to the CO_2-bearing vapour phase. Gas-hydrate melting yielded salinities from 6.2 to 11.5 eq. mass % NaCl for these FI. Their variable phase proportions are characteristic for the trapping of a heterogeneous fluid, suggesting unmixing of the CO_2 phase. T_H to the liquid phase were measured in all aqueous inclusions, ranging between 90° and 196°C. The two-phase aqueous FI exhibited salinities between 1.7 and 16.6 eq. wt% NaCl. Late hydrocarbon FI showed no phase changes on cooling, while on heating they homogenised to the liquid phase between 61° and 115°C. The partial yet systematic overlap with earlier datasets supports the hypothesis of a singular, regional process, while the new data also allow for broader-ranging interpretations. The earliest FI consist of a CO_2-bearing aqueous fluid with modest salinities, while the variable aqueous and CO_2 proportions indicate a fluid entering the two-phase field, leading to immiscibility. Inferences from phase proportions and experimental data suggest relatively low trapping pressures. Thus, the initial mineralising fluid type in the region was probably a single-phase aqueous-CO_2 fluid that migrated upwards in fractures to lower pressures, unmixed upon cooling, and was subsequently variably mixed with low-salinity external fluids. A later fracturing episode led to the entrapment of a hydrocarbon-rich fluid, possibly unrelated to mineralisation.

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Collapsing Glaciers

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Glacier collapses combine the large volumes of glacier surges and the mobility of ice avalanches. The rapid detachment of large portions of a low-angle glacier is a rare process, and has first been documented in detail for the 130 million m3 avalanche released from the Kolka Glacier in the Russian Caucasus in 2002, an event that was until recently considered globally unique (Huggel et al. 2005, Evans et al. 2009). In 2016 however, two similar giant glacier collapses, 68 million m3 and 83 million m3 in volume, occurred from two neighbouring glaciers in the Aru range on the Tibetan Plateau, rising critical questions about the causes of these detachments, and the potential for similar events to occur elsewhere (Kääb et al. 2018, Gilbert et al. 2018). In particular the twin Aru events have raised the awareness for the possibility for such massive glacier detachments, and led to the (re-)discovery and reporting of several potentially comparable events worldwide. The Aru events have also contributed to modulate and advance the understanding of glacier stability, and of processes involved in a range of glacier dynamic instabilities – such as the substrate and the thermal regime at the glacier base. In this contribution, we review and compare a number of glacier collapses and glacier-dynamic instability events in order to discuss potentially common causes. We also discuss the potential role of climatic changes in the occurrence of glacier collapses and the consequences for hazard monitoring and management.

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Constructing a tephrochronological framework for Finland

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Tephrochronology is a powerful tool for dating and correlating sedimentary records, landforms and archaeological sites both in proximal and distal areas. This is reflected in increasing number of tephrochronological studies across Europe during past decades. However, very little tephra work has been done in Finland so far. The main aim of our research is therefore to construct a tephrochronological framework for Finland through a systematic search and geochemical characterization of tephra from Finnish palaeoenvironmental records. Our main research area comprises of 15 peat bogs and 4 lakes in southern and central Finland. Cryptotephra was detected in 17 sites using methods outlined in Dugmore et al. 1995, and tephra shards were enriched with a micromanipulator for electron probe microanalysis (EPMA). Despite using a narrow 3–5 µm beam during EPMA (Hayward, 2012), geochemical composition of just 18 of the 37 detected cryptotephra deposits could be determined due to high vesicularity and small size of the shards. Our results reveal the presence of one Alaskan tephra and at least 10 separate Icelandic tephras in Finnish sites. Most of the identified tephras originate in historical eruptions (e.g. Askja 1875; Hekla 1845; Hekla 1510). This is different from what has been recorded in Swedish sequences where tephra from the large mid-Holocene Hekla eruptions forms the backbone of the tephrochronology and historical products of Hekla are largely absent (Wastegård, 2005). Presence of the historical Hekla 1845 and 1510 tephras in Finland, as well as the fall-out of Hekla 1947 tephra in southern Finland (Salmi, 1948), reveals a similarity between the tephra historical records in Britain, Ireland, Northern Ireland and Finland, indicating a similar meandering transport pathway for each of these tephras.

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Mechanisms for Sb, Sn and HFSE incorporation in garnet through the discovery of a new Si-free garnet endmember: Monteneveite: $Ca_3Sb^{5+}{}_2(Fe^{3+}{}_2Fe^{2+})O_{12}$

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Monteneveite, ideally $Ca_3Sb^{5+}{}_2(Fe^{3+}{}_2Fe^{2+})O_{12}$, is a new member of the garnet supergroup. Associated minerals are mainly magnetite, sphalerite, tetrahedrite-(Fe) and oxycalcioroméite. Monteneveite occurs as black, subhedral crystals with adamantine lustre. Grains are equidimensional and up to 400 µm in size, with a subconchoidal fracture. Monteneveite is opaque, gray in reflected light, and isotropic under crossed polars. The crystal-chemical formula calculated on the basis of a total of 8 cations + 12 anions, and taking into account the available structural and spectroscopic data, is $(Ca_{2.97}Mg_{0.03})_{\Sigma=3.00}(Sb^{5+}{}_{1.73}Sn^{4+}{}_{0.10}Fe^{3+}{}_{0.17})_{\Sigma=2.00}(Fe^{3+}{}_{2.43}Fe^{2+}{}_{0.37}Zn_{0.20})_{\Sigma=3.00}O_{12}$. The most significant chemical variations encountered in the sample are related to a substitution of the type $^{Y}Sn^{4+} + {}^{Z}Fe^{3+} \rightarrow {}^{Y}Sb^{5+} + {}^{Z}Fe^{2+}$. Mössbauer data obtained at RT and 77K indicate the presence of tetrahedrally coordinated Fe^{2+}. Raman spectroscopy demonstrates that there is no measurable hydrogarnet component in monteneveite. The six strongest Bragg peaks in the powder X-ray diffraction pattern are [*d* (Å), *I* (%), (*hkl*)]: 4.45, 100, (220); 3.147, 60, (400); 2.814, 40, (420); 2.571, 80, (422); 1.993, 40, (620); 1.683, 60, (642). Monteneveite is cubic, space group *Ia*-3*d*, with *a* = 12.6093(2) Å, *V* = 2004.8(1) Å^3, and Z = 8. The crystal structure was refined up to *R*1 = 0.0197. Monteneveite is related to the other Ca-, Sb- and Fe-bearing, nominally Si-free members of the bitikleite group, but differs in that it is the only known garnet species with mixed trivalent and divalent cations (2:1) at the tetrahedral *Z* site. Monteneveite and other Si-poor garnets all have HFSE (Sb^{5+}, Sn, Zr, U, Ti) located at the octahedral *Y* position. These elements are normally not analysed for in garnet, but may host considerable amounts of these elements under certain metamorphic conditions, typically in skarn environments. Textural and mineralogical evidence suggest that monteneveite formed during peak metamorphism (at *ca*. 600°C) during partial breakdown

of tetrahedrite-(Fe) by reactions with carbonate, under relatively oxidizing conditions.

Survival of pre-overturn lithosphere: implications for Venus' resurfacing history

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Despite its similarities in bulk properties to Earth, Venus portrays a fundamentally different mode of surface tectonics. Venus currently displays characteristics of a stagnant lid mode of mantle convection. However, the planet is debated to undergo an episodic lid regime with long quiescent periods, separated by rapid subduction-driven resurfacing and global recycling of crust over geologically short periods of time. However, the tesserae regions, that cover approximately 10 % of the surface of the planet, may be older than the remaining surface. The composition and age of the tesserae are unknown, but they appear to be strongly deformed, which suggest that they have survived at least the last global recycling event.
Based on mantle convection modelling of Venus, this project aims to further the understanding of the effects of tesserae on the mantle dynamics and post-overturn survival of old lithosphere. We assume tesserae to be thick, compositionally anomalous and rheologically strong units, similar to terrestrial cratons. We use thermomechanical modelling carried out with the StagYY code to model Venus with a varying number of pre-imposed tesserae units and a varying yield stress of the lithosphere in both 2D and 3D spherical geometry. The impact of tesserae on mantle dynamics and the survival of old lithosphere is investigated by examining the thermal evolution, the crustal thickness and the surface age. We find that the number and timing of overturns are highly dependent on the yield stress and, to some degree, also on the number and size of the pre-imposed tesserae regions. Tesserae regions in particular have a significant effect on the wavelength of convection and may foster the survival of even non-cratonic lithosphere.

Deformation signs of sill linkage: Field observations from San Rafael Swell, Utah

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Igneous intrusions, such as dikes, sills and laccoliths, are important components of volcanic plumbing systems in extensional tectonic settings, e.g. rifted margins and sedimentary basins (Hutton, 2009; Jerram and Bryan, 2018; Magee et al., 2016; Spacapan et al., 2016). In contrasts to dikes (i.e. vertical conduits), sills appear as layer parallel, tabular bodies of magma with structural signatures. Recent studies by Magee (2019) suggest that sills display stepped intrusion geometries (such as magma bridges and steps) due to segmentation of propagating tensile elastic fractures. Magma fills the propagating fractures, which causes inflation and further development through lateral tip propagation. Further, this results in eventual segment coalescence, as shown by magma bridges and steps.
Even though sills have been a topic of study in the last decades, questions regarding their architecture, flow conditions, inflation and relationship to sedimentary heterogeneity remain unanswered. This contribution presents a detailed case study on sill segment coalescence within excellent 3D outcrops in shallow (c. 3 km emplacement depth) shonkitic transgressive sills, emplaced at c. 3.7 to 4.6 Ma in San Rafael Swell, Utah.
Our results involve a vast range of data, ranging from large outcrop 3D models (>100m) to microscale (<1mm). Three outcrops were selected in San Rafael Swell based on variability in sill morphology, adjacent sedimentary formations, and spatial location. The following data was collected in the various outcrops: high—resolution images by UAV, sedimentary- and igneous-logging of host rock and intrusions, and 20 rock samples that will be used for petrological investigations. In addition, a more detailed study of certain features, such as magma bridges, steps, liquid immiscibility sheets, were carried out to understand how magma is transported within intrusions.

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Holocene slide events in Bjørnafjorden, western Norway, and their trigger mechanisms

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Slide events in fjords have been a known phenomenon for decades. The last years these slide processes have received much attention from the Norwegian Public Roads Administration (NPRA), due to plans to upgrade the coastal highway E39 to become a ferry free highway. One of the fjord crossings is a large bridge project just south of Bergen. A 5000 m long floating bridge is planned to cross the 570 m deep Bjørnafjorden. Due to the length of the bridge combined with the water depths, the bridge is planned to be side anchored to the seabed. Many of these anchors are susceptible for slide events, and the past slide frequency is important for geohazard risk assessments. In order to study past slide events, the seabed has been mapped with bathymetry of 0.5 m resolution and sub-bottom profiling with 50 m spacing. Sediment analyses are performed on 16 gravity cores and 4 geotechnical cores. The age of the identified slide events was estimated using the radiocarbon dating method. More than 15 past slide events are identified within the basin the anchors are planned situated. The trigger mechanisms for deep fjord slides, are often suggested to be sediment accumulation or earthquakes. If all slide events occurred at different times, they may have been triggered by sediment accumulation. However, if many slide events occurred at the same time, it is considered more likely that they were triggered by an earthquake. Based on the extensive mapping and dating of slide events in Bjørnafjorden, our study shows a cluster of slide events occurring around 1800 BCE and around 680 CE, which we have concluded were triggered by earthquakes. Two younger events, dated to 1420 CE and 1800 CE, lack evidence of coinciding events. From this we cannot conclude if the two youngest events were triggered by an earthquake or sediment accumulation. This is in accordance with geotechnical slope stability analyses, showing many natural slopes with low safety factors (marginally stable), even without added earthquake loads.

Emplacement mechanisms of a dyke swarm across the brittle-ductile transition and the geodynamic implications for magma-rich margins

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Igneous dykes are the main magma transport pathways through the Earth's crust, and they are considered to contribute to tectonic extension in volcanic rifts. Dykes are typically considered to result from brittle fracturing, even in the ductile crust. A common assumption is that dyke orientation is controlled by tectonic stresses, such that dykes in rifts are expected to be vertical and perpendicular to extension. Here we report on detailed field observations of a spectacularly well-exposed dyke swarm to show that dykes were not systematically emplaced by purely brittle processes and that dyke orientation may differ from the dominant tectonic stress orientations. The dyke complex formed near the brittle-ductile transition during opening of the Iapetus Ocean and is now exposed in the Scandinavian Caledonides. Distinct dyke morphologies related to different emplacement mechanisms has been recognized: 1) Brittle dykes that exhibit straight contacts with the host rock, sharp tips, en-echelon segments with bridges exhibiting angular fragments; 2) Brittle-ductile dykes that exhibit undulating contacts, rounded tips, ductile folding in the host rock and contemporaneous brittle and ductile features; 3) Ductile "dykes" that exhibit rounded shapes and mingling between the soft ductile host rock and the intruding mafic magma. The brittle dykes exhibit two distinct orientations separated by c. 30° that are mutually cross-cutting, suggesting that the dyke swam did not consist of only vertical sheets perpendicular to regional extension, as expected in rifts. We were able to use the well-exposed host rock layers as markers to perform a kinematic restoration to quantify the average strain accommodating the emplacement of the dyke complex: it accommodated for >100% extension, but counter-intuitively it also accommodated for 27% crustal thickening. We infer that the magma influx rate was higher than the tectonic stretching rate, implying that magma was emplaced forcefully, as supported by field observations. Finally, our observations suggest that the fast emplacement of the dyke swarm triggered a rapid shallowing of the brittle-ductile transition, and lead to a considerable weakening of the crust. The interpretations presented here could potentially have large impli-

cations for surface topography and seismicity in active rifts and volcanic areas around the world.

Xinjie layered intrusion and lavas within the Miyi rift segment, Emeishan (SW China)

Klausen, M.,*Updated abstract page 244

The ~260 Ma Emeishan igneous province is linked to a mantle plume source; yet, also formed behind a coeval collision zone between the SE Asian and South China cratons. Its more voluminous and often picritic low-Ti 'center' coincides with the edge of a complexly deformed Tibetan foreland, surrounded by better preserved but thinner piles of high-Ti Emeishan flood basalts in the west. These two areas are separated by a N-S trending Panxi Rift, within which an isolated 30 x 14 km-large volcanic Miyi segment appears surrounded by lava-barren horsts. This Miyi area hosts the Xinjie mafic-ultramafic layered intrusion as well as an estimated 4 km-thick lava pile with basal ankaramites. The ultramafic lower zone of Xinjie becomes both more diffusively and heterogenously layered towards the south-east as well as its steep NE-contact. Towards the north-west, a 'basal' reversal is more distinctly 'overlain' by a peridotitic, clinopyroxenitic and gabbroic zone, the latter of which has oxide-rich margins and is bound on both sides by clinopyroxenites. This apparent axial symmetry, combined with an elongated and almost vertical geometry of the Xinjie intrusion, is tentatively interpreted as reflecting an overall symmetrically disposed dyke-like layered intrusion. Average Mg# of clinopyroxenes within Xinjie's ultramafic cumulates range between 76-83, markedly similar to phenocrysts in the basal ankaramites, and all in equilibrium with near-primary basaltic melts. It is tempting to interpret these ankamarites as potential parents to the Xinjie intrusion, were it not for the intrusion cutting across overlying younger lavas. Nevertheless, we use this theoretical link between a layered intrusion and its surrounding lava pile to investigate magmatic processes within a volcanic Miyi segment that appears to have formed in isolation, between Emeishan's central low-Ti and peripheral high-Ti zones. This in turn may possibly provide additional petrogenetic clues as to how this enigmatic igneous province formed.

Geological control on dinosaurs' rise to dominance: Late Triassic ecosystem stress by relative sea level change

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The Late Triassic, from 237–201 million years ago (Ma), was a time of significant biotic upheaval, with the origination of new groups such as dinosaurs, lizards, crocodiles and mammals on land, and modern-style corals, molluscs and fishes in the oceans. However, the epoch was also characterised by a prolonged period of extinctions prior to the major phase of mass extinction at its termination, which distinguishes it from other great mass extinction events. The mid-Carnian pluvial event (232 Ma) has been linked to massive volcanism of the Wrangellia basalts and inferred as trigger for the second stage in dinosaurian diversification, but further steps in ecosystem restructuring and the gradual rise of the dinosaurs during the late Carnian to Norian (232–208 Ma) have not been explained.

Here we show that key extinctions and the rise to ecosystem dominance by dinosaurs during the early Norian might have been triggered by major sea-level changes, detected from new studies of the largest delta plain in Earth's history. This delta was situated in the Triassic Boreal Ocean (TBO) - a basin then located in a favourable climatic zone on the margins of northern Pangea. Fossil and rock records demonstrate extensive marine inundations with floral turnover, demonstrating how susceptible widespread low-gradient delta plains were to transgressions and how vulnerable its associated ecosystems were to these processes. Significant landward translocation of the coastline implies decrease in the areal extent of important coastal regions and ecological stress on the dominant Archosauria, thriving in these habitats, and we argue that this geomorphological factor played an important role in dinosaurs the gradual rise to dominance during the Late Triassic.

A deep lying sub moraine tunnel valley deposit, Bø in Telemark, Norway

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A deep buried small tunnel valley deposit in Bø in Telemark was identified by Quaternary surficial map, sound drillings, grainsize distributions from odex drillings, refraction seismic, and ground penetrating radar (GPR). The tunnel valley deposit is at a depth of 22 m and is 5 - 7 m thick, 70 m wide and 500 m long. It is beneath a moraine complex, which again is beneath a glaciofluvial delta deposit. The top till layer is 5 – 6 m thick. During the melting of the glacier a subglacial and sub marginal river came from Mountain Lifjell 15 km away and split up in a marginal subglacial network for then to concentrate into one single subglacial channel. The subglacial flowing meltwater then met a transverse cleft where the buried tunnel valley deposit was formed. The tunnel valley deposit ends at the former grounding line and ice front where the meltwater met the sea and the sediments formed a subaquatic fan. This fan can be read from the Quaternary surficial map as sandy marine deposits. The tunnel valley deposit contains a confined aquifer contaminated of leachate water from a municipal landfill for 45 years and, together with the phreatic fan aquifer, it has worked as a good treatment plant for those years. It is an important aquifer, which produced groundwater outflow all through the very dry summer of 2018 saving the apple production at the neighbouring farms.

Utilizing benthic foraminifera and geochemical parameters in modern stratigraphy as a tool to solve challenges in biomonitoring

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This study investigated the potential impact of fish-farming using fossil and living benthic foraminiferal assemblages, as well as associated geochemical parameters, in dated sediment cores from inner-Øksfjord, Northern Norway. Previous studies suggest that organic carbon emissions from fish-farming have introduced algal blooms and spatial changes in organic carbon loading of fjord sediments, ecosystem functioning and benthic community structures. Currently, these spatial changes are difficult to interpret as long-term (last 100 years and thus pre fish-farm) changes have not been studied making it difficult to exclude natural causes of observed gradients. Furthermore, in the majority of cases pre fish-farm environmental conditions are unknown as the initiation of the farm often pre-dates biomonitoring efforts. The aim of this study was to reconstruct long term changes to identify potential impact(s) of fish-farming in the fjord. To assess such potential impact(s), sediment cores were collected from the inner fjord's main and sub-basin. The geochemical parameters total organic carbon, C/N ratios, sediment stable carbon isotopes and trace metal concentrations showed no temporal changes. Pre fish-farm benthic foraminiferal assemblages indicated that environmental conditions naturally differed between the basins. The assemblages showed no temporal changes in the diversity indices (H'_{log2}, ES_{100}) traditionally used in Norwegian biomonitoring studies and indicated that good ecological conditions persisted. The sensitivity index AMBI didn't change for the main-basin but higher AMBI scores were found in upper part of the sub-basin core signifying a larger abundance of organic matter tolerant species. Increasing relative abundances of *Brizalina skagerrakensis* in the main-basin and *Epistominella vitrea* in both basins indicated increased phytodetritus input during the past decades. In both basins *Cassidulina reniforme,* a species sensitive to increased organic matter input, declined. In the sub-basin opportunistic *Stainforthia* showed a rapid increase in relative abundance. This study illustrates the sensitivity and suitability of foraminifera as a biomonitoring tool.

Holocene magnetostratigraphy and paleoenvironmental changes in the Barents Sea with oceanographic implications in the Nordic Seas

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Natural remanent magnetization (NRM) and anhysteretic remanent magnetization (ARM) from u-channels of a 3m long sediment core recovered in the South-Eastern Barents Sea at 72.5°N 32.5°E were stepwise demagnetized and measured using an automatically operating cryogenic magnetometer at the Geological Survey of Norway. The magnetometer setup comprises an automated sample feeding, dynamic measurement design, operation and measurement monitoring, plus a customised output-to-database data handling with 24/7 remote quality control and operator interaction.
NRM and ARM demagnetization data are combined with measurements of magnetic suscepti-

bility, wet bulk density and XRF elemental composition from high-resolution core-logging. The u-channel NRM measurements at 3 mm resolution reconstruct the palaeoinclination, relative declination and relative palaeointensity. Comparison to FENNOSTACK (Snowball et al., 2007) and EGLACOM-SVAIS (Sagnotti et al., 2011) establishes a robust chronostratigraphic framework for the core which otherwise contains little datable material. This allows to detect millennialscale climate variability with the onset of the Neoglaciation (~5 ka) as the most prominent signal.
Besides palaeomagnetic age information, the combined results offer the opportunity to study sediment transport and deposition during the regional deglaciation history, spatial and temporal sea-ice fluctuations and the variability of marine palaeoproductivity in the South-East Barents Sea during the Holocene. Comparison to other records from the Nordic Seas enables the reconstruction of oceanographic changes over time with implication to responses and vulnerability of high arctic marine ecosystems.

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A Plio-Pleistocene sea ice record for the Arctic Ocean

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The Research Council of Norway funded project "PACT – Pliocene Arctic Climate Teleconnections "– provides new knowledge on the response of Northern Hemisphere climate deterioration on Arctic Ocean sea ice expansion and tropical climate. Here, we combine multi-biological proxy data with sedimentary physico-chemical characteristics of Integrated Ocean Discovery Program (IODP) material from the Arctic-Atlantic gateway to present a Plio-Pleistocene record of sea ice variability in the Arctic. We show that sea ice in the Arctic was absent or limited in extent (analogous to modern summer conditions) prior to 4-4.5 million years. Sea ice significantly advanced to pre-industrial winter conditions with the intensification of Northern Hemisphere glaciations, ~2.7 million years ago and parallels an increase in Atlantic meridional overturning circulation and stronger monsoon winds. The mid-Pliocene Warmth (~3 million years) likely caused a summer ice-free Arctic Ocean. Over the past 0.8 million years, Antarctic-type coastal polynyas, i.e. open waters surrounded by sea ice, developed in front of the Eurasian ice sheets and sustained glacial ice build-up, ocean ventilation, and marine productivity.

Modelling of PFOS transport from soil to surface water using a box model

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At the firefighting training facility at Oslo Airport, Gardermoen, the soil has been contaminated by highly persistent perfluorinated alkyl substances (PFAS) due to previous use of fluorine-based firefighting foam. Perfluorooctanesulfonic acid (PFOS) has been the main compound of concern. To investigate the transport and mobility of PFOS from the site a box model was developed. The model has been used to evaluate the potential impact of contaminant migration from existing soil pollution to a nearby creek. The model is adapted to site specific conditions using a limited number of input parameters defining the various boxes that are assumed to be fully mixed. The model uses equilibrium partitioning between the soil and the porewater in the unsaturated zone. Transport to the groundwater is based on infiltration of precipitation. Porewater is mixed with groundwater in the saturated zone and transported to the receiving water. The different functionalities of the model will be demonstrated, and uncertainties will be discussed. Results will be shown to demonstrate that the model can be a useful tool for risk assessments and evaluation of remediation requirements.

Spherical shock experiments with Chelyabinsk meteorite: Shock-induced changes in reflectance spectra

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Spherical shock experiments with Chelyabinsk meteorite produced gradual pressure changes from ~30 GPa up to complete melting. At ~50 GPa peak pressure a shock darkening of silicates is observed, equivalent to the shock-darkened Chelyabinsk lithology. This process is due to the troilite melt penetrating cracks within silicate grains. The pressure interval of shock-darkening is, however, surprisingly narrow, only ~10 GPa. At increasing pressures the darkening process stops as partial melting of silicates along grain boundaries isolates troilite melt from its injection into silicates. At this stage, the material is again brighter than in the shock-darkened region. Second-stage darkening occurs again upon material complete melting at pressures higher than ~100 GPa.
VIS-NIR reflectance spectra follow this trend with relative darkening and reduction in intensity of silicate 1 and 2 µm absorptions at the shock darkening zones. In MIR region, spectral trends are similar, however the silicate features as Christiansen and transparency features, and reststrahlen silicate bands are still resolved in shock-darkened or impact melt zones. Thus, the shock-darkening does not obstruct diagnostic silicate features in MIR region.
The narrow pressure interval of shock darkening is surprising finding implying limited yield of shock-darkened material during planetary collisions. Shock-darkened ordinary chondrites, just represent unique material originating at specific conditions.

Dynamics of the northern Barents Sea Ice Sheet during the last glacial – interglacial cycle: preliminary results

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Previous work has shown that a grounded ice sheet in the Barents Sea reached the northern continental shelf edge during the Last Glacial Maximum (LGM). However, the precise timing and dynamics of the ice sheet, its triggering mechanisms, as well as older glacial fluctuations remain poorly constrained. This study aims to investigate the continental slope of the northeastern Svalbard-Barents Sea margin, in particular offshore of the Kvitøya Trough, to better understand the dynamics of the northern Barents Sea Ice Sheets during the LGM and the subsequent deglaciation. The identification of sediment deposits elucidates the interplay between downslope processes resulting from input of subglacial sediments, glacimarine processes of ice sheet meltwater and ice rafting, and alongslope processes from ocean currents.
A total of four gravity and Calypso cores (4.61 to 18 m long) were retrieved from the inter-fan areas at the continental slope offshore of the Kvitøya Trough in water depths from ca. 500-3300 m. In addition, swath bathymetry and high-resolution sub-bottom profiles were acquired by the *Helmer Hanssen* and *Kronprins Haakon* research vessels as parts of *the Arctic Marine Geology and Geophysics Research School* cruise of UiT The Arctic University of Norway and the *Nansen Legacy* paleo cruise, respectively.
Preliminary results from multi-proxy analyses including lithostratigraphy, physical properties, grain-size distribution and XRF core scanning of the sediment cores will be presented.

Groundwater dating - the hydrogeological characteristics of an exploration target area in Northern Finland

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This study increases understanding of groundwater recharge and mixing of waters in the Sakatti exploration target area in Northern Finland. Water sampling (N=25) was performed from a deep (900 m) aquifer, from 100-300 m deep bedrock boreholes, from shallow wells as well as surface waters. To observe the hydrogeochemical characteristics, T, pH, EC, DSi, as well as main ion and trace element concentrations have been analysed. To estimate groundwater recharge age, tracers: d^2H - $d^{18}O$, ^{14}C, $^3H/^3He$ and CFC/SF_6 have been used.

The samples from a depth of about 900 m represent the oldest water type. Radiocarbon analyses suggest a minimum age ca. 32 000 years, but the real age could be higher by orders of magnitude. This Na-Cl type water has δ^2H and $\delta^{18}O$ values similar to those in the present-day mean annual precipitation, indicating that the environmental conditions during the infiltration probably resembled conditions today. No clear signs of admixture with modern recharge could be observed.
The δ^2H and $\delta^{18}O$ values of many shallow waters in the sediment and in the bedrock give strong indications of evaporated surface water. The T/He and CFC-12 analyses provide evidence for active recharge during the past 40-60 years and mixing of old and more resent waters. This surface-derived water circulation has reached a depth of nearly 100 m in the proximity of the present river channel.
Shallow Ca-HCO_3 type groundwater samples generally have δ^2H and $\delta^{18}O$ values similar to those in the mean annual precipitation representing relatively young groundwater with a short residence time in the aquifer.
Some tracers seem to have additional sources or sinks in the groundwater system and tracer methods are sensitive to contamination. However, the reliability increases, if different methods give similar results and if the dates can be connected to the chemical or isotopic characteristics of the waters.

On calcite carbonate deposits and the potentials for new industrial developments

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Carbonates of industrial interest on the Norwegian mainland have formed in a variety of geological situations from the Paleoproterozoic to the Silurian. They show large variations in chemical and mineral characteristics due to their complex geological history. The large complexity is an advantage, since different ore-qualities provide raw materials for a large spectrum of industrial applications.
Of special interest are deposits with a high-whiteness potential, i.e. marbles with low contents of carbonate crystal-bound iron and manganese. Since these elements reduce whiteness, the lower concentration the better. Attractive deposits for high whiteness, in which the rock itself is very pure with only small contents of non-carbonate minerals, are rare. With a few exceptions such as calcite marbles at Rolla (Ibestad), they are either in operation, or for other reasons not available for new development.
Of potential interest for new developments are some very large deposits, low in carbonate-bound iron and manganese, but with a distinct content of non-carbonate minerals such as graphite and quartz, of which graphite tends to occur as finely distributed inclusions in carbonate. Two such deposits have been investigated in detail: Evenesmarka east-northeast of Evenes airport, and Nestbylia near Rognan, both in Nordland county. Of these Nestbylia is regarded as the more favourable, mainly since there is no settlements in the deposit area. However, due to complex mineralogy, exploitation of such deposits requires new developments in mineral processing.
The favourite option is to develop a mineral processing based on selective dissolution and precipitation of calcite carbonate. Nature may provide the key: Carbonate rocks break down during weathering processes under the influence of weak carbonic acid (CO_2 dissolved in water); in this process calcium dissolves in the water as bicarbonate, and precipitates as calcite.
An analogous industrial process to nature's mechanism may be developed if the reaction can be speeded up sufficiently. This can be done by using powerful ultrasound that break down the carbonate rock into fine particles, thus exposing a very large surface area to react with the carbonic acid. Calcite dissolves selectively and can be precipitated as a high-purity calcium carbonate in the next processing stage.

Determination of geotechnical properties in gyttja and high plasticity meltwater clay in the Baltic Sea

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During a big project in the Baltic Sea, several geotechnical parameters have been determined on the soils encountered. Cores have been described geologically and photographed, and a range of different tests has been carried out. Determination of loss on ignition, natural water content, plasticity index, specific density, wet and dry density and shear strength. Problems start to arise when determining whether a sample is high plasticity meltwater clay, organic clay or gyttja, due to the high natural water content and varying values in loss on ignition. Another indicator previously used is the casagrande diagram, which seems to have

some difficulties regarding high plasticity gyttjas. When plotting the plasticity index against the liquid limit, they have a higher plasticity index than expected. A better indicator for determining whether a sample is organic or not may be to look at the specific grain density, which in this project seems to correlate nicely with the geological descriptions as gyttja samples which have low specific density.

Failure of the Veslemannen Rockslide

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Veslemannen failed the 5th of September 2019 after five years of monitoring, several acceleration phases and 16 evacuations of people in the hazard zone. Veslemannen was a small and very active part of the high-risk rockslide Mannen in Romsdalen. It has been monitored since 2014, primarily by ground based InSAR, one of the few methods that works for such high displacement rates. Here we evaluate the development leading up to the failure, the event, volume and run-out.

In 2015 NVE estimated the volume of Veslemannen to 120-180.000 m^3 and with a run-out that might impact houses in Romsdalen and the Raumabanen railway. The number of evacuations increased in time, from one in 2014, 2015 and 2016, two in 2017 and 6 in 2018. NVE tried to release the rockslide by supplying water, but this was not a success. Therefore, we started to evaluate risk mitigation by building a protection dam and started also to re-evaluate the rockslide scenario and volume, based on movements pattern and accounting for the volume lost by smaller rockslides and rock falls. The intent was to reassess the potential run-out and hazard zone. New drone surveys and photogrammetric model were done shortly before the failure, showing that 15.000 m^3 had been released since 2015. The most likely scenario was estimated to 53.000 m^3.

Movements in 2019 started early, and in particular, movements in the lower parts were larger than earlier. In late 2018 and in 2019, we measured large accelerations that were unrelated to precipitation, initiated by rock falls from the lower part. Towards the final failure the difference of movement in the upper part and lower part decreased, and the active area moved more or less like one body the last day, probably due to breaking of rock bridges in the front that earlier kept the instability in place.

The final failure occurred over some minutes. The failure area and volume was almost identical to the revised scenario. A new photogrammetric model, done after the failure showed that 54.000 m^3 had failed. The run-out was shorter than anticipated with the main deposit left along the gulley down to the fan. Erosion has occurred in the deposit subsequently, and debris flows from here could possibly reach a field or the railroad. The remaining volume in the release area will not reach buildings. NVE continues to monitor Mannen, but expects no more crisis related to Veslemannen.

detzrcr: a user-friendly R-package for graphical and statistical comparison of detrital zircon samples

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Detrital zircon geochronology has through the years become a much-used tool in provenance studies, basin analysis, continent reconstruction etc. With the widespread use of the method it is important that software for graphically and statistically comparing samples are easily available. The R-package *detzrcr* was made with this in mind. It implements the "traditional" probability density plot, as well as "proper" kernel density estimate (KDE) plots. Empirical cumulative density function (ECDF) plots, for which confidence bands can be easily calculated taking the inherit uncertainty of geochronological data into account, are also implemented. These plots give a much better visual guide to the similarities/dissimilarities of samples than the commonly used KDE plot. Some statistical parameters for likeness testing are also implemented: likeness (Satkoski et al., 2013) which is based on KDEs and the O-parameter (Andersen et al., 2016) based on ECDFs and their 95% confidence bands, both of these parameters can be used with univariate and bivariate data – the latter through the use of Hf depleted mantle model ages. Additional graphical outputs implemented are: Hf-plots - both as ε_{Hf} vs. age and $^{176}Hf/^{177}Hf$ vs. age; upper quartile vs. lower quartile plots – essentially taking the 75th percentile (upper quartile) and 25th percentile (lower quartile) of ECDFs and plotting them as points making the comparison of multiple ECDFs in the same plot less cluttered and cumbersome.

The intent of the package is that it should be easy to use, therefore it has a user-friendly graphical

user-interface where data can be input, and plots and statistical parameters are automatically created. *detzrcr* is freely available through the R-package repository CRAN and also as a web-app hosted by the British Geological Survey (http://shiny.bgs.ac.uk/shiny/detzrcr/). Its source code can be found at https://github.com/magnuskristoffersen/detzrcr.

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Possible small impact features in 1235 m water depth in the Arctic Ocean

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The flat-lying and laterally uniform sediment package (~1 km thick) on top of Lomonosov Ridge (87° N, 60° W) shows two adjacent sites with local (< 1 km wide) deformation in the upper 300 m decreasing with depth. The water depth is ~1200 meter. One of the sites display a symmetric depression flanked by a rim of truncated layering above a vertical stack of point diffractors down to 250 m depth and the other site a depression flanked by a symmetric rim. In the absence of any accompanying tectonic or gas/fluid induced characteristics on a local as well as regional scale, we suggest the deformation may have been generated by a train of bodies (<40 m wide) impacting the seabed. The deformation is covered by a <30 m thick sediment drape which suggest the event may be Late Miocene/early Pliocene.

Numerical flow modelling of PFOS-contaminated groundwater at the firefighting training location at Oslo Airport, Gardermoen

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This master's thesis in environmental geology will investigate a perfluorooctanesulfonate (PFOS) contaminated location at Oslo Airport (OSL), Gardermoen, situated at Norway's largest glaciofluvial ice-contact delta and aquifer.

From 1990 to 2001, firefighting foam containing PFOS was used at the firefighting training location at OSL. PFOS is a synthetic compound that has proven to be bioaccumulative, resistant to degradation, and toxic in smaller concentrations. The compound consists of a carbon-fluor chain that is both hydrophobic and lipophobic, and a polar sulfonate group resulting in some unique surface properties.

In order to prevent further spreading of PFOS in the environment, the Norwegian government has instructed OSL to remediate the polluted area so the concentrations in the groundwater are below 300 ng/L. To meet the demands, OSL has constructed a treatment plant that started operating in October 2015. The plant consists of 12 wells pumping up contaminated groundwater which is lead through a carbon-filter and finally re-infiltrated through 15 injection wells. The pumping wells are situated in the contaminated unsaturated zone. The injection wells are situated upstream or downstream of the pumping wells, respectively.

At present (2019) there is no evidence of decrease in PFOS-concentrations in the groundwater downstream the injection wells. This can be due to;

1. Contaminated water is introduced from the unsaturated zone and bypassing the pumping wells instead of being treated.
2. Already existing PFOS contaminated groundwater is lingering at the area from before the treatment started.

As a part of planning the design of the treatment plant, a numerical model of the groundwater flow was made with the software MODFLOW. The model has not been calibrated or verified after the plant started operating.

The aim of this master thesis is to improve the existing numerical groundwater flow model in order to estimate if contaminated water is flowing through the pumping wells. A determination of the influence radius around the injection and the pumping wells affecting the groundwater flow-pattern, will be of particular interest. The old model will be calibrated with new groundwater level measurements. Field data from a pumping test will be used for validating the model. The improved model will hopefully reveal if scenario 1) mentioned above is the reality. In that case, new measures to optimize the plant will be modelled. If scenario 2) is more correct, the expected time for PFOS being transported to the recipients will be modeled.

Experimental approach to understand mineralogy and aqueous alteration history of Oxia Planum, Exo-Mars 2020 landing site

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Oxia Planum, the selected landing site for ESA's ExoMars 2020 rover mission, is a wide phyllosilicate-bearing plain. The Fe,Mg-rich phyllosilicate deposits in Oxia are one of the largest exposures of this type on Mars, with a thickness of more than 10 m [1, 2] and as such are important source of information about Martian Noachian (>3.9 Ga) water-mediated interactions between lithosphere, hydrosphere and atmosphere. The regional compositional mapping of Oxia Planum conducted in spectroscopic studies by OMEGA and CRISM [2] suggests that the phyllosilicates are mainly trioctahedral in nature, with a local presence of dioctahedral Al-rich varieties. Although no exact spectral match was found for Oxia phyllosilicates among terrestrial analogue rocks, the closest consistency is revealed by vermiculite or Fe,Mg-rich smectite-saponite [2, 3].

The understanding of how vermiculitic-like clays may have formed on Mars is very limited though. The goal of our study is to experimentally reproduce mineral assemblages that spectrally match those detected at Oxia Planum. With such approach, our purpose is to address the aqueous alteration history of this place. This work is a part of the PTAL (Planetary Terrestrial Analogue Library) project, the general aim of which is to build a spectral library for analogue mineralogical studies of Mars.

To better understand the mechanism of formation of vermiculitic-like clays at Oxia Planum, we have been performing laboratory alteration experiments under controlled physico-chemical conditions. Comprehended from terrestrial analogue environments, we focus our research on possible alteration pathways of biotite and chlorite [4-8]. Additionally, considering geomorphological manifestations of plausible past aqueous environments at Oxia Planum [1, 3], we test various conditions of surface weathering and hydrothermal activity.

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Tectonostratigraphy of the eastern Trondheim Nappe Complex

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The Trondheim Nappe Complex comprises an extensive collection of magmatic and sedimentary rocks that originated within the Iapetus ocean (e.g. Gee et al., 1985). With Laurentian faunal affinities in the western part of the complex, and black shales typically associated with Baltica in its eastern part, the Trondheim Nappe Complex includes the main Iapetus suture and is thus a key area to study the opening and closure of the Iapetus ocean and the resulting Caledonian orogeny and subsequent orogenic collapse. Additionally, a variety of ore deposits of economic significance formed in the Trondheim Nappe Complex during the life cycle of the Iapetus ocean (e.g. Grenne et al., 1999). Several large-scale mapping projects and seminal research papers of the 1960-1980s (summarized in Gee et al., 1985) established the key position of the Trondheim Nappe Complex within the Caledonian orogen. However, the region has received significantly less attention in the following decades. In the last few years, renewed research interest and geological mapping in the western Trondheim Nappe Complex have resulted in an updated tectonostratigraphy for the Støren-Hovin-Horg area (Gasser et al., 2016, Grenne & Gasser, 2017). Now, the eastern Trondheim Nappe Complex is the target of a new, research-supported mapping program, targeting (1) the tectonostratigraphic evolution of the Røros schists and potential correlations with either the Trondheim Nappe Complex or Seve Nappe, (2) the volcanosedimentary evolution of the Fundsjø Group and the overlying metasedimentary Sulåmo, Kjølhaug, Slågån and Liafjellet groups, and (3) the complicated rela-

tionship between the Gula Complex and Fundsjø Group in the Ålen area. Preliminary results from a first field season in the area between Røros and Meråker indicate that significant revisions to existing maps are necessary and the present tectonostratigraphy needs to be re-evaluated.

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Investigation of the Forkastningsfjellet rock slide, Spitsbergen: anatomy and state of activity in a changing climate

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Climate change and the related permafrost degradation are thought to influence slope stability, landscape evolution, and the natural hazard potential in polar- and high mountain regions. In this context, we investigate a large-scale rock slide affecting the coastal ridge of Forkastningsfjellet, Spitsbergen. Based on a detailed structural description, we discuss the kinematics, possible timing, potential drivers of rock slide activity, and present the current status of follow up investigations. The Forkastningsfjellet rock slide involves a minimum rock mass volume of 0.10 km³ and was displaced either catastrophically or over a longer time period. Initial movement in the hanging wall of a NW-dipping listric sliding surface led to the fragmentation of the sliding mass into separated tilt blocks that created the present-day, stair-stepped morphology. The initial failure was probably related to the deglaciation of Isfjorden and the resulting instability of the weakened rock mass along the oversteepened slopes.
Currently, mass wasting and seacliff erosion take place along the steep slopes of the coastal tilt blocks. In particular, a substantial increase of superficial active-layer detachments and debris flows is observed. Reactivation of the entire rock slide or individual blocks could have severe consequences for the coastal regions of Longyearbyen and its surroundings.
However, the lack of data does not permit sound conclusions regarding the current hazard potential. Consequently, a field campaign was conducted in summer 2019 to initiate displacement measurements based on UAV- and DGPS surveys. Also, a bathymetric survey along the coastline of Forkastningsfjellet was performed to gain detailed information about the subaquatic portions of the rock slide deposits and to improve the understanding of the rockslide geometry and kinematics.
In the next two years, the UAV- and DGPS surveys will be continued to monitor superficial mass wasting processes and the activity state of the Forkastningsfjellet rock slide.
Thereby, the Forkastningsfjellet rock slide will serve as a showcase for a multiscale assessment of mass movements (number and affected volume) in a changing climate, as we will measure displacements and quantify the activity of large scale block slides (> 1 Mio m³), the medium scale coastal slope instabilities (several 100.000 m³) and the small scale superficial active-layer detachment failures.

Electrum from the Kongsberg silver district, Norway – evidence for a Proterozoic gold province?

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Native silver from the Kongsberg silver district occurs in calcite veins, associated with other phases such as silver sulfides and sulfosalts, base metal sulfides and Ni-Co sulfarsenides. The Au content of native silver is very low (e.g. Neumann 1944, Kotková et al. 2018). However, electrum (silver-gold alloy) has been reported from more than 15 silver mines in the district. In contrast to the native silver, hosted in calcite veins, electrum is associated with older quartz veins (Hiortdahl 1869, Neumann 1944). Native silver occurs in several forms: as euhedral crystals, as wires and as massive fracture fillings, whereas electrum most often occurs as thin flakes on the surface of quartz and calcite.
We have studied twelve samples of electrum from four localities within the silver district, where electrum is hosted in hydrothermal veins with varying contents of quartz, calcite and barium-rich feldspar. For most of the studied samples, electrum shows nearly constant composition within one sample; however, there are large variations in the Au content of electrum between the samples. For two samples from the northern part of the district,

electrum shows diffusional zoning indicating Ag-loss along the grain margins.
Bournonite ($PbCuSbS_3$), boulangerite ($Pb_5Sb_4S_{11}$), and hessite (Ag_2Te), which not yet have been described from any of the silver mines at Kongsberg before, occur in the electrum-bearing samples, whereas native silver is missing. Because of differences in both mineral content and mineral textures between the common native silver-bearing samples from Kongsberg (see Neumann 1944, Kotková et al. 2018) and the studied electrum-bearing samples, we suggest that the electrum-bearing veins were formed by different processes than the native silver ore. The native silver deposits are attributed to interactions between externally derived $AgCl_2^-$-bearing fluids and the sulfide-rich host-rock in Permian time, resulting in the precipitation of argentite (see Neumann 1944, Kotková et al. 2018 and references therein), and subsequent native silver formation during de-sulfurization of the rock. In contrast, we suggest that electrum formed during epithermal processes from an externally derived fluid carrying gold and silver as $Ag(HS)_2^-$ and $Au(HS)_2^-$-complexes, possibly during Proterozoic time.

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Hyperspectral imaging applied to shallow drill cores from the Møre Basin Margin, central-Norway

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Hyperspectral imaging is an emerging non-destructive method for analysing mineral content and distributions of rocks. Utilising the unique spectral response of minerals and rocks at different light wavelengths within the visible and infrared spectral range allows both identification and quantification of mineralogy on core surface. The very high spatial resolution within a sub-millimetre scale provides continuous mineral information about the entire length of a core. The core logging system available at the Geological Survey of Norway has been designed as a portable hyperspectral core scanning laboratory which can be temporarily setup at core archives and allows collecting up to 200 m core metres per day. This system is equipped with a SisuRock hyperspectral imaging system from Specim which measures within the visible, near and short wave infrared spectral range (300-2500nm) allowing the identification of a wide range of mineralogy and materials such as clays or carbonates and is therefore appropriate to map mineral distributions in weathered or altered rocks.
In this contribution, results from hyperspectral core imaging of shallow drill cores from the Møre Basin Margin (central Norway) are presented. These cores represent Triassic and Jurassic sediments consisting mainly of sandstones, mudstones and conglomerates with boulder-size fragments of crystalline basement rocks. The Jurassic conglomerates are used as case study of deep weathering processes of crystalline basement rocks. Utilizing hyperspectral imaging allows consisting and detailed mapping of weathering products such as kaolinite and smectite. XRD data of sample measurements are used to calibrate hyperspectral measurements and to validate spectra mapping results. Hyperspectral imaging provides an innovative technique for interpretation of core and allows separation of minerals of key importance in weathered crystallin rocks which are otherwise difficult to map with other methods.

Sedimentological and Palynological Investigations of Neoproterozoic sediments of the Barents Sea Group, Varanger Peninsula, Finnmark, Norway

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Stratigraphical and sedimentological analyses of the Neoproterozoic formations of the Varanger peninsular (Finnmark) were conducted in the 1970-80's by Siedlecka, Vidal and coworkers (Siedlecka, 1978; Siedlecka and Vidal, 1983). During these studies acritarchs were found in several formations. During an excursion in June 2019 several of the original Siedlecka and Vidal locations were revisited, in order to collect new material. In particular, the Kongsfjord, Båsnæring and Båtsfjord Formations of the Barents Sea Group were sampled with the main goal to study the distribution of the organic walled algae remains (acritarchs) and their relationship with the depositional environment. In our poster we present preliminary results of our palynological and sedimentological investigations.

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Greenland fjord productivity under climate change - multiproxy late-Holocene records from two contrasting fjord systems

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The Greenland Ice Sheet (GIS) has been losing mass at an increasing rate (Khan *et al.*, 2015) due to atmospheric and oceanic warming (Box, 2002; Ahlstrøm *et al.*, 2017). As a result, freshwater discharge from the GIS has doubled in the last two decades and is expected to strongly increase in the future (Bamber *et al.*, 2012), with a large impact on coastal marine ecosystems (Hawkings *et al.*, 2015).
We will present results from a master's project developed within the framework of project GreenShift: Greenland fjord productivity under climate change. Four sediment core records from two contrasting fjord systems in NE and SW Greenland were analysed to assess the impact of Greenland Ice Sheet melt on sediment fluxes and primary productivity, focusing on the time period from the Little Ice Age until present. The overall goal of this work is to gain a better understanding on the possible linkages between GIS melt and productivity in Greenland fjord systems, with a view to improve future projections. We followed a multiproxy approach including grain-size analysis and XRF scanning to assess sediment composition and provenance; carbon and biogenic silica fluxes; and dinoflagellate cyst analyses. Our preliminary results show an overall trend towards increased stratification and reduced productivity in recent decades for both fjords affected by land-terminating (NE) and marine-terminating (SW) glaciers.

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Cenozoic uplift and erosion of the Barents Sea area – where are we?

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The two main events responsible for the overall landscape development of the greater Barents Sea area during the Cenozoic were: 1) the early Cenozoic northward propagating rifting, breakup and sea-floor spreading in the Norwegian – Greenland Sea and Eurasian part of the Arctic Ocean, and 2) the late Cenozoic climate deterioration including the establishment of continental-wide ice sheets.
During and after the separation between the North American and Eurasian plates, a "highland" of various elevation developed all along the eastern rim of the newly formed ocean basin, from North Norway to east of Svalbard. Erosional products from this highland are found in basins to the east (e.g. Central Basin, Svalbard) and west (e.g. Sørvestnaget Basin, and Vestbakken Volcanic Province) of the highland. The height of this highland at that time was a result of the interplay of crustal compression and uplift to the north (Labrador Sea spreading, west Spitsbergen fold-and-thrust belt), thermo-mechanical coupling and uplift at the Senja Shear Zone, footwall uplift and subsidence from thermal cooling further south (Northern Norway), clastic sediment transport and erosion as well as isostatic uplift from the erosion. These processes were of less influence further east (eastern Barents Sea) which remained a shallow water/subaerial epicontinental lowland.
Onshore ice sheets are interpreted to have reached the coast at about 2.7 Ma, and further to extent to the shelf break in the southwestern Barents Sea repeatedly from ~1.5 Ma. As a result, large trough mouth fans developed at the rim of epicontinental lowlands (Barents Sea), smaller fans outside the highlands (Svalbard, North Norway). These larger fans have been geographically stable throughout their period of development, sourced from a large and low-relief drainage area, implying that the western Barents Sea and east of Svalbard parts of the highland was partly or mostly gone by the onset of the fan growth. Smaller fans on the other hand, developed where the high-relief drainage area remained. The trough mouth fans were fed from paleo-ice streams within the ice

sheets, i.e. glacial erosion was focused and selective forming shelf troughs, fjords and fjord valleys, and the sediment yield was controlled by bedrock composition and ice basal properties. The glacial erosion was initially located by the pre-glacial relief, i.e. a fluvial to shallow marine landscape transforming into a glacial. This also included coastal erosion and the formation of the strandflat. The late Cenozoic uplift of the greater Barents Sea area during this period was due to the glacial erosion, isostatic compensation of this erosion to be gradually influenced westward by sediment loading causing subsidence of the western and northern margins.

Reliability and risk concepts for improved safety against geohazards

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Increasingly, society and construction standards require "risk-informed" decisions. The lecture describes the benefits of implementing, as a complement to conventional deterministic analyses, reliability and risk concepts for the evaluation of the risk due to geohazards. The lecture describes the basic concepts of reliability-based approaches. Risk assessment can range from qualitative estimates and simple statistical evaluations to full probabilistic modelling of the hazards and consequences associated with single geohazards or cascading geohazards. Geohazards are often intensified by climate impact. Projections of climate change and the more frequent occurrence of extreme weather have shown that one can expect more frequent and more intense rainfall in Norway, and thereby increased landslide activity and risk to population, material property and infrastructure. Risk assessment and risk management can account for the uncertainties in the triggering, failure mechanisms and dynamics of each threat and help select the most appropriate and adaptive mitigation measures. The lecture illustrates the application of the reliability-based concepts with case studies of landslides onshore and offshore Norway and in Hong Kong where numerous intense rain-induced landslides occur every year. Combining traditional analyses with risk assessment and management analysis leads to an improved treatment of geohazards and provides information on how to reduce risk and how society can best cope to the risks due to natural and man-induced geohazards. One can also update the risk on the basis of observations and assess the need for and the effectiveness of risk reduction measures. Enhanced preparedness to forthcoming risks contributes significantly to making infrastructure and society safer and improving response to the inevitable risks due to geohazards and climate change. The lecture also discusses key issues such as tolerable and acceptable risk, the meaning of factor of safety and the targets for a margin of safety. Reliability-based approaches provide useful insight and complementary information. They enable the analysis of complex uncertainties in a systematic and more complete manner than traditional analyses alone. Reliability-based approaches assist with preparing safe recommendations and making decisions.

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A late Younger Dryas maximum ice-sheet extent in the Trondheimsfjorden region, central Norway

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The Scandinavian Ice Sheet responded to the Younger Dryas climatic deterioration in an apparent time-transgressive fashion, with large regional variations. In the area of Trondheimsfjorden, central Norway, two prominent ice-marginal zones related to the YD—the Tautra Moraines and the Hoklingen Moraines—have been dated to c. 12.7 and 11.6 cal. ka BP respectively (Olsen *et al.*, 2015). The Tautra Moraines represent the maximum ice-sheet extent during the YD, and this ice-front position dammed the Leksvik pro-glacial lake on the northern shore of Trondheimsfjorden (Selnes, 1982), which submerged the present-day site Lomtjønnmyran and drained through a spillway via present-day Lake Rørtjønna. Some 20 km inland from this location, the site Damåsmyran would have been ice-covered during this time. By examining sediments from these three sites and performing age-modelling based on radiocarbon dates and occurrences of volcanic ashes (both visible and cryptotephra), we present evidence that the ice front must have remained at the Tautra Moraine until a thousand years later than the previously suggested 12.7 cal. ka BP—and even later than the previously suggested age of the Hoklingen Moraines. These results are in agreement with several recent reconstructions from other sites in western

(Lohne *et al.*, 2012; Mangerud *et al.*, 2016) and southern Norway (Romundset *et al.*, 2019), entailing major implications for the overall view of the Younger Dryas palaeoglaciology and the following deglaciation.

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Per Geijer iron oxide-apatite mineralizations in Kiruna, northern Sweden

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The Per Geijer (PG) area comprises five iron oxide-apatite deposits (Rektorn, Haukivaara, Henry, Nukutus and Lappmalmen) located north of Kiruna in northern Sweden. Four of these deposits have been in production by open pit mining with a total production of ~11 Mt of iron-phosphorus ore between 1925 and 1987. The Lappmalmen orebody located ~500−1000 m under the surface has not been mined. However, it seems to represent the largest orebody in the PG, with ore intercepts of up to 150 m in drill holes.

The PG deposits are spatially closely related mineralized bodies emplaced at distinct levels in the volcanosedimentary stratigraphy of the upper Kiirunavaara Group: at the contact of the Luossavaara formation and the Matojärvi formation and within the latter (see Martinsson 2004). Several iron oxide-rich zones are recognized, with magnetite dominating in the lower units and the amount of hematite increasing towards the upper units. Krolop et al. (2019) classified the iron ore types into 11 classes, of which four are magnetite-dominated, four hematite-dominated and three represent mixed magnetite-hematite ore. Apatite is present both within the iron oxide units and as crosscutting veins. The apatite-rich parts have REE_{tot} up to 0.5 %. A separate high-REE mineralization (REE_{tot} up to 2.7 %) with allanite as the dominant REE mineral is found higher up in the stratigraphy.

A preliminary geological model of the PG deposits was constructed based mainly on existing drill core data and geophysics. The modelled magnetite volume extends from the deep-seated Lappmalmen ore body in the south to the northern part of the Nukutus orebody; however, the northern part is only modelled down to the depth of 250 m due to lack of drilling data. Geophysical modelling of magnetic and electromagnetic data suggests that magnetite-bearing rocks continue to deeper levels also in the Nukutus area. The models need to be verified both by deeper drilling in the northern PG and by further investigations of the existing ore intercepts using the classification of Krolop et al. (2019).

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Dynamics of Glacier Ice-Contact Speleogenesis and CO_2 sequestration

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The terrain position of relict phreatic caves in formerly glaciated areas demands mechanisms for generating an elevated water-table in order to make them functional. This can be accommodated by filling the adjacent relief with rock or with ice. The two scenarios had different timing and duration, of which the glacier ice-contact alternative would be the most recent, and therefore probable. The formation of endokarst is an important carbon sink, where CO_2 is transferred into dissolved bicarbonate; the glacier environment is no exception. It is therefore of interest to investigate the dynamics between glaciers, water flow, sediment content and the kinetics of calcite dissolution. Basal and surface glacial waters have different chemistry, the former is close to saturation, whilst surface meltwater is in open-system equilibrium with atmospheric CO_2. *In vitro* experiments have demonstrated an inhibition effect on speleogenesis from suspended rock flour. This is basically due to the large specific surface of crushed mineral particles with a high free energy, compared to the relatively limited wall surface of a cave. Most of the dissolution potential is consumed before water can enter the karst. Effects of ice burden is not well understood, and a new series of experiments investigate the pressure effect on dissolution rate and saturation capacity, corre-

sponding to up to ca. 2 km thick ice-sheet cover. These results will be discussed against the dynamics of speleogenesis, glacial CO_2 sequestration, subglacial carbonate precipitates and possibly the formation of ikaite in cold environments.

Vanadium removal from real mining water effluent

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Various sorbent materials, such as iron sorbents, organo-zeolites and biosorbents, have been proven to adsorb vanadium efficiently from aqueous solutions. Nevertheless, it is important to confirm the removal rates in a real environment. The water matrix and initial vanadium concentration may have a significant effect on the vanadium uptake efficiency.

This research work was conducted under the VanProd project (Innovation for enhanced production of vanadium from waste streams in the Nordic region, 2017-2020, funded by the Interreg Nord program). The overall goal of the project is to develop vanadium recovery technologies for solid and liquid wastes, which are currently not utilized in the Nordic area. This study focused on the testing of different types of sorbent materials for the removal of vanadium from real mining effluent (initial V ~5-6 mg/L, pH 7, conductivity 235 µS/cm, chloride 12 mg/L, sulfate 56 mg/L), which was collected from the closed Mustavaara mine site (Finland). Sorbent materials were selected according to their performance with synthetic vanadium solutions, and they were commercial iron sorbents (CFH-12 and GEH 101), ferric groundwater treatment residual (Fe-GWTR) and Fe-GWTR-modified peat (Zhang et al., 2019). The removal of vanadium was investigated with batch shaking tests and by studying the effect of contact time and dosage. Results showed that all the selected sorbents were capable of removing vanadium from real effluent (>80% removal with a dosage of 4 g/L; >90% removal with a dosage of 6 g/L), and there was not significant difference between different sorbents. The removal rate was significantly affected by the contact time with all sorbents except with ferric groundwater treatment residual, probably due to smaller particle size. XPS studies showed that vanadium was bound by the surface functional groups. This study confirmed that iron-based products can remove efficiently vanadium from real mining effluent.

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Medium-deep geothermal energy: modelling studies from Finland

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Shallow geothermal energy has been utilized in Finland for over 30 years using groundwater filled borehole heat exchangers (BHEs). In the past 10 years, the feasible depth of energy wells has increased to the current “standard” of 200−300 meters. Today, shallow geothermal energy is a popular heating and cooling solution for single-family homes as well as for apartment and industrial buildings. However, as the energy demand and the size of ground source heat pump systems increase, land area needed for the BHE field also extends. One solution is to drill deeper. The concept of medium-deep geothermal energy and 800−3000 meter deep BHEs has quickly gained general interest in Finland in 2018−2019. Currently, there are not any medium-deep BHEs in use in Finland, but there are a few ongoing pilot and research projects.

The Geological Survey of Finland investigated the potential of medium-deep geothermal energy in 3 different locations in Finland by modelling heat transfer in a 2000 m deep borehole. Two of the sites were in southern Finland and one in central Finland. The bedrock in all of the sites is granitic with good thermal conductivity. In the southern Finland sites geothermal heat flux density was set to 0.053 W/m^2 and in central Finland to 0.038 W/m^2. Average ground surface temperature in southern Finland is 6−7 °C and in central Finland around 5 °C.

The numerical models were created with COMSOL Multiphysics. The modelled physics included conductive heat transfer in bedrock and in insulated coaxial collector, and conductive-convective heat transfer in heat carrier fluid. The models were used to simulate heat extraction from bedrock for 25 years.

In the southern Finland sites a single 2 km deep coaxial BHE could produce 600−900 MWh/a, whereas in the central Finland site the output could be 500−700 MWh/a. Energy output in the simulations depended heavily on the constraints

imposed on the models. In these sites, one 2 km deep BHE can produce the same energy amount as 30−50 standard 300 m deep BHEs.
The results indicate that medium-deep geothermal energy is an interesting option for heating in buildings, especially in urban areas, as well as for heating networks. Compared to the conventional shallow geothermal energy solutions, medium-deep borehole heat exchangers save land area and offer more energy in higher temperatures. However, there are still many unresolved technical issues concerning medium-deep BHEs, regarding drilling, heat exchanger design and cost efficiency.

Geophysical mapping of Silurian reefs offshore and onshore Gotland, Sweden.

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Low latitudes, relatively warm sea temperatures and the presence of a shallow marine environment led to the development of reefal structures during the Late Ordovician-Silurian in the present-day Baltic Sea. Several barrier reefs developed east of Gotland extending offshore the island. The Palaeozoic barrier reefs, namely the Klinte reef, Östergarn reef, Millklint reef and Burgsvik reef, have previously been studied intensively using seismic reflection, well data and drillings. During the 1970's and 1980's, the oil company Oljeprospecketering AB (OPAB), acquired large amounts of seismic and well data, largely unpublished, which has recently become available for research purposes. Furthermore, the island of Gotland and Öland are an important target for groundwater investigations with the Geological Survey of Sweden (SGU) acquiring airborne electromagnetic data (SkyTEM and VLF). Moreover, newly acquired seismic reflection data acquired on a research vessel during 2017 complement the OPAB data over certain areas.
In this contribution we combine the historic seismic and well data with the newly acquired resistivity data and seismic reflection data to investigate the Silurian barrier reef succession. A basement velocity map over a large portion of the Swedish section, within the Baltic Sea, is generated by an automated refraction velocity analysis, of the first arrivals in the marine seismic data. Through a statistical approach, we can convert the mapped velocities to lithology. Finally, from the velocity/ lithology map, we provide a modified map of the barrier reef succession within the Swedish sector.

Quaternary sedimentation along the NE Atlantic continental margin and its implications for spatial and temporal glacial dynamics, sediment yield and erosion of catchment areas

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High-latitude marine sediment archives deposited adjacent to past and present continental ice sheets reflects climate changes, the dynamic nature of ice sheets and the intensity of erosion-uplift in catchment areas. In this study we focus on output of glacial-related erosion products into the NE Atlantic region, from the North Sea to off Svalbard. This margin segment represents a region where such studies have been hampered by only focusing on individual archives. Available information has been utilized to generate isopach maps for the time periods 2.7-1.5 Ma (TS1), 1.5-0.7 Ma (TS2) and 0.7-0 Ma (TS3), which represents significant time steps in Northern Hemisphere ice sheet development. The compilation shows that approximately $1085*10^3$ km^3 of sediments were deposited along this part of the NE Atlantic margin during the Quaternary. Of these, $331*10^3$ km^3 (30%) were deposited in the earliest Quaternary (TS1), whereas sediment volumes of $503*10^3$ km^3 (46%) and $251*10^3$ km^3 (24%) are estimated for time steps TS2 and TS3, respectively. Significant sedimentary input to the NW Barents Sea margin, and the fan systems off Svalbard, suggests glacial activity and development of a large ice sheet over Svalbard in the earliest Quaternary (TS1), while relatively low sediment input along the Norwegian margin imply a restricted, mostly land-based Fennoscandic Ice Sheet in the same period. The most prominent overall change in style and volume of margin sedimentation occurred during the time of the Mid Pleistocene Transition (TS2), whereas in the latest Quaternary (TS3) sediment input along the western Barents Sea and Svalbard margins decreases considerably while sediment supply form the Fennoscandic Ice Sheet remain high. Our results, thus, illustrate considerable spatial and temporal variations in the source and sink areas through the Quaternary, illuminating the dynamic nature and build-up of the marine based Eurasian Ice Sheet.

Towards a national inventory of continuous rock glaciers movement in Norway based on InSAR

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Creeping permafrost landforms in Norway are widely distributed over the country. In Southern Norway active permafrost landforms are mainly related to glacial activity and high elevations, while Northern Norway has clusters of both active and relict rock glaciers derived mainly from talus slope deposits. Previous inventories of these features were mainly based on interpretation of aerial photos of varying spatial and temporal quality and resolution, which opens for misinterpretation of both type and activity status. E.g., in the northern part of Finnmark in Northern Norway, a group of rock glaciers exists close to sea level, and was mapped as relict features in our 2011 inventory. Since 2015, we have investigated one of these rock glaciers (Ivarsfjord rock glacier) more closely using high resolution (10 cm) SfM, DEM comparison and ERT and seismicity surveys. It reveals a significant displacement pattern, and frozen interiors, indicating an active rock glacier. The Norwegian Geological Survey (NGU) published a nationwide database of radar interferometry measurements (InSAR; https://insar.ngu.no/) in late 2018. The dataset is based on Sentinel-1 satellite images, part of the EU Copernicus program, processed using a Persistent Scatterer Interferometry (PSI) algorithm. Ground displacement measurements are available between 2015 and 2018 with a temporal resolution of up to 6 days during the snow-free season. The database is openly available, and has until now be used to identify unstable rock slope areas and vertical movement of buildings and infrastructure. To evaluate the activity of Norwegian rock glaciers we systematically compared the InSAR database to our existing rock glacier inventory. Complementary regional InSAR processing in Troms and Finnmark considering only short time intervals between image pairs allows for a better documentation of fast-moving landforms affected by non-linear displacement patterns. In most cases, we revealed good correspondence between mapped rock glaciers and ground displacement. Also, our field measurements from the Ivarsfjord rock glacier largely correspond to the InSAR-derived displacements. Further, we discovered areas of large displacement in the InSAR dataset that with closer investigations have proved to be rock glaciers and could be added to our inventory. Here we will present some results of our dataset comparison in terms of activity classification, flow velocities and their variations in time and space in Norway.

Exploring the evolution of ice falls along road cuts – Can they be predicted? A case study from Trøndelag, Norway

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The growth of icicles along road cuts poses a serious threat to traffic in the Artic and sub-Arctic. A collapse may interrupt traffic or impact vehicles, causing economic and personal losses. Freezing water is also an important weathering process on rock slopes, which may over time increase the rock fall hazard. Mitigation measures such as rock fall and ice nets may be damaged by the weight of the ice, increasing costs related to rockfall protection. The landslide database of the Norwegian Water Resources and Energy Directorate has close to 6000 registered ice fall events in Norway, and many events are not being registered. Yet there is very limited research about the topic of the temporal evolution and the meteorological influence on ice growth and collapse, or the impact of ice on rock falls.

This study aims to increase the understanding of growth, decay and collapse of ice along road cuts. The study area is located along Fylkesvei 715 between Trolla and Flakk in Trøndelag, Norway. The road is known for frequent rock and ice fall events. As a consequence, the Norwegian Public Roads Administration has installed a variety of rock fall mitigation measures along the road. Every year the road cut is covered in thick ice formations, for the benefit of ice climbers, and disadvantage for traffic.

Based on a multidisciplinary approach, the study attempts to (1) correlate historical ice fall events from the landslide database with meteorological data from existing weather stations in Trøndelag county and (2) analyse the ice growth and decay on a selected part of the road using LiDAR scans and photogrammetric modelling. For the latter, the temperature in the rock mass, on the ice surface and in the air will be monitored using temperature loggers installed at the site, as well as using infrared thermography. This may give a better understanding of how the air and rock temperature impacts the growth and decay of icicles. Furthermore, photogrammetry and LiDAR will be used

to point out change in the rock wall before and after winter, in order to indicate the impact of ice on the rock. The study is ongoing, and provisional results will be presented.

Distinct petrographic changes across the Triassic-Jurassic boundary in the southwestern Barents Sea

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A general increase in sandstone maturity from Triassic to Jurassic strata in the southwestern Barents Sea basin brought an important shift from predominantly immature, mudstone-rich reservoir packages to more sandstone-dominated, mature reservoir packages. Petrographic and geochronological provenance data suggest that the shift from immature to mature sandstones initiated during the deposition of the Norian-Rhaetian Fruholmen Formation, and varies with basin location. Strong petrographic maturity contrasts between the Fruholmen Formation and underlying formations are associated with proximity to the rejuvenated Caledonian and Fennoscandian hinterlands and are mainly restricted to the southern basin margins. The long-lived misconception of a regional compositional contrast in the Arctic at the turn of the Norian can be attributed to sampling bias along the southern basin margins and masking by subsequent maturation processes, such as increased annual precipitation and reworking.

Geothermal signatures and rearrangement of ferric clay material across the Carnian-Norian transition support a recycled origin for the Fruholmen Formation in the basin interior. As the closest tectonically active region at the time, the Novaya Zemlya fold-and-thrust belt represent the best provenance candidate for polycyclic components in Norian-Rhaetian strata.

In addition to recycling in the hinterland during the Late Triassic, local erosion of uplifted intrabasinal highs and platforms in the SWBSB at the Triassic-Jurassic transition represents a second reworking cycle of sediments originally sourced from the Uralides. Textural and mineralogical modification may also have occurred in marginal-marine depositional environments during periods with elevated sea level.

Mature sediment supply from the rejuvenated hinterland in the south, multiple cycles of reworking and stratigraphically upwards accumulation of polycyclic grains have led to the extreme compositional maturity registered in the Tubåen, Nordmela and Stø formations in the SWBSB. It is likely that increased annual precipitation since the latest Carnian also had an amplifying effect on sandstone maturation across the Triassic-Jurassic boundary.

Mechanical compaction of chlorite-coated sandstone reservoirs in the southwestern Barents Sea

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The Middle-Late Triassic channel system of the southwestern Barents Sea is characterized by chemically unstable mineralogy and well-developed chlorite coatings. Chlorite coatings in the investigated fluvial channels are interpreted to be diagenetic overprints of a precursor clay phase, which appears to have a strong link to the Uralian provenance. Because coatings occupy potential quartz nucleation sites on the framework grain surfaces, chlorite-coated sandstones have a potential for preserving porosity in reservoirs exceeding temperatures of 70°C. As a consequence, *mechanical compaction* remains the dominating porosity-reducing agent in the fluvial channels from the southwestern Barents Sea. The Triassic sandstone reservoirs are therefore expected to follow compaction trends of sandstones with similar mineralogical and textural compositions. Hence, modelling and prediction of reservoir porosity is possible by coupling initial sediment composition and depositional facies with basin burial history.

Despite their potential for porosity prediction, fluvial and tidally influenced channels investigated in this study show significant variation in reservoir quality. Differences are linked to amount of allogenic matrix and grain size, which significantly reduces the permeability in the tidally influenced channel. If seismic distinction between different channel types is impossible, the distribution of permeability is considered unpredictable prior to drilling.

Implications of apparent cosmogenic nuclide surface exposure ages from bedrock surfaces on Andøya (69°N, 16° E) for ice cover and glacial erosion during the last glacial period

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Andøya (69°N, 16°E) is situated 8-15 km from the shelf-break in the Vesterålen archipelago. The oldest postglacial sediments onshore the Scandinavian Peninsula are found on the northern tip of the island (e.g. Vorren et al. 2015). The island's proximity to northward flow of ocean currents, and to the margin of large continental ice sheets, is expected to have had a strong impact on its glaciation history. A compilation of more than 100 published and unpublished cosmogenic ^{10}Be surface exposure ages from boulder and bedrock surfaces provides new information on the timing and extent of regional and local glaciation during the last glacial period. In this dataset, bedrock surfaces (n=20) give *apparent* ^{10}Be surface exposure ages from 15.8 to 82.1 ka, with the majority of ages in the range of 35-55 ka, i.e. > 15 ka older than expected. As the highest and lowest ages are from the same elevation above sea level (but different sites), there appears to be no trend in apparent ^{10}Be ages with elevation. Corresponding ^{26}Al ages from a handful of these surfaces overlap with the ^{10}Be ages, and ^{26}Al/^{10}Be ratios are between 6.40 ± 0.26 and 7.11 ± 0.20. The paired cosmogenic nuclide data will be used to investigate surface histories with respect to duration of ice cover, sub-glacial and sub-aerial erosion rates. In order to potentially increase the temporal resolution of simulated surface histories, a handful of the paired nuclide samples have been complemented with ^{36}Cl analyses. In addition, analysis of *in situ* ^{14}C is pending to shed light on post-glacial erosion rates at this coastal location.

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Feasibility study of vanadium extraction and recovery from solid and liquid waste streams in the Nordic region

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Vanadium is an important element for industry. However, there is no primary production of vanadium within the EU. Therefore, it is of great importance to investigate the practical feasibility of extracting and recovering vanadium resources from solid and liquid waste streams in the Nordic region. In Interreg Nord project VanProd, the possibility to extract vanadium from solid waste streams in the Nordic region was investigated in laboratory leaching experiment and the possibility to its recovery from liquid waste streams was investigated in batch, column, and pilot scale experiment. Data for both extraction and recovery were collected to calculate the total cost of the procurement of vanadium from the waste, which is compared with the monetary benefit of selling the obtained vanadium. Linear or nonlinear optimization will be conducted to minimize the total cost. The extraction and recovery method whose monetary benefit from the obtained vanadium is less than the total spent cost was identified as the economically feasible method. New approaches will be developed during the VanProd project period to compare the probabilistic cost benefit to figure out the best cost-effective vanadium procurement approach.

Development of coal forming environment in a transgressive coastal plain setting

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The coal-bearing Paleocene Firkanten Fm is a transgressive succession deposited in the Central Tertiary Basin of Spitsbergen (Svalbard). This is the first thorough facies description, sequence stratigraphic analysis and paleogeographic reconstructions of the succession describing the depositional environment and the development from coastal plain to shallow marine deposits. The interpretation is based on analysis of numerous cores from Store Norske Spitsbergen Kullkompanie. Firkanten Fm represents the onset of sedimentation in the

basin and is overlying a larger hiatus from Albian-Aptian Carolinefjellet Fm. It consists of thick coal deposits, carbonaceous mudstone and sandstone with rare conglomerate beds. Thick coals and carbonaceous mudstones were formed in coastal mires protected from marine incursions by muddy lagoons and sandy barrier bars. The coastal deposits show moderate tidal influence. The coastal plain deposits are overlain by well-sorted, fine-grained sandstone formed in foreshore and upper shoreface environments containing abundant glauconite, with thin pebbly beach deposits occurring in places. There is little to none evidence for fluvial influence in the Firkanten Fm. The correlation and sequence stratigraphic interpretation was challenging due to absence of marker horizons. Therefore, a new method for correlation was used involving construction of paleogeographic maps as part of the process of correlating. This was made possible by considering analogous modern coastal areas as indicators of facies belt widths, creating a correlation scheme that provides patterns of facies distribution that are consistent in three dimensions. The resulting stratigraphic framework reveal an environment dominated by aggradation in a step-wise transgressive setting showing an overall retrogradational pattern over a basin floor that was subsiding due to flexural subsidence. The flexural subsidence was sufficient to keep pace with eustatic sea level falls, indicated by the lack of evidence for sea-level fall or incision in the entire succession. Coal seams occur mainly in the eastern part of the basin, where clastic input was limited, and the flexural subsidence was lowest. Changes in accommodation space can be recognised within coal seams and peat accumulation was terminated when marine flooding occurred. The series of paleogeographic reconstructions show a shoreline stepping northwards through the basin and rotating from W-E to NW-SE as transgression proceeded through the Firkanten Fm. This new facies model and interpretation of the subsidence history of the basin provides a framework for understanding the distribution of sediments within a coal-bearing coastal plain succession.

Expulsion and Primary Migration of Hydrocarbons – Observations in Outcrops

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Hydrocarbons efficiently expel from fine-grained organic-rich source rocks upon thermal heating. Expulsion and primary migration through hydraulic fractures is a commonly cited process, but good outcrop examples are few. Occasionally, hydraulic fractures are permanently filled with, e.g., bitumen or fibrous carbonate cement, and we have studied them in the Green River Fm, Utah, USA, and the Vaca Muerta Fm, Neuquén Basin, Argentina. The aims of this paper are to show the visual expressions of expulsion and primary migration and to discuss associated mechanisms.

Layer parallel fractures (max 1cm thick) filled with massive black bitumen exists within the organic-rich Mahogany Zone (Green River Fm). Immediately above the Mahogany Zone are vertical, near parallel, regularly spaced (0.5-1m) thin fractures (mm), also filled with bitumen. Thickness increases upward through the overlying fine-grained rock. Reaching the overlying Uinta Fm sandstone, the bitumen-filled fractures are up to 5m wide and extend laterally for up to 20km.

Within the Vaca Muerta Fm are numerous layer-parallel fractures filled with fibrous calcite that contains hydrocarbon inclusions. These range from mm to cm in thickness and from cm to tens of meter in length. Vertical bitumen-filled fractures are observed above and below the organic-rich zone. In one location we observe a several meters wide fracture comprising Vaca Muerta source rock blocks in bitumen matrix.

Our observations indicate that organic-rich layers were ductile when the fractures formed (isotropic stress, $\sigma1=\sigma2=\sigma3$). Simultaneously, general stress conditions ($\sigma1>\sigma2>\sigma3$) existed in the rocks embedding the organic-rich shales. High fluid pressure together with seepage force cause layer parallel fractures to open within organic-rich shales and vertical fractures in the embedding rocks. Hydrocarbons migrate through these fractures to permeable rocks. Increasing temperature causes the softening of the organic rich-shales and we therefore term this model “The thermal expulsion engine”.

The North Atlantic shift to an ice-house world

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A dramatic climate shift led the North Atlantic into an Ice Age around 2.6 M yr ago at the beginning of the Quaternary Period. In deep-ocean sediments this transition is recorded as increasing volumes of iceberg-rafted debris (IRD) delivered to the surrounding seas as ice sheets built up over the adjacent mid-latitude land masses. Until now, however, the detailed changes in continental-margin sedimentary architecture associated with this tran-

sition from a 'greenhouse' to an 'icehouse' world have remained obscure. The recent availability of large blocks of high-resolution industry three-dimensional (3D) seismic data from the northern North Sea, between Norway and the Shetland Platform (60-62°N), allows imaging on changing geological processes. Spectacular 3D-images of palaeo-surfaces and buried landforms within the late Neogene and Quaternary sediments make environmental and depositional process interpretation robust. The seismic data record the change from relatively warm and fluvially dominated sediment delivery from land to sea during the Neogene to a Quaternary environment influenced largely by erosion, transport and deposition from glaciers and ice sheets. Here, we report our observations and interpretation of the sedimentary architecture relating to the pre-glacial and early glacial evolution into the icehouse world of the Quaternary.

Fracture characterization of the Agardhfjellet Formation in central Spitsbergen: insights from drill core and outcrop data

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The shale-dominated Upper Jurassic–Lower Cretaceous Agardhfjellet Formation forms the main top seal for the heterolithic reservoir of the Late Triassic-Middle Jurassic Wilhelmøya Subgroup where CO_2 from Longyearbyen's coal-fuelled power plant may be injected. The sealing integrity of the Agardhfjellet Formation is confirmed by a large pressure difference across the unit. However, structural characterization of the formation using drill cores and outcrop studies highlight an extensive natural fracture system in addition to several normal faults with offsets of up to 7 metres of strata. In view of possible CO_2 injection in the underlying aquifer, we strive to quantify to what extent these heterogeneities may affect the local caprock integrity. More specifically, a total of 322 meters of core was logged from two boreholes, DH2 and DH4. We observe a significantly higher fracture frequency in the upper part of the formation, the Slottsmøya Member, than in the lower part (the Oppdalen and Lardyfjellet members). Generally, the fractures are sub-horizontal, polished and exhibit slickensides. In addition, the results reveal that finer-grained units promote higher fracture frequencies. Furthermore, we conducted a structural characterization of the formation where it outcrops 15 km northeast of the boreholes. The structural characterization consisted of sedimentary logging, structural mapping and virtual outcrop modeling. The preliminary results reveal sets of steeply dipping fractures, with predominantly ENE-WSW and N-S orientations. In addition, sub-seismic structures were observed in the study area. Within the lower part of the formation, NE-SW to ENE-WSW striking extensional faults were mapped, whereas compressional features, such as reverse faults, were observed in the upper part. The reverse faults exhibit a NW-SE orientation. Fault and fracture orientations generally coincide with an overall ENE-WSW compressional regime associated with the West Spitsbergen fold-and-thrust-belt. Integrating the core- and outcrop data, we define fracture networks that potentially affect the caprock integrity of the Agardhfjellet Formation. Preliminary results suggest extensive fracturing in the upper part, likely associated with a regional decollement surface, promoting fluid flow, whereas fewer migration pathways occur in the lower part.

Automatic Procedures for Mapping Glacier Velocity from Repeat Satellite Data – example of Southern Svalbard

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Interconnections between glacier´s behaviour and climate changes are profound. Being able to predict climate changes and mitigate their effects requires an extensive understanding of both glacial and sub-glacial activities, amongst other things. In the other hand as climate changes intensify, glaciers behaviour become more and more unpredictable, diverting from their historical patterns and cycles, fact that make glacier monitoring almost a necessity. Changes and destabilization in glacier dynamics can profoundly affect communities located around them, but not only them, the whole socio-economic structure can be seriously challenged if glacier degradation continues with the same rhythm. Because of that whether glaciers are surging, retreating or accumulating urges not only academic interest anymore.
Glaciers surface velocity indicates weather glaciers are surging, advancing or retreating. Using remote sensing tools, one is able to compute glacier surface velocity with high accuracy, using high temporal resolution data with no geographic restriction.
In this project automated procedures are developed to compute glacier velocity using Synthetic

Aperture Radar (SAR) images from Sentinel-1. Being weather independent, able to acquire data day and night combined with high temporal resolution makes Sentinel-1 very efficient for tasks such as glacier monitoring. Sentinel-1 revisits the same scene every 6 days, enabling a monitoring ability that has not been possible before.
South Spitsbergen located in southern Svalbard is chosen as a testing site. Glacier velocities from southern Svalbard are computed with Gamma and Sentinel Application Platform (SNAP) algorithms using level-1 single-look complex (SLC) and Grand Range Detection (GRD) data. Velocity images computed with Gamma and SNAP are compared to each other and their quality assessed individually and with respect to each other.

What are the future challenges of geoscience higher education in Norway?

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Society is facing major global challenges related to the Earth system, including changing climate, resource demands, and shifting energy landscapes. In an uncertain future, the only certainty is that Earth science experts will be involved in addressing increasingly complex problems. Therefor our geoscience students must learn ways of thinking and practicing that allow them to handle ill-structured problems. Universities play an important role in preparing the students for these tasks. In this presentation we ask how this can be achieved and discuss ways of developing our present programmes. We present data on what skills staff (n=256) and students (n=210) at the universities of Oslo, Bergen, Tromsø and the University centre in Svalbard believe will be important in the future and how the current study programmes realise these needs. Changing the geoscience education in Norway will require collaborative effort from staff and students; to what extent are the universities prepared for such a collaborative undertaking? We present data on teaching staff's attitudes to teaching, collaboration and teaching development as a proxy for the teaching culture at the departments. We use these data to discuss in what ways geoscience students can be supported to meet the future and what it takes for our programmes to change.

Ice-flow patterns and precise timing of ice sheet retreat across a dissected fjord landscape in Hordaland, western Norway

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We reconstruct patterns of ice flow and retreat of the Scandinavian Ice Sheet across a landscape where fjords hundreds of metres deep are oriented parallel, obliquely and at right angles to the dominant paleo-ice-flow direction. We combine field observations of glacial striae (n = 2900) with LiDAR/GIS-mapping of 60 ice-marginal delta locations and altitudes to resolve the pattern and timing of retreat. Each ice-marginal delta is dated with decadal precision by reference to a regional shore-line diagram constructed from two relative sea-level curves dated with over 100 radiocarbon dates from isolation basins. This approach allows us to date the pattern of ice margin retreat and timing of deglaciation with unprecedented precision. Rapid retreat commenced immediately at the Younger Dryas/Holocene boundary at 11,600 cal. years BP. Retreat rates were fast in the deepest fjords (160 ma^{-1}), slower in shallower fjords (60-80 ma^{-1}) and even slower on land. The fastest retreat rates, 240 ma^{-1} and 340 ma^{-1}, were experienced in the largest fjords, Hardangerfjorden and Sognefjorden, bordering the study area to the south and north, respectively. Cross-cutting glacial striae along wide fjords indicate the development of calving bays during retreat, which can be mapped up-fjord with decadal resolution. Observations of glacial striae directions confirms the isolation of ice caps/remnants on islands and peninsulas as retreat progressed. The combination of the complex pattern of deep fjords with fast ice-margin retreat, further increased the speed of deglaciation by isolating such ice remnants from the source areas of the main ice sheet. Ice-margin retreat paused, or slowed down, between 11,300-11,100 BP, probably due to cooling and/or increased precipitation during the Preboreal Oscillation. The final section of the ice margin that reached sea level is dated to 10,900 BP, and may be contemporaneous with the well-mapped Eidfjord-Osa moraines near the head of Hardangerfjorden. During the Last Glacial Maximum, ice flow was towards the west across the entire study area, including across and independent of several-hundred meter deep fjords. During deglaciation the ice flow adjusted to the topography and the dominant flow direction switched towards the south-west.

The identification of inter-volcanic exploration targets in the NE Atlantic

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Inter-volcanic reservoirs are increasingly recognized as potential targets and are proven in the NE Atlantic at the Rosebank oil and gas field, where non-volcanic sand reservoirs occur between basaltic lavas. The identification of potential sand-rich reservoirs, structural closures and hydrocarbon indicators is significant for improving exploration success where volcanics occur. We describe an inter-basalt sand-rich reservoir interval that potentially occurs within four basalt-ridge closures, which have overlying hydrocarbon indicators.

Eleven horizons, including Top and Base Basalt, were mapped in neighboring 3D seismic volumes within the UK sector north of Shetland (TGS EWW18 and TGS NL-X). EWW18 is at the fast-track stage of processing. Amplitude anomalies are mapped using root-mean-square (RMS) amplitude extractions. Well data from the TGS Facies Map Browser is used for well-ties.

A well-tie between the gas discoveries at Tobermory (214/4-1) and Bunnehaven (219/9-1) finds that Top and Base Basalt are diachronous between the two wells, and that there is an intervening non-volcanic Flett Formation sand-rich unit. At Tobermory the sand-rich unit (c. 250 m thick) occurs above the older basalts while at Bunnehaven (c. 90 m thick) it occurs below the younger basalts. This indicates that there was a hiatus in volcanism in this area during the latest Paleocene to earliest Eocene when the sand-rich unit was deposited.

The two volcanic units are found to overlie each other to the NE. Here, four elongated ridge structures have been identified within the basalts, forming 4-way dip closures. The elongated geometries of the ridges, their orientations approximately parallel to the oceanic spreading axis, and their independence to basalt (TWT) thickness changes, suggest they formed during deformation after emplacement of the basalts. Vertically stacked amplitude anomalies are imaged above the ridges. The geometries of the amplitude anomalies and their locations above the underlying ridges suggest they are caused by migrating hydrocarbons. Stacked amplitude anomalies, a type of direct hydrocarbon indicator, suggest there could be larger volumes of hydrocarbons trapped deeper in the succession. Here, the sand-rich unit that is penetrated at Tobermory and Bunnehaven forms a potential inter-basalt reservoir.

Analogous ridges in the outer Vøring Basin, Norway (Fenris Graben), with similar vertical amplitude anomalies above them, have been found to be associated with thermogenic oil and gas seeps during seafloor sampling (NAMS18). These findings support the interpretation that the amplitude anomalies in EWW18 are caused by hydrocarbons and that basalt ridge structures with overlying amplitude anomalies are viable exploration targets.

Improving long-term CO_2 models for the Phanerozoic: What can be done?

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CO_2 is the most important greenhouse gas in the Earth's atmosphere and has fluctuated considerably over geological time, with solar, tectonic and biological forcings driving changes in concentrations. However, proxies for past CO_2 concentrations have large uncertainties and are mostly limited to Devonian and younger times. Consequently, modeling plays a key role in reconstructing past climate fluctuations by estimating the relative importance of different carbon sources (e.g. volcanic emissions) and sinks (e.g. silicate weathering).

The current long-term carbon models differ substantially and at certain time intervals, large discrepancies with the proxy records exist. From investigations of GEOCARBSULF, an inverse model that assumes that volcanic CO_2 emissions are balanced in the long-term by CO_2 uptake through mostly silicate weathering, improvements of certain input parameters can be done. The silicate weathering is largely influenced by the paleography of the continents and derived climatic parameters such as temperature and runoff. Our study aims to develop better-constrained climatic forcings from paleogeography and full-plate tectonic models using in-house developed plate reconstructions software (GMAP and a special CEED version of GPLates) and test their influence on atmospheric CO_2 levels.

The latitudinal distribution of the continents (temperature) and the continental area located within the humid climatic belts (availability of water) is argued to dominate silicate weathering. Climate gradients are assumed to have remained broadly similar to today, and a defined zone of high weatherability near the equator is assumed stable through time. However, paleoclimate studies have

revealed that equatorial latitudes have not always been wet, particularly during the early Mesozoic, leaving the equator under arid conditions. This shift in climatic gradients would have affected the distribution of weathering activity and therefore the global CO_2 levels. The construction of biome maps to reconstruct past climate gradients is probably a key to get more accurate paleoclimatic reconstructions. Combined with improved quantification of plate tectonic CO_2 degassing (using full-plate tectonic models) we aim at reducing model-proxy CO_2 mismatches.
During the Mesozoic, the CO_2 levels from proxies are highly fluctuating due to raised temperature and anoxic events, assumed to be caused by the volcanic emissions from large igneous provinces (LIPs). The implementation of LIPs in terms of gas emissions and derived uptake from weathering into long-term atmospheric CO_2 models may also resolve model-proxy CO_2 mismatches. However, it would require other models (e.g. COPSE) as the GEOCARBSULF model estimates CO_2 levels through geological time in 10 million year intervals.

Geological controls on widespread gas leakage at the seafloor in the northern Barents Sea

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During the last couple of years many research cruises and other surveying have been carried out in the northern Barents Sea. One of the recurring research topics has been mapping of gas flares in the water column. This is done by interpreting the water column data acquired by the same multi-beam echosounder as used for mapping the bathymetry. There has now been mapped many thousands of gas flares at the seafloor in the northern Barents Sea. Here we particularly focus on data from the southern parts of Storbanken (just north of the Olga basin) and on the Kong Karls Land platform in the eastern parts of the northern Barents Sea. This is an area with many large anticlines/structures and a potential interesting petroleum system. In addition to the water column data some in-situ samples of gas bubbles leaking out at the seafloor has in this area been acquired by ROV.
The Norwegian Petroleum Directorate (NPD) has participated on several of the research cruises in the area and we have used our knowledge of the subsurface to relate the gas leakage at the seafloor to geological features and structures observed on seismic data. The results so far show a very strong correlation between the gas flares and the subsurface geology, both structures/closures, faults, bright-spots/hydrocarbon-indicators and erosion/non-erosion of cap rocks. Due to the severe erosion in the area sedimentary rocks of Mesozoic age, both Cretaceous, Jurassic and Triassic of age, subcrop at the seafloor. Combined with the fact that the whole area has a very thin, if none, cover of Quaternary sediments, which could prohibit the gas from leaking directly vertically from the geological layers into the water column, the direct linkage of the seafloor leakage to the subsurface geology is very strong. Here we will also try to show how regional information about gas leakage at the seafloor interpreted from the water column data can be useful for better understanding the petroleum systems in the area.
The gas leakage observed at the seafloor seems primarily to be related to three main geological factors: 1) faults offsetting reservoir / closures and mapped to seafloor, 2) where reservoir and cap rocks sub-crop at the seafloor, 3) the crest of large geological structures where erosion is into the Triassic or Jurassic reservoirs.

Mineralogy and geochemistry of the Mansjöberget skarn, central Sweden

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The skarn-bearing marble and associated Palaeoproterozoic host rocks at Mansjöberget in central Sweden were the subject of a detailed mineralogical-petrographical study by von Eckermann (1922), who interpreted the skarn formation to be a result of metasomatic reactions during the intrusion of late-orogenic pegmatites. We have now undertaken a new investigation of this classic locality, utilising modern mineral chemical and geochemical methods, by means of EPMA, XRF and LA-ICP-MS on recently field-collected samples. Mica group minerals are dominated by phlogopite, while abundant clinopyroxene is wholly dominated by diopside compositions. Garnets belong to the grossular-andradite solid solution with the compositions close to almost pure grossular ($Grs_{91}Adr_9$) and pyralspite less than 10%. Analyzed apatites have F contents between 2.9-3.2 wt. % and are thus fluorapatite; all have SiO_2 < 0.3 wt.%. Some fluorapatites exhibit markedly high REE concentrations of up to 1789 ppm total REE. Of humite -group minerals, chondrodites are mainly composed of 34.0-34.9 wt. % SiO_2 and 55.4-56.9 wt. %

MgO. Additionally they contain up to 6 wt. % fluorine and 3.1-3.8 wt. % ferrous iron. Wollastonite is present and essentially near-ideal in composition, while vesuvianites contain approximately 36.7 wt. % SiO_2, 36.3 wt. % CaO, 17.8 wt. % Al_2O_3, 2.1 wt. % FeO, and 2.3 wt. % MgO. Bulk geochemical analyses of marble samples yield CaO contents varying between 39.3-48.4 wt. % and MgO values of 2.3-13.5 wt. %. The loss of ignition (LOI) estimates of CO_2 gave values ranging from 12.5-36.3 wt. %. Three whole-rock samples were additionally analyzed by XRF without LOI in order to measure the concentrations of other potentially volatile elements which could affect the LOI values. The measured fluorine content in them varies from 0.1-1.3 wt. %. The Mansjöberget marble generally show flat REE patterns and all samples show a negative Eu-anomaly.

The available new data, in combination with our geological observations and petrographic studies, are consistent with the original interpretation by von Eckermann (1922). That is, that the Mansjöberget skarn most likely formed by small-scale metasomatic reactions associated with the intrusion of late-orogenic granites and granitic pegmatites.

Reference:

von Eckermann, H. 1922. The rocks and contact minerals of the Mansjö mountain. Geol. Fören. Stockholm Förh. 44, 203-410.

Nb-enrichment processes in carbonatites: insights from Oldoinyo Dili, Tanzania

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Carbonatites hold the bulk of the world's supply of Nb and REE, and have as such received considerable scientific interest over the last couple of decades. A more precise knowledge on how, and where, Nb and the REE's are enriched within individual carbonatite complexes will help us to better understand the inner workings of such magmatic systems, and will further allow for targeted prospecting and future exploration of these economically important elements. In the current study, we have focused on a suite of carbonatitic dikes that transect Archean basement gneisses at Oldoinyo Dili in northern Tanzania. The composition of the carbonatitic dikes is variable, but a unifying feature is a relatively high Nb-content (up to 2000 ppm in whole-rock samples). Based on a combination of the whole-rock geochemistry and stable isotope analyses (C and O), we identify two separate processes that controlled the Nb-enrichment within the Oldoinyo Dili carbonatite complex. Process (*i*) is dominated by magmatic fractionation of a parental carbonatite magma (with a minor hydrothermal overprint) as evidenced by curvilinear element trends coupled with a positive correlation between $\delta^{13}C$ and $\delta^{18}O$. Process (*ii*) appears to be entirely dominated by hydrothermal activity, characterized by significantly elevated $\delta^{18}O$ values clustering around +26 ‰ (VSMOW). Hydrothermal remobilization predominantly affected the iron-oxides from the carbonatitic rocks (i.e., similar to a Bayan-Obo-type mineralization), but significant amounts of Nb have also been enriched within the magnetite-ores (exceeding 2100 ppm Nb, in a sample that contains 51 wt. % $Fe_2O_3^T$). In the various carbonatites, the main Nb-bearing mineral is pyrochlore, whereas the exact mineralogy of the Nb-rich magnetite-ore samples is currently being investigated (preliminary reflecting-light microscopy analysis yield no pyrochlore crystals in the magnetite-rich samples).

The seismic structure of the Scandinavian lithosphere from finite-frequency body-wave tomography

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We will present a new model of the P and S-wave seismic velocities in the upper mantle beneath Fennoscandia obtained by teleseismic body wave tomography. This model will provide constraints and new insight in the geodynamical processes at play in the lithosphere and asthenosphere beneath Fennoscandia, both in the regions with high topography and in the more flat areas to the East. The model is obtained by inversion of finite-frequency P- and S- wave travel-time relative residuals. We use teleseismic signals from earthquakes at epicentral distances from 30° to 104° and with magnitudes larger than 5.5, gathered from 200 broadband seismic stations installed in Norway, Sweden and Finland, which operated during 2012-2017.

We measure the relative travel-time residuals of direct body waves from teleseismic earthquakes in high- and low-frequency bands, paying attention to appropriate frequency-dependent crustal corrections. As a result, the average residuals show clear trends for different regions and back-azimuths, which demonstrate the presence of significant heterogeneity in the region. Based on these travel-time residuals**,** we carry out finite-frequency body-

wave tomography to determine the P and S wave seismic velocity structure of the upper-mantle. The resulting seismic model will be related to the existing and past topography in order to contribute to the understanding of mechanisms responsible for the topography of the Fennoscandian region in the framework of the general tectonic and geological evolution of the North Atlantic region. The models provide basis for deriving high-resolution models of temperature and compositional anomalies that may contribute to the observed, enigmatic topography.

Erosion-driven vertical motions of the circum Arctic: Comparative analysis of modern topography

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Deep and complex geodynamic processes, including the effects of plumes, heat, plate tectonics, and local tectonics control the Earth's surface. In the Arctic these deep processes are masked by extensive glaciations and associated or roughly synchronous erosion. In this study we aim to reveal these hidden geodynamic processes by modeling erosion backward in time by numerically restoring eroded material and calculating the flexural isostatic response repeatedly iteratively until eroded features are filled. This method estimates erosion recorded in the modern topography and models the influence of that erosion. Although the obvious topographic response to erosion is a lowering of the elevation, our coupled erosion-isostatic response method results in dramatic vertical motions leading to km-scale uplift in fjord carved areas of Scandinavia, Greenland, and Canadian Arctic Archipelago and supporting ancient orogenic belts of northern Siberia and northern Alaska to stay at high elevation. Sensitivity testing confirms the utility of our method over a range of effective elastic plate thicknesses as well as for laterally varying elastic thickness. Comparison of modelling results with observed gravity anomalies shows that our method is valid for both glacial and fluvial affected landscapes but more importantly links surface and deep Earth dynamics. Combined analysis of the gravity anomalies and model results also explains erosion as one of the main mechanisms responsible for gravity signal for tectonically inactive regions and illustrates the interaction of short wavelength erosional processes and large scale, regional processes like active orogenesis and dynamic topography.

Development of sedimentary basins: differential stretching, phase transitions, shear heating and tectonic pressure

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Classical models of lithosphere thinning predict deep synrift basins covered by wider and thinner post-rift deposits. However, synextensional uplift and/or erosion of the crust are widely documented in nature (e.g. the Base Cretaceous unconformity of the NE Atlantic), and generally the post-rift deposits dominate basins fills. Accordingly, several basin models focus on this discrepancy between observations and the classical approach. These models either involve differential thinning, where the mantle thins more than the crust thereby increasing average temperature of the lithosphere, or focus on the effect of metamorphic reactions, showing that such reactions decrease the density of lithospheric rocks. Both approaches result in less synrift subsidence and increased postrift subsidence. The synextensional uplift in these two approaches happens only for special cases, that is for a case of initially thin crust, specific mineral assemblage of the lithospheric mantle or extensive differential thinning of the lithosphere. Here, we analyse the effects of shear heating and tectonic underpressure on the evolution of sedimentary basins. In simple 1D models, we test the implications of various mechanisms in regard to uplift, subsidence, density variations and thermal history. Our numerical experiments show that tectonic underpressure during lithospheric thinning combined with pressure-dependent density is a widely applicable mechanism for synextensional uplift. Mineral phase transitions in the subcrustal lithosphere amplify the effect of underpressure and may result in more than 1 km of synextensional erosion. Additional heat from shear heating, especially combined with mineral phase transitions and differential thinning of the lithosphere, greatly decreases the amount of synrift deposits.

Influence of glaciations on North Sea petroleum systems

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Even in tectonically inactive areas/times, the vertical motions of the Earth's interior may be significant due to glaciation. The most recent ice age massively changed the surface of northern Europe, leading to isostatic re-equilibration. We quantify the vertical motions resulting from three glacial-related mass redistribution mechanisms using, as an example, the North Sea throughout the Quaternary: (1) ice-sheet loading, (2) erosion, including glacial carving of fjords; (3) and sediment deposition. These processes yielded up to 1 km of vertical displacement of the lithosphere across the North Sea, and the corresponding sediment-tilting changed the geometry of petroleum systems and hydrocarbon migration routes. Using the Base Cretaceous Unconformity as a top seal proxy, we analyse the consequences in the Norwegian North Sea. Comparing well data to models, we suggest that tilting the Troll Field back towards its early Quaternary position flattens the palaeooil–water contact (palaeo-OWC), which today is tilted by up to 70 m. The Johan Sverdrup Field shows a more complex history. Hints of a palaeo-OWC tilted can be seen in permeable reservoirs, whereas deeper sporadic oil shows cannot be explained by simple tilt models. Our study illustrates how glacial-related processes may influence the development of giant oil and gas accumulations.

Carbonates in the upper Ediacaran of the Digermulen Peninsula, Arctic Norway

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The Neoproterozoic-Cambrian succession on the remote Digermulen Peninsula of the Tanafjord area in eastern Finnmark, Arctic Norway, has attracted renewed research interest because of new findings of Ediacaran-aged fossils (e.g. Jensen et al., 2018, Canadian Journal of Earth Sciences). Hitherto, the entire upper Ediacaran and Cambrian succession here was believed to be siliciclastic. However, during recent fieldwork, the Digermulen Early Life Research Group made the first discovery of carbonates within the 2nd cycle of the Manndrapselva Member of the Stáhpogieddi Formation of the Vestertana Group (Meinhold et al., 2019, Precambrian Research). Carbonates occur as calcareous siliciclastic beds, lenses, and concretions, some with calcite spherulites and cone-in-cone calcite, in a mudrock to fine-grained sandstone succession from approximately 3 m to 26 m above the base of the 2nd cycle of the Manndrapselva Member. They occur c. 40 m below the Ediacaran–Cambrian boundary, well defined by trace fossils. Thin-section petrography and scanning micro X-ray fluorescence elemental mapping reveal a layered composition of the calcareous sedimentary rocks. In some of those, well-developed nested cone-in-cone calcite form the outer layer. Thin clay coatings outline the individual cones. The inner layers are composed of (1) carbonate with calcite spherulites (grainstone) and (2) thinly laminated fine-grained calcareous siliciclastics (mudstone and wackestone) indicated by elevated concentrations of Al, Si, Fe, and Ti. The inner siliciclastic layers contain framboidal pyrite and probably organic matter. Formation of calcite spherulites probably took place at the sediment–water interface or a few centimetres below, either in a coastal littoral environment or in situ in the sublittoral zone under high alkaline conditions. The cone-in-cone calcite formed during burial diagenesis and clearly before low-grade metamorphism and cleavage formation. Timing of deformation and metamorphic overprint match the Caledonian orogeny (Meinhold et al., 2019, GFF). This new record of carbonates with calcite spherulites and cone-in-cone structures from the Ediacaran of Arctic Norway adds to their rare occurrences in the geological record.

Tectonic overpressure drives fluid expulsion and fracturing at the base of the seismogenic crust

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Aseismic creep is commonly accompanied, initiated, or followed by transient seismic deformation. Various models have been suggested for the interplay between seismic and aseismic deformation on a single structure, including spatially heterogeneous composition and viscosity, fluid pressure, or deforming thickness. Models also vary between seismic deformation triggered by creep, and creep triggered by seismic slip. Here, we address this problem by detailed structural investigation of a brittle-viscous shear zone at Sagelvvatn, Northern Norway. The shear zone occurs along a thrust zone that accommodated the top-to-ESE nappe emplacement in the Upper Allochthon of the Norwegian Caledonides.

The shear zone is dominantly ductile, but locally sigmoidal quartz veins crosscut the subhorizontal mylonitic fabric at a high angle. The veins are only observed within a coarse-grained mylonitic metaconglomerate horizon sandwiched between mica schists. The veins have tips oriented at approximately 45° to the shear zone margins, and are rotated and folded with the sense of shear of the mylonite. Fold hinge lines in the veins and stretching lineations in the mylonite are approximately perpendicular. Vein quartz long axes are subparallel to the stretching lineation in the mylonite, and at a high (70 – 80°) angle to the vein margins. Chlorite thermometry indicates that vein emplacement and mylonitisation occurred at ca. 400°C.
The mylonitic metaconglomerate consists of monomineralic quartz pebbles embedded in a quartz + carbonates recrystallized cement. The pebbles are highly elongated and lack fractures or boudinage. Quartz microstructure is consistent with dynamic recrystallization by subgrain rotation and limited grain boundary migration. The average recrystallized grain size of quartz is 110 mm, which indicates differential stresses around 20 MPa during mylonitic flow.
The veins reflect the same kinematics as the shear zone, and are interpreted as triggered and controlled by the viscous flow within the mylonite. We suggest a model where brittle failure arises spontaneously within a creeping shear zone. Progressive shear strain within a stretching shear zone dynamically increases pressure within the deforming zone, requiring expulsion of fluids from within the shear zone. In fine-grained shear zones, a dynamic porosity may be maintained by creep cavitation, but the coarse grain size in the Sagelvvatn metaconglomerate does not allow this. Instead, the increased fluid pressure leads to episodic fracturing as a direct consequence of creep, when the hydrofracture criterion is reached. These fractures accompany creep, and their geophysical expression will likely depend on the stiffness of the shear zone relative to the surrounding elastic materials.

Late Mesozoic-Cenozoic tectono-stratigraphic evolution of the Vesterålen margin, offshore northern Norway

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The Lofoten-Vesterålen margin in the Norwegian-Greenland Sea is one of the relatively underexplored segments offshore northern Norway. The main purpose of this MSc thesis is to study the structural styles and constrain it to the geological evolution of the basin sedimentary infill history. The Vesterålen margin is the focus area, and it will be study trough 2D seismic data (e.g. selected profiles from surveys: LO-86/87/88/89), 3D seismic data (NPD-LOF1-09), and potential anomaly field grids (gravity and magnetic). Detailed seismic interpretation is expected to provide new insights in timing and faulting styles, margin segmentation, and basin architecture for both, along and conjugate margin. An overview of potential geological plays in the area will be part of the discussion.

EPOS-Norway Web Portal for Solid Earth Science Data

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The European Plate Observing System (EPOS) is a pan-European infrastructure for solid Earth science data.
The EPOS-N Portal is a recently developed portal within the EPOS-Norway project (https://epos-no.uib.no) which is integrating data from various geoscientific disciplines in Norway. The main goal is to simplify access to data and allow cross-disciplinary interoperability and data analysis. The system is implemented by adapting Enlighten-web software developed by NORCE. Enlighten-web facilitates interactive visual analysis of large multi-dimensional data sets. Supported plot types are bar charts, table views, scatter plots, vector plots, line plots and map views. A workflow can start by selecting available datasets from the EPOS-N metadata database and cross-analysing them and compare them, also with your own uploaded dataset (import of CSV files as for now). The EPOS-N Portal access remote datasets via web services, e.g. FDSNWS for seismological data or WMS – Web Map Services for map layers (e.g. bedrock geology, unstable massifs, marine bottom sediments and abruptness). Standalone datasets from EPOS-N project partners are available through preloaded data files on our hosting server. After selecting datasets, the user can create various visualizations of the data. Brushing and linking is the key feature of the portal allowing exploration of complex datasets and discovery of correlations and interesting properties hidden in the data. Brushing refers to selecting a subset of the data in plots by

cursor (rectangle). Linking involves two or more plots of the same data sets, linked by attributes allowing interactive filtering of the dataset. The plots are linked to each other, so highlighting a subset in one plot automatically leads to highlighting of the corresponding subsets in the all linked plots which can be done in real-time interaction. This interactivity requires GPU acceleration of the graphics rendering. In Enlighten-web, this is realized by using WebGL.

Among the six EPOS-N project partners, five institutions are actively participating and providing data in the EPOS-N project – University of Bergen (UIB), University of Oslo (UIO), Norwegian Mapping Authority (NMA), Geological Survey of Norway (NGU) and NORSAR. Before the data are integrated into the e-infrastructure their formats need to follow international standards. For now, there are 33 Data, Data Products, Software and Services (DDSS) described in the EPOS-N list. The seismological waveform data (provided by UIB and NORSAR) are available through an EIDA system, seismological data products (receiver functions, earthquake catalogues, macroseismic observations) as individual datasets or through a web service, GNSS data (provided by NMA) through the GLASS framework (web service) and geological and geophysical (magnetic, gravity anomaly) maps (provided by NGU) as WMS.

The EPOS-N Portal provides a new level of data visualization and quick access to geoscientific datasets in Norway. Those aspects make the tool ideal for education of young scientists, especially in cross-disciplinary context. Testing the software and further discussion with the developers will be possible during the whole conference in a designated PC-room.

EPOS ICS Data Portal

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The European Plate Observing System (EPOS) addresses the problem of homogeneous access to heterogeneous digital assets in geoscience of the European tectonic plate. Such access opens new research opportunities. Previous attempts have been limited in scope and required much human intervention. EPOS adopts an advanced Information and Communication Technologies (ICT) architecture driven by a catalog of rich metadata. The architecture together with challenges and solutions adopted are presented. The EPOS ICS Data Portal is introducing a new way for cross-disciplinary research. The multidisciplinary research is raising new possibilities for both students and teachers. The EPOS portal can be used either to explore the available datasets or to facilitate the research itself. It can be very instructive in teaching as well, for example by demonstrating scientific use cases.

EPOS is a European project about building a pan-European infrastructure for accessing solid Earth science data. The finished EPOS-IP project includes 47 partners plus 6 associate partners from 25 countries from all over Europe and several international organizations. However, the community contributing to the EPOS integration plan is larger than the official partnership of EPOS-IP project, because more countries are represented by the international organizations and because there are several research institutions involved within each country.

The recently developed EPOS ICS Data Portal provides access to data and data products from ten different geoscientific areas: Seismology, Near Fault Observatories, GNSS Data and Products, Volcano Observations, Satellite Data, Geomagnetic Observations, Anthropogenic Hazards, Geological Information and Modelling, Multi-scale laboratories and Geo-Energy Test Beds for Low Carbon Energy.

The presentation focusses on the EPOS ICS Data Portal, which is providing information about available datasets from TCS and access to them. We are demonstrating not only features of the graphical user interface but also the underlying architecture of the whole system.

UpDeep Web Tool for surface geochemical mineral exploration

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Upscaling deep buried geochemical exploration techniques into European business – UpDeep - is an EIT Raw Materials funded project consortium (2017-2020, http://projects.gtk.fi/updeep/) upscaling the surface geochemical exploration consulting business to the European market to facilitate mineral discoveries at depth. Surface geochemistry

with plants and soils is a cost-efficient environmentally low impact approach on overburden and vegetation covered regions in the early stages of mineral exploration at camp and target scales. The UpDeep team has developed several technical aspects required to smoothly run a geochemical exploration project with plant and soil sampling. This presentation highlights the functionalities of the UpDeep Web Tool – an internet based software developed for data collection, management, analysis and interpretation of plant biogeochemical and soil geochemical data. Through the web tool all project stages after contract signing all the way to result reporting of a project can be managed including sampling planning, field sampling, sample preprocessing, reference sample management, geochemical laboratory analysis, data analysis and interpretation. The web tool is modular meaning that the workflow can be entered and exited at any point. Field data collection and sample bag labeling can be done fully digitally with client specific field devices and data collection systems. The power of the UpDeep Web Tool is in data management: all related files regardless of their type can be stored in the underlying database. This will ease the information flow between a geochemical consultant and an exploration company allowing the focus to stay on exploration. In the first version of the web tool, geochemical data is specific to plants and soils and the data is analyzed in absolute concentrations. Data analysis tools include quality assurance and quality control, descriptive statistics, explanatory data analysis plots, compositional data analysis based correlation and clustering and map plots for transect and grid sampling schemes. Data can be exported from the web tool to external software for analysis if necessary. The future versions may include extension of the compositional data analysis tools and other types of geochemical sampling media. The web tool can be installed and run on a server of a geochemical consultant and accessed by the client securely. Optionally, the web tool can be run internally in a mining company for exploration projects between a company geochemists and exploration geologists. As a result from the UpDeep project Ab Scandinavian GeoPool Ltd (http://www.geopool.fi/index.php) is launching a surface geochemical consulting service utilizing the UpDeep Web Tool.

Interpreting the spatial curvature of log-ratios approach for mineral exploration with plant biogeochemistry

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Mineral exploration with plant biogeochemistry is most commonly based on detecting spatial patterns of absolute element concentrations along a sampling transect or a grid across an expected exploration target and its background. Recently, Miksova et al. (2019) proposed an approach for detecting geochemical anomalies using spatial curvature of pairwise log-ratios of elements. In practical target scale mineral exploration, the sampling density is often low compared to heterogeneity of underlying mineralized lodes causing apical and so-called 'rabbit ear' anomaly patterns or noisy signals on single element maps. Focusing on the curvature of the log-ratios highlights these rapidly changing spatial patterns in geochemical compositional data. The absolute concentrations are first smoothed in space with Generalized Additive Models (GAMs), log-ratios of the smoothed signals of element pairs are then calculated followed by curvature calculation of the log-ratio pairs. Finally, an overall measure of curvature is computed to rank the element log-ratio pairs in terms of most indicative elements of a potential underlying mineralization.

In this presentation the applicability of the approach is demonstrated with plant biogeochemical data, acquired on a transect across the Juomasuo hydrothermal Au-Co mineralization in SE Finnish Lapland. The focus is on geochemical interpretation of the highlighted element ratios verified with the drill core lithogeochemistry. The differences between the sampled circumboreal shrubs crowberry (*Empetrum nigrum L.*), Labrador tea (*Ledum palustre*) and bilberry (*Vaccinium myrtillus L.*), and one conifer, common juniper (*Juniperus communis L.*) for target scale mineral exploration are discussed. The results show that the commodity element Co and pathfinders Ag, As, Bi, Co, Se and U are present in many highly ranked log-ratio pairs amongst all possible log-ratios indicating applicability of the technique for mineral exploration. The new spatial curvature based approach considers the compositional nature of the geochemical data and is unsupervised, meaning that required prior knowledge of underlying deposit is few. The technique should be further tested on a variety of exploration geochemical dataset to be approved as a standard geochemists' tool. The research was funded by the EIT Raw materials project UpDeep - Upscaling deep buried geochemical exploration techniques into European business.

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UpDeep Online Statistics Tool for plant biogeochemical and soil geochemical concentration levels to aid mineral exploration

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An EIT Raw Materials funded project consortium UpDeep - Upscaling deep buried geochemical exploration techniques into European business - has developed a surface geochemical exploration consulting business for the European market in order to facilitate mineral discoveries at depth (2017-2020, http://projects.gtk.fi/updeep/). As one of the technical solutions to support surface geochemical exploration in camp and target scale green field exploration the UpDeep team launched an open source web service of concentration levels of plants and soils. Interpretation of the plant biogeochemistry and soil chemistry data in exploration is commonly based on detection of spatial patterns of concentrations in samples collected on sampling stations over an expected anomaly and its background. Previous results (Torppa and Middleton, 2017), however, indicate that overall concentrations may also provide hints of an underlying mineralization, a metallogenic region or a nearby contamination source. In contradiction of many other geochemical sampling media, the concentration levels of plant species, their tissues and soil horizons are not common knowledge and scattered in literature. The UpDeep Online Statistics Tool is designed to be a worldwide database to store geochemistry of plants and especially partially leached concentrations of soils. The UpDeep Online Statistics Tool can profit two phases of a surface geochemical survey: 1) In sampling planning the map interphase and search functions of the tool could be used to discover existing surface geochemical data collected in similar environments, similar sampling materials and similar deposit types to aid the sample material and analytical method selection in a user's current case study. 2) In data analysis and interpretation phase the concentration levels in the user's own data can be compared to existing data in the UpDeep database. The current database is limited to be fully utilize for these purposes, only including data from northern Finland, Greenland and France. To populate the database and increase its applicability we invite anyone to upload their own data in the UpDeep Online Statistics Tool accessible at http://gtkdata.gtk.fi/updeep/ by following the instructions on the web page and sending the data in a standardized format to updeep.online(at)gtk.fi.

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Testing arctic tectonic plate models with Cretaceous sediment source to sink budgets

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A numerical architectural analysis of an outcrop belt is coupled with grain size analysis and zircon data to constrain river dimensions, load, and capacity. This data is used further to quantify sediment volumes that passed through the outcrop belt in order to improve estimates on downstream strata and the catchment area size. This substantiates a refinement of upstream palaeogeography and palaeotectonic plate configurations. The study object is the lower Cretaceous fluvial strata on Spitsbergen and its basinward equivalent in the Barents Sea. The onshore outcrops are a fluvial braidplain deposit up to 20-m-thick and mappable across southern Spitsbergen, while offshore subcrops, mapped by seismics 300 km further to the SE, are marine shelf platform strata. The river discharge supported up to five contemporaneously active braided channels, each at least 200 m wide. A ~50,000 km^2 drainage area is estimated based on application of the mass balance fulcrum test when a temperate climate model is used.

The results have implications for the palaeotectonic configuration in the since fragmented Cretaceous source area, and is used to promote a revised plate tectonic model for the present-day Arctic during the Barremian. The notion of a landmass of sufficient size to feed large-size rivers across and beyond Spitsbergen, and into the western Barents Sea area is supported.

Digital monitoring of CO_2 storage projects (DigiMon)

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A key component of any CCS project is measurement, monitoring and verification (MMV), which must demonstrate that projects are planned and executed in a societally acceptable manner and that adequate technologies are implemented to ensure safety and security.
The presentation gives an overview of a monitoring system, DigiMon, that is under development. The overall objective of the ACT CCS DigiMon project recently started, is to "accelerate the implementation of CCS by developing and demonstrating an affordable, flexible, societally embedded and smart Digital Monitoring early-warning system", for monitoring any CO2 storage reservoir and subsurface barrier system.
The innovation of the DigiMon approach lies in that it integrates a broad range of technologies for MMV at CO2 storage sites (i.e. distributed fibre-optic sensing technology (DxS), seismic point sensors and gravimetry). Combined with ethernet-based digital communication and near real-time, web-based smart data processing software, the DigiMon project presents a novel and cost-efficient early-warning solution for monitoring CO_2 storage reservoirs and subsurface barrier systems. In addition, it uniquely considers the possibilities of monitoring technologies for CCS from the point of view of societal acceptability and benefit. Such a system is not currently available.

Geothermal energy systems – understanding the heat exchange by distributed temperature sensing

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The Nordic Countries are among the world leading countries utilizing geothermal energy (Lund et al., 2015). There are more than 700 000 Ground Source Heat Pump (GSHP) installations producing more than 30 TWh heat yearly (Gehlin & Andersson 2019, Kallio, 2019, Kvalsvik et al. 2019, Poulsen et al., 2019). Most of the large installations are Underground Thermal Energy Storage (UTES) that store surplus heat or cold until it is needed either for heating or cooling purpose.
Despite the prevalence of GSHP and UTES installations, there is a lack of detailed understanding on how these systems are operating, how do they affect the ground and the underground heat exchange mechanisms.
Distributed Temperature Sensing (DTS) technologies reveals detailed insight of the temperatures in the entire wells or borehole heat exchangers (BHE) during operation. Using this information, the heat exchange and storage mechanisms in the boreholes, wells and UTES can be understood. Fiber-optic cables have been installed in 6 Norwegian GSHP installations (Bergen (Steinerskolen, Fellesbygget), Ørlandet, Asker, Gardermoen, Drammen) and two more planned at NTNU and Vensmoen, Saltdal. These installations in addition to Emmaboda, a medium temperature borehole temperature energy storage (BTES) in Sweden storing industrial waste heat, are monitored and followed up in the research project RockStore. Data and interpretation of the subsurface temperature development during operation of the GSHP systems will be presented.

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Magmatism in wet sediment environments: processes, deposits and implications for prospective volcanic rifted margins

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Volcanism along volcanic rifted margins results in a wide range of different volcanic facies that have been studied in detail from field, borehole, seismic

and potential field data for several decades. The discipline of seismic volcanostratigraphy was developed in order to place key stratigraphically resolvable seismic facies into a genetic volcanic rifted margin model including Outer SDR, Outer High, Inner SDR, Landward Flows, Lava Delta and Inner Flows. Within this study we focus on the mid-Norwegian Inner Flows seismic facies which comprise generally chaotic seismic facies beginning at the foot of the Lava Delta and expanding out into the deep Cretaceous Møre and Vøring basins and can also be imaged extending beneath the Lava Delta facies. Originally based on 2D seismic observations, the nature of the volcanic facies incorporated within the Inner Flows domain were assigned to a combination of massive and fragmented basalts including volcaniclastic and shallow intrusive rocks emplaced into a sub-aqueous environment.

Using field and borehole analogues from the North and South Atlantic we identify several key volcanic facies that likely exist within the Inner Flows seismic facies domain including: 1. shallow intrusions; 2. invasive lava flows; 3. lavas with associated rootless cones; 4. debris flows and associated loading; 5. sub-aqueous lava flows, and 6. pillow lava complexes. The definitive identification of these separate facies is not always possible from seismic, however, with recently expanding 3D seismic data coverage over the Inner Flows domain, and the application of igneous seismic geomorphology, we propose that useable and geologically important subdivisions are now possible at least locally. 3D seismic imaging examples from the Møre, Vøring and Faroe-Shetland basins are used to highlight key Inner Flows domain components including shallow intrusions, debris flows, hyaloclastite delta collapse structures and invasive lava flows.

It is clear that a single umbrella term for the volcanic facies encountered within the complex and wide-ranging system of pre-, syn- and post-volcanic sedimentary environments landward of the prominent marginal highs has limitations. Significant differences in physical properties (e.g. density, velocity and porosity) and their 3D distribution are known to exist within the volcanic facies identified in the Inner Flows domain. Therefore, improved understanding of the distribution of these different facies is key for improving knowledge of seismic velocities, anisotropy, attenuation and scattering in order to further improve seismic processing, imaging and interpretation in these complex settings where volcanic rocks meet prospective sedimentary basins.

Upper mantle thermochemical heterogeneity constrained by geophysical data in the northeast Atlantic

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Uplifted passive continental margins of northeast Atlantic, had a central role in the development of tectonic and ice-sheet models. Seismic tomography and numerical modeling suggest that the Iceland-Jan Mayen mantle plume had a strong long-distance impact on intraplate deformation affecting both onshore and offshore areas. The episodic uplift and exhumation recorded in sediment stratigraphy has been previously linked to the pulsations of the Iceland hotspot and episodic outward flow of hot asthenosphere. A number of mechanisms controlling the plume-lithosphere interaction within this type of channelized flow has later been suggested such as drainage of plume material by gravity flow, shear-driven upwelling, viscous fingering instability and solitary waves.

In this study, we test the sensitivity of the geophysical observables in the Northeast Atlantic region to the uncertainty of the crustal and mantle models, evaluate of the impact of realistic chemical compositional variations of the mantle and perform a 1D probabilistic joint inversion based on surface wave dispersion curves and gravity data. The inversion results provide quantitative constraints on the magnitude of thermal and chemical heterogeneities in the upper mantle of the northeast Atlantic region. We discuss the origin of these heterogeneities in context of spatial variability of the obtained model compare to the null model, according to which, the lithosphere overlying a hot adiabatic mantle was uniformly stretched.

Timing of formation of orogenic gold deposits during the Svecofennian orogeny in the northern part of the Fennoscandian shield

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Timing of formation of orogenic gold deposits during the evolution of orogenic belts is a critical parameter for establishment of mineral exploration models. It is generally accepted that the major source of fluids and metals in orogenic gold mineral systems is the devolatilization of rocks during prograde metamorphism. Formation of

deposits requires focussed flow of fluids from the sources to the sites of deposition along crustal scale fault systems. However, in many orogenic gold belts, the deposits formed late (e.g. Kalgoorlie Gold Field, Australia, Juneau Gold Belt, Alaska), after post-peak metamorphism of the tectono-metamorphic evolution or in several distinct time slices corresponding to the major deformation events (e.g. Birimian Belt, W-Africa). Orogenic gold is among the most important mineral resources in the northern part of the Fennoscandian shield where Paleoproterozoic basins were turned into fold and thrust belts during the Svecofennian orogeny (1.92-1.77 Ga). We completed systematic geochronological work using the LA-ICPMS analytical method for U-Pb dating of hydrothermal monazite, xenotime and uraninite and Re-Os dating of molybdenite and arsenopyrite in several orogenic gold deposits from the Central Lapland Greenstone Belt, Kuusamo Schist Belt and Peräpohja Schist Belt. In these belts, two major gold deposition events at 1.92-1.91 Ga (CLGB) and 1.81-1.76 Ga (all belts) have been found. Data also constrain the timing of barren hydrothermal pulses between these fertile hydrothermal events and confirm that the major structures controlling localization of gold deposits formed during the early stages of the Svecofennian tectonic evolution. However, the repeated fertile and barren hydrothermal events along the same faults together with diverse yet systematic sulphur and boron isotope and trace element data from ore and alteration minerals suggest that the major structures tapped distinctive fluid reservoirs in these belts. The ore stages are temporally and in some cases spatially associated with felsic magmatism indicating that in addition to the prevailing effect of the prolonged thermal re-bounding after early stage fast burial (e.g. accretion), magmatism may have had a local role in providing elevated temperatures for circulation of fluids during the late- (final collision) and post-orogenic stages of the Svecofennian orogeny.

Rock physics diagnostics of Geitungen discovery

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Det norske oljeselskap ASA made an oil discovery in well 16/2-12 in the Central North Sea in 2012. The exploration well was drilled on the 'Geitungen prospect-a basement terrace' north-west of the Johan Sverdrup field on the Utsira High. The primary objectives to drill the well were to investigate the hydrocarbon potential, reservoir quality, and lateral distribution of Intra-Draupne Formation sandstones, and the underlying sandstones of the Hugin and Sleipner Formations. The secondary objectives were to explore the hydrocarbon potential and reservoir properties in the fractured granitic Basement (NPD FactPages, 2019). The well proved a 35 m oil column in an excellent quality reservoir sandstones of Intra Draupne Formation. The other two sandstones of Hugin and Sleipner Formations were water-bearing. The top of the granite Basement was picked at 1939 m containing fractures in the uppermost part filled with oil. The estimated volumes in Geitungen's discovery are between 140 and 270 million barrels of recoverable oil equivalents (o.e). This study focuses on rock physics diagnostics of two oil-filled units (Intra Draupne Formation sandstone and fractured granite Basement) on assessing lithology and fluid signatures on seismic data.
Rock physics analysis suggests that the lithology and fluid content of Draupne Formation sandstone can be readily delineated using the crossplot of elastic properties with the rock physics template. As expected, the fractured granite Basement does not follow the standard rock physics diagnostic scheme and requires a new rock physics model to discriminate lithology and fluid content. We present a new rock physics modelling approach to capture the elastic behaviour of fractured and non-fractured basement rocks as well as their fluid content (hydrocarbon- or water-bearing). The prior knowledge, such as the mineralogical composition of the basement rocks and lithology of the overlaying caprock can help to construct a more efficient rock physics template, including the effects of weathering, fracture pattern, and fluid content.

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The glacial geomorphology of the Baltic Sea and its implications for the last deglaciation

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The Baltic Sea constitutes one of the largest sectors of the former Fennoscandian Ice Sheet. The northern parts hosted the main ice divide during the maximum configuration of the ice sheet and the basins of the Baltic are thought to have been one of the major zones for fast ice-flow and marine

-based grounding-line retreat during deglaciation. Yet, research into the pattern and style of ice flow and grounding line retreat through the Baltic is lacking, with a dearth of offshore and basin-wide investigations precluding both regional and ice-sheet-wide understanding of the last deglaciation. Based on similar configurations in formerly and presently glaciated areas, ice streaming has been thought to have occurred in the Baltic. However, the patterns of flow and retreat have traditionally been interpolated across the data-poor offshore zone between the much better investigated and dated terrestrial geological records surrounding the basin, leading to uncertainties regarding the existence of ice streams. Here we present a first map of the glacial geomorphology of the Baltic Sea, interpreted from basin-wide moderate- to high-resolution bathymetric data, showing subglacial (lineations, ribbed moraines and hummocky terrain), glaciofluvial (eskers and meltwater channels) and ice-marginal (terminal and retreat moraines) features. The distribution of these landforms provides us with information of the style and spatial pattern of ice flow, both during streaming phases and during deglaciation. In the Baltic Proper and the Bothnian Sea lineations indicating fast-flowing ice are dominant, whilst the lack of ice-marginal features indicates a rapid retreat, with few slow-downs or short re-advances. Farther north, in the Bothnian Bay, there are more ice-marginal features, which lead us to postulate that the retreat was slower here, giving the sediment time to accumulate in distinct moraines. Meanwhile, the presence of numerous large esker- and meltwater-channel systems indicates a sustained discharge of sediment and meltwater during deglaciation.

Well logging techniques for mapping groundwater flow in fractures

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For a project near Oslo, four deep geothermal wells were planned to 1500 m in order to circulate water in a closed geothermal system. However, due to large influx of water, the drilling had to be stopped short of this depth target. Consequently, the closed geothermal system was discarded, to be replaced by an open geothermal system. Ruden AS were tasked with finding a way to extract 24 L/s of water at a temperature of 12°C, thereby producing the planned amount of heat with wells of less than half the planned depth.
The wells intersect several fracture systems with high capacities for delivering water. The pumped water maintained a temperature of 9°C at the surface, implying that the main challenge was to extract water at sufficiently high temperatures. The chosen solution was to exclude high capacity shallow, low-temperature aquifers from contributing to the flow. Well logging in combination with pumping was used to map the individual contributions of each fracture system. The method is described below.
First, a simple step test is performed on each of the wells in order to determine their specific capacities. Second, an impeller flowmeter log and a temperature log are recorded simultaneously with a pump running at a constant rate in the same well. Pumping at the surface induces flow from all water bearing fractures throughout the well profile, revealing flow and temperature characteristics. Going down, the flow velocity decreases each time the flowmeter passes a fracture which contributes to the pumped flow. By measuring the flow velocity decrease over each fracture, in light of total specific capacity at the well head, the specific capacity of each water-bearing fracture in the well is determined. Similarly, the temperature log shows the temperature of all underlying flow contributions at each measurement point. This approach provides information on water flow and temperature below any point in a well. Armed with this knowledge, a packer will be installed at a strategic point in order to optimise flow and temperature from the well, and at the same time isolate the shallower, colder and higher producing part of each well.
Drilling of deep crystalline rocks is expensive. Based on the combined well logging and pumping procedure a solution was presented having an energy output similar to a much deeper and more costly well field.

Stories of Geological Heritage using Virtual and Augmented Reality Technology (VR / AR).

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New ways to communicate geological heritage are the use of VR and AR technology. With Augmented Reality (AR) it is possible to add virtual elements in the real world by looking for objects that are not physically present in the space. A mobile phone can be used as a device for AR. By pointing the camera on it against a location, one can look through the phone by looking at the screen. It will display the real world in addition to one or many virtual objects layer on top. It is also possible to

use AR-glasses where virtual elements (or holograms) are projected on to the glasses, blending virtual elements with the reality. With Virtual Reality (VR), one is omitted from the real world and immersed in a virtual world. With a headset you only see the virtual world and with controls you can maneuver in this world. Both VR and AR are suitable as knowledge providers for dissemination to geo-tourists, AR for both off-site and on-site interpretation, while VR for off-site presentations. Both technologies will have great potential for creating new jobs in tourism. Inland Norway University, Norway's Geological Survey, Sweden's Geological Survey, and others, is working on a pilot project GEARS to test VR / AR technology at selected locations in Inner Scandinavia: a) Jutulhogget in Hedmark, Norway, one of Scandinavia's largest canyons and b) Siljanringen in Dalarna, Sweden, which is Northern Europe's largest meteorite crater. These new technologies allow you to reconstruct the formation of these areas and experience this through VR & AR technology while on the spot. This will provide a truly unique experience through a new dimension.

Trace elements and cathodoluminescence of detrital quartz in Arctic marine sediments – a new ice-rafted debris provenance proxy

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The records of ice-rafted debris (IRD) provenance in the North Atlantic–Barents Sea allow the reconstruction of the spatial and temporal changes of ice-flow drainage patterns during glacial and deglacial periods. In this study a new approach to characterization of the provenance of detrital quartz grains in the fraction > 500 µm of marine sediments offshore of Spitsbergen is introduced, utilizing scanning electron microscope back-scattered electron and cathodoluminescence (CL) imaging, combined with laser ablation inductively coupled plasma mass spectrometry (Müller & Knies, 2013). Based on their micro-inclusions, CL and trace element characteristics, the investigated IRD grains can be classified into five distinct populations. Three of the populations are indicative of potential IRD provenance provinces in the Storfjord area including Barentsøya and Edgeøya. The results imply that under modern (interglacial) conditions IRD deposition along the western Spitsbergen margin is mainly governed by the East Spitsbergen Current controlling the ice-drift pattern. The presence of detrital quartz from local provinces, however, indicates that variations in IRD supply from western Spitsbergen may be quantified as well. In this pilot study it is demonstrated that this new approach applied on Arctic continental margin sediments bears a considerable potential for the definition of the sources of IRD and thus of spatial/temporal changes in ice-flow drainage patterns during glacial/interglacial cycles.

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Fault stability of seismic-scale normal faults: Implications for CO_2 storage on the northern Horda Platform

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Pre-existing weaknesses (such as faults and fractures) in a volume of rock are prone to reactivation where they are preferentially orientated to the in-situ stress regime. Fault reactivation is commonly associated with increased along-fault permeability, and as such provides a mechanism for seal-breach in hydrocarbon or CO_2 storage formations. Fault stability analysis considers several parameters in assessing reactivation potential, i) in situ stresses (orientation and magnitude), ii) fault geometry and orientation, iii) pore-pressure gradients (where higher pressure reduces the magnitude of stress required for failure) and (iv) the mechanical rock properties of the fault rock (e.g., cohesion and friction). In this contribution, we apply a seismic-scale fault reactivation analysis to Smeaheia, a rotated fault block located on the Horda Platform in the Norwegian sector of the North Sea. The Smeaheia fault block presents a potential offshore CO_2 storage site where shallow-marine deposits comprising the Jurassic Viking Group provide good reservoir potential. This area hosts two potential prospects comprised of fault-bound structural closures, i) Alpha in the footwall of the Vette Fault Zone, and Beta in the Hanging wall of the Øygarden Fault Complex. Both pro-

spects require bounding faults to be sealing. Further, intra-block second order faults intersect the envisaged caprocks where reactivation may facilitate seal-bypass. Conventional fault stability analyses model pre-existing faults as non-cohesive structures, where frictional resistance must be surpassed to reactivate a structure. Outcrop studies, however, suggest this is a simplification and may overestimate fault reactivation potential. Further, the sensitivity of the analysis with regard fault geometry challenge the quality of the fault surface description. Despite these shortcomings (which attempt to mitigate), we model fault reactivation potential for the prospective fault block. Results are displayed for various pore-pressure regimes, which are uncertain given potential pressure communication with the nearby hydrocarbon fields. Preliminary conclusions suggest fault reactivation potential in proximity to storage formation prospects is low.

Stability of Cu-sulphides in submarine tailing disposals: A case study from Repparfjorden, northern Norway

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Mineralogical and geochemical analyses of the sediment-hosted Cu deposits Nussir and Ulveryggen located in the Repparfjord Tectonic Window, northern Norway, as well as the associated historical submarine tailings deposited in Repparfjorden, were performed to assess the Cu-speciation and the role of soluble Cu-complexes in mobilization of Cu in the submarine tailing disposal site. The Cu mineralization in the Repparfjord Tectonic Window shows a high risk for the generation of acid mine drainages (AMDs) due its high Fe^{2+}/Fe^{3+} and S^{2-}/SO_4^{2-} ratios. A low carbonate content of some deposits, including the Ulveryggen deposit, additionally increases this risk. In contrast, the trace element geochemistry revealed that the mineralization is depleted in most of potentially toxic elements, such as Zn, As, Pb, Cd, and Hg, diminishing the environmental threat of these deposits. Furthermore, relatively simple mineral assemblages decrease a risk of galvanic interactions between sulphide minerals.

The mineralogical analyses of the submarine tailings and non-contaminated marine sediments from Repparfjorden revealed that most of the sulphide minerals are well preserved in both types of accumulations. However, chalcopyrite sampled from the uppermost part of the tailings showed traces of incipient weathering.

Thermodynamic modelling confirmed that pH and redox potential of the infiltrating seawater are the key factors that control the stability of Cu sulphides in submarine tailings. Although a high carbonate content of base metal tailings has been considered as an advantage due to the buffering capacity of carbonates, this study revealed that in submarine anoxic conditions the presence of carbonates may promote the formation of soluble Cu-bicarbonate and carbonate complexes and, therefore, increase the Cu-sulphide solubility even in near-neutral conditions.

Magmatic and metamorphic ages near Mandal, Vest-Agder; a key area elucidating Sveconorwegian and pre-Sveconorwegian orogenesis

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The study area lies between the villages Øyslebø and Try in Vest-Agder southern Norway; located within the Telemark lithotectonic unit (believed to be < 1.52 Ga) along the eastern margin of the Sirdal Magmatic Belt (SMB), a 1070-1010 Ma voluminous granitic batholith. The area lies between rocks that underwent continuous 1070-920 Ma ultra-high temperature metamorphism in Rogaland and more discrete short-lived metamorphic events in the east (i.e. 1140-1130 Ma Bamble high-temperature metamorphism, 1050-1020 Ma Idefjorden high-pressure metamorphism, and 970 Ma Eastern Segment eclogite facies metamorphism). The aim is to describe magmatic and metamorphic events in the area and relate them to the regional geology; this by U-Pb geochronology and Lu-Hf isotope measurements of zircons with *Laser Ablation – Split Stream – Inductively Coupled Plasma - Mass Spectrometry* (LA-SS-ICP-MS) and *Sensitive High-Resolution Ion Microprobe* (SHRIMP) analysis.

The lithologies found in the area include a disperse (relations between biotite and quartzofeldspathic minerals) migmatite and two gneiss units with tectonic relations. These lithologies are intruded by the SMB and hornblende-biotite granite (HBG), pegmatites, and mafic rocks.

Three different samples of disperse migmatite yields ages older than the Telemarkian orogen (1.52-1.48 Ga), that is believed to be the earliest

rock formation event in the Telemark lithotectonic unit; these measured ages are 1566 ± 7 Ma,1565 ± 11 Ma, and 1532 ± 38 Ma. This questions the validity of using Gothia- and Telemarkia- orogens as a spatial divide between 1.66-1.52 Ga, and 1.52-1.48 rocks in Southern Norway. Porphyric magmatism at 1210 ± 31 Ma and 1208 ± 16 Ma resulted in two gneiss units; this coincides with a pre-Sveconorwegian period of rifting from 1.34 to 1.10 Ga.
1078 ± 14 Ma and 1066 ± 67 Ma granitic intrusions found close to the eastern margins of SMB marks one of the earliest found onsets of SMB. Further within the SMB-batholith ages yields between 1050 and 1025 Ma, which fits well with the known peak of SMB magmatism. SHRIMP analysis of zircon rims in migmatite shows migmatisation at 1011 ± 9, Ma coeval with late-SMB magmatism; this closely followed with end of foliation. HBG-suite magmatism in the area yields at 945 ± 14 Ma and 975 ± 11 Ma, and is the source of local pegmatites.
In addition, Lu-Hf isotope measurements of zircons indicate the the rocks involved in the Gothian-Telemarkian orogen formed somewhere around 1.75 Ga.

Eclogite- and upper amphibolite-facies metamorphosed Iapetus units within Precambrian basement, Roan, Vestranden, Norway

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Vestranden is a large basement window composed mainly of Precambrian granitic gneisses, analogous to the Western Gneiss Region (WGR) in Norway. Both windows are exposed west of the thick south-central Caledonian nappe pile, and both contain eclogite and garnet peridotite. Some of these HP rocks were metamorphosed in-situ, and others originated elsewhere and were tectonically inserted. Distinguishing between these radically different origins is critical, with consequences for large-scale models of the tectonic evolution and the crustal architecture.
We have undertaken detailed investigation of the metamorphic petrology, zircon geochronology, and geochemistry of HP mafic, ultramafic and associated rocks in Vestranden. Metagabbro and metadolerite that belong *sensu strictu* to the Precambrian orthogneiss complex record high-pressure granulite-facies Caledonian metamorphism. However, other types of mafic rocks occur interfolded with the Precambrian rocks: thick complexes of layered amphibolite with variable amounts of Grt–Bt–Ky paragneiss and subordinate marble and calc-silicate. The origin of these rocks has been unknown, but they also record high-pressure granulite- and amphibolite-facies conditions. Moreover, two km-sized eclogite-facies complexes occur in Roan. One of them, the Kråkfjord complex, is a one km^2 layered intrusion with a basaltic carapace. The core consists of MgAl-rich kyanite eclogite with layers of garnet peridotite and Grt–Opx–Cpx pyroxenite. The carapace is FeTi-rich retro-eclogite with minor Grt–Ky paragneiss.
U–Pb spot dating of composite zircon grains from FeTi-rich eclogite, Grt-Ky paragneiss, and a leucocratic meta-tonalite layer in the Kråkfjord complex (SIMS), and 0.1–0.5 m thick meta-tonalite layers and dykes in banded amphibolite elsewhere in Vestranden (LA–ICP–MS), reveals an Ordovician igneous origin of the tonalitic rocks, and Siluro-Devonian metamorphism of the complexes. Tonalite dykes are absent in the host orthogneiss complex, implying that the amphibolitic and eclogite–peridotite complexes were derived west of this Precambrian continental basement, from the Iapetus ocean, and have been tectonically emplaced into their present positions.
Trace element data (particularly the REEs) from the Kråkfjord FeTi eclogites indicate a MORB affinity. The peridotites, pyroxenites, and kyanite eclogites have significantly lower trace element contents, especially the LREEs. The tholeiitic AFM trend suggests that the rocks are related by fractional crystallization, with the core being cumulate layers. Enrichments in the alkalis, Pb, Sr, U, Th, and Ba suggest interaction with crustal fluids.

Paradigms in provenance and meaningful dates

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The circumstance of deposition of a rock is complex with many interdependent factors: the tectonic setting or type of depositional basin it was formed in; the depositional environment and sedimentary processes that lead to deposition – transportation mechanism and direction, climatic conditions, etc.

These parameters are often difficult to determine in recent rocks, but is even more so in ancient rocks with long, overlapping geological histories that may record more than one depositional cycle, obscuring the original depositional context.
A great deal of our understanding of the evoultion of the Earth's upper crust comes from studying radiogenic isotope ratios, mainly in zircon. The study of detrital zircon populations for provenance and geochronology has become standard practice but the interpretation of resultant data is not, which can lead to misconceptions and misleading conclusions when reconstructing the geological scenario.
From a study of diverse siliciclastic samples collected from various areas associated with SW Gondwana evolution, and spanning the Cambrian divide, a combination of U-Pb and Lu-Hf analysis using LA-ICP-MS was applied to resolve depositional timing and history, as well as crustal evolution in a particular region.
The results presented many challenges and gave significant insight regarding the applicability of detrital zircon dating in establishing provenance and solving certain geological problems.

Early Cretaceous hydrocarbon seep carbonates from Wollaston Forland, Northeast Greenland

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Methane seeps are discrete sites where fluids rich in methane flow onto the seafloor. First discovered in 1984, they are now known from all the World's oceans. Methane seeps support highly unusual biological communities where the primary energy source for these ecosystems is not solar, but reduced chemicals, such as methane and hydrogen sulphide. The current project focuses on methane-derived carbonate bodies in the Kuhnpasset Beds, which are Late Barremian (Early Cretaceous) aged silty mudstones, cropping out on Wollaston Forland, Northeast Greenland (Kelly et al. 2000). The Kuhnpasset Beds contain a sparse mollusk fauna whereas the carbonate bodies contain an unusual faunal assembage dominated by large bivalves, including the lucinid *Cryptolucina kuhnpassetensis,* the modiomorphid *Caspiconcha whithami* and *Solemya*. In addition there are ammonites, belemnites, nautiloids, and abundant driftwood, sometimes bored by the bivalve *Turnus*. Recent field work has revealed that in addition to that published there is a much richer macrofauna, including thyasirid bivalves, scaphopods and a diversity of gastropod species. The carbonate bodies have calcite cemented tube systems, zoned calcite crusts and sparite void fills. The carbonate bodies formed on the seafloor in a mid- to outer shelf situation at the end of a period of extensional rifting on the eastern Greenland passive Atlantic margin. The underlying faults may have acted as migration pathways for methane migration to the seafloor. The source rocks for this methane were probably the underlying Late Jurassic black shales at depths of <600-1200 m. Material from the 2019 field work will be subjected to systematic treatment of the rich macrofossil material, microfacies analysis, as well as micropalaeontological analysis (palynology and foraminiferans). C and O isotope analysis will be performed on the seep carbonates, which will give important information about the sources of the methane. The palaeontological data from the Northeast Greenland seeps will be compared with Upper Jurassic – Lower Cretaceous methane seeps from Svalbard (Hryniewicz et al. 2015a), the Canadian Arctic (Beauchamp & Savard 1992) and Novaya Zemlya (Russian Arctic) (Hryniewicz et al. 2015b), in an integrated taxonomic, palaeobiogeographic and palaeoclimate modelling study.

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3D numerical simulations of continental rifting and breakup

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Observations of rifted margin architecture suggest continental breakup occurs through multiple phases of extension with distinct styles of defor-

mation. A wide body of recent work suggests that these distinct phases of extension in turn produce distinct structural domains, whose first-order characteristics are widely observed globally. However, across a range of length-scales rifted margins do exhibit significant along-strike structural variations, and numerous 2D numerical investigations suggest many of these variations can be explained through changes in the rate of extension and initial lithospheric structure. An alternative explanation is that rifted margin heterogeneity may develop naturally through the complex evolution of fault networks as they transition from distributed to localized deformation. Here, we test both hypotheses using high-resolution 3D thermal-mechanical simulations of continental rifting.

The simulations of continental rifting are run with the open-source and CIG-supported mantle convection and lithospheric deformation code ASPECT, which uses advanced solvers and parallel computing to efficiently solve nonlinear and computationally massive problems. Deformation in the simulations is driven by velocity boundary conditions and the rheological behavior is a combination of non-linear brittle (plastic) and viscous (diffusion and dislocation creep) deformation mechanisms. The results of a wide range of 3D numerical experiments suggest that numerous factors can produce significant along-strike heterogeneity within rifted margins, including fault network evolution, variations in lithospheric structure, fault strength, and structural inheritance. These findings will be discussed within the context of specific rifted margins, global observations, underlying numerical assumptions, and how future studies can build and improve upon current simulations.

TUTORIAL : Introduction to numerical modeling of tectonic processes

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I propose a session that will provide training, including hands on exercises, for modeling mantle convection and lithospheric deformation using the state-of-the-art, CIG-supported code ASPECT. The tutorial will begin with a general overview of relevant numerical methods and best practices for modeling complex, non-linear solid Earth deformation. After the introduction, participants will complete hands-on exercises that examine realistic geophysical problems including mantle convection, subduction and lithospheric extension. The session will conclude with a discussion of the exercises and questions regarding developing future numerical studies. Participants are encouraged to come prepared with ideas and hypothesis potentially suited for numerical investigations. No prior modeling experience is required and all interested student, faculty, professional research and industry attendees are encouraged to apply.

Origin and evolution of the early magmatism in the Oslo Rift (southeast Norway): evidence from multiple generations of clinopyroxene

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Two models have been proposed in order to explain the mantle sources of the magmatism in the Oslo Rift: (i) partial melting due to extension and passive rifting, and (ii) active rifting involving a deep mantle plume. The first model implies that the enriched nature of the Oslo Rift magmatism, e.g., the B1 lavas in the Brunlanes, Skien, Vestfold and Jeløya areas, was the result of partial melting in enriched parts of the sub-continental lithospheric mantle (SCLM), or of interaction between MORB-type asthenospheric melts and enriched SCLM. The second model infers that the enriched character is a primary feature, originating in a deep mantle plume. Resorbed, homogeneous cores of Cr -diopside in zoned clinopyroxene phenocrysts in many B1 basalts give evidence in favor of the second model. The Cr-diopside is strongly depleted in Zr-Hf and Yb-Lu, relative to MREE, and have higher εNd_{300} (≤+6.0) than found in any magmatic rock in the Oslo Rift (≤4.4). The cr-diopside cores and the host basalts must thus originate in different mantle sources. The Cr-diopside cores are overgrown by Cr-poor, concentrically zoned diopside that change into augite towards the rims. Reaction zones along the contacts between Cr-diopside and the overgrowths are common. The concentrations in incompatible trace elements increase from the Cr-diopside, through the Cr-poor diopside, to the outer rims of the augite. The augites are in equilibrium with their host basalts. The Cr-diopside cores are interpreted as xenocrysts originating in depleted SCLM beneath the rift, whereas the Cr-poor diopside and the augite formed from B1 magmas undergoing fractional crystallization, magma mixing and assimilation of crustal melts. The enriched trace element signatures of the B1 magmatism in the Brunlanes, Skien, Vestfold and Jeløya areas are thus primary, as implied by the plume model (ii). This interpretation is supported by high positive ΔNb values (ΔNb =

1.74 + log[Nb/Y] - 1.92 * log[Zr/Y]) in the B1 basalts in the Brunlanes, Skien and Vestfold-Jeløya areas, which is typical of plume-related magmatism. Depleted MORBs and the continental crust have negative ΔNb values.

A palaeobotanical investigation of the uppermost Rhaetian (Upper Triassic) Boserup beds in Norra Albert Quarry, Skåne, Sweden: taphonomical and palaeoenvironmental implications

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The uppermost Rhaetian (Upper Triassic) Boserup beds (basal part of the Helsingborg Member, Höganäs Formation) exposed in the Norra Albert Quarry (Skåne, SW Sweden) comprise numerous horizons with organic debris and rare plant macroremains preserved as sideritized or silicified wood fragments and foliar compressions or impressions. Poorly-preserved cuticle material of gymnosperm plants have also been recovered from two fossiliferous beds. The most abundant macroremains in the Boserup beds are representatives of Ginkgophyta. Nearly all collected foliar specimens are fragmentary, indicating that the plant material either was transported over a significant distance or were destroyed in a high-energy environment before deposition. Only one local, lens-like, accumulation of fossils shows larger plant fragments and some collected fossils contain nearly complete leaves. Preliminary observations suggest that the allochthonous flora from the Boserup beds represents at least two plant communities that developed in a relatively dry/cold habitat located on elevated areas, or around the margins of the rivers that deposited the sediments in which the plant fossils were found. New finds, together with previously reported palynological data, considerably expands our knowledge about the flora content of still poorly know palaeontologically the basalmost part of the Helsingborg Member. The Boserup beds exposed at Norra Albert Quarry represent the latest Rhaetian Ricciisporites-Polypodiisporites palynomorph Zone, which: 1) corresponds to the marine end-Triassic mass extinction interval and 2) occurs just below the Triassic-Jurassic boundary in Skåne.

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Theropod dinosaur fossils from the Gipsdalen and Fleming Fjord formations (Carnian-Norian, Upper Triassic), East Greenland

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The Gipsdalen and Fleming Fjord formations exposed in the eastern part of Greenland contain still poorly known assemblages of early dinosaurs. Here we report several isolated bones and footprints of large- and small-sized dinosaurs from the Kolledalen Member (lower part of the Gipsdalen Fm.) and Malmros Klint Member (middle part of the Fleming Fjord Fm.), which represent the middle Carnian and middle-upper part of Norian respectively. The studied material was collected at MacKnigth Bjerg and Liasryggen area (Jameson Land, Carlsberg Fjord) by the Polish-Danish expedition that took place in 2014. The fragments of bones seem to preserve synapomorphies, which allow us to confidently place them within Theropoda. The most interesting bone material, collected from the so-called "Theropod Mound" at MacKnigth Bjerg, represents a new coelophysoid theropod (possesses several autapomorphies) and suggests presence of relatively large sized theropod in the middle-late Norian of Greenland. The "Theropod Mound" collection includes a part of maxilla, two isolated teeth, two cervical vertebrae, a few fragments of tibia and fibula, several fragments of pubis and ischium, dorsal and caudal vertebrae and other remains. The most informative is distal tibia, which is transversely expanded and is almost identical morphologically and proportionally to that of the large coelophysoids *Liliensternus* from the late Norian-earliest Rhaetian of Germany and *Zupaysaurus* from the Los Colorados Formation (middle-late Norian) in Argentina. These remains represent the first unambiguous theropod dinosaur bones reported from the Upper Triassic of East Greenland, enlarging the meagre record of the group. The recognition of a new coelophysoid dinosaur and other theropod taxa or ichnotaxa further demonstrates the predominantly Late Triassic diversity and widespread geographic distribution across Pangea of the early theropod dinosaurs.

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The early deglaciation of Bjørnafjorden, Western Norway

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The deglaciation of Bjørnafjorden, W-Norway, is revised based on high-resolution TOPAS data and sediment analyses from deep geotechnical borehole samples. Bjørnafjorden is a 595 m deep fjord located near coastal areas of western Norway, ca. 30 km south of Bergen, occupied with up to ca. 75 m of sediment where the stratigraphic units consist of either acoustic transparent or laminated type of deposits. Radiocarbon dates on cold benthic forams (*N. labradoricum*; *Triloculine* sp.) retrieved from one of the lowermost stratigraphic units are dated to 15 190 +/- 40 ^{14}C BP (17 978 cal. age BP). The result of this dating implies that the outer Bjørnafjorden area must have been ice-free at a similar time as the Troll field area in the Norwegian Channel. The stratigraphically younger acoustic laminated sequence, indicating a glaciomarine (plumite) type of depositional environment, is dated to 12 650 +/- 40 ^{14}C BP (13 726 cal. BP), related to the Bølling-Allerød period. The early stage of the Younger Dryas readvance is identified in the high-resolution TOPAS data as an acoustic laminated sequence with high-amplitude reflectors, dated to 11 940 +/- 30 ^{14}C BP (13 389 cal. BP). The Younger Dryas readvance is restricted to Fusafjorden and the inner parts of Bjørnafjorden, where the outline of the Younger Dryas terminal moraines are mapped out. Our study shows that the deglaciation processes in Bjørnafjorden are in accordance with the general reconstruction from Bølling/Allerød and Younger Dryas. However, the deep marine sediment samples collected just above bedrock strongly suggest that the deglaciation of Bjørnafjorden area started 3000 years earlier than previously thought.

Melt formation in the southernmost Finland granite-migmatite belt

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The Paleoproterozoic Svecofennian orogenic domain of Southern Finland consists principally of belts of strongly migmatized infra- and supracrustal rocks in upper amphibolite to granulite facies, with areas of less migmatized rocks in between. The granite-migmatite belts are presumably related to each other. However, the relationship between the formations of the anatectic melts and deformation, and thus the tectonic setting, remains unclear. Especially limited are interpretations of melt formation in the southernmost granite-migmatite belt, which represents the last stages of the Svecofennian orogeny in Finland.
The southernmost granite–migmatite belt is 100 km long and E–W trending in the onshore and archipelago of the Gulf of Finland. Its location on the edge and below the Baltic Sea between Finland, Estonia and Sweden makes it a crucial piece in understanding the tectonic history of the Svecofennian domain.
We have studied melt formation by field observations, geochemistry, and geochronology of the granitic rocks, and by structural analysis of melt pockets (deformation bands). Anatectic melts form an interconnected network (metatexites) and are oriented with prevailing stress conditions. Hence, we can interpret the stress field during the melt formations by studying the orientation of the anatectic melts in the deformation bands.
Based on zircon U-Pb age determinations the granitic rocks can be divided into three major groups, 1.9 Ga, 1.88 Ga and 1.83 Ga, representing pre-accretional volcanism, syn-accretional magmatism and the final crystallization of the granite-migmatite belt, respectively. The structural analysis suggests that during the final crystallization, the anatectic melts in the metatexites were generated during N-S compression. Extraction of the melts formed extensive areas of leucocratic granites, which marks the end of the of the melt flow at 1.83 Ga.

Detailed studies on multi-scale brittle structures in Inkoo, southern Finland

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Fractures and faults create the principal planes of weakness in the bedrock that affect the stability of the underground volumes and also form pathways for groundwater flow. Thus, these structures play an important role in the suitability of bedrock volumes for different underground applications.
The evolution and properties of faults and fracture networks are dependent on the tectonic evolution of the crust but their development is also influenced by major fault zones, lithological properties and ductile precursors. To enhance characteri-

sation procedures and the current understanding of the tectonic development and of brittle structures we have targeted brittle structural geological investigations to areas with exceptionally well-exposed outcrops along the coastline of southern Finland. For these areas, new brittle data is collected at several different scales - regional lineament interpretation on the basis of geophysical and topographic data, fracture trace data based on UAV (Unmanned Aerial Vehicle) photogrammetry and detailed-scale outcrop mappings. The collected data can be analysed for properties such as; orientation, fracture length, intensity and topology, and the influence of e.g. lithological differences can be investigated. The data may also give indication about age relationships between different fracture sets and about the prevailing stress field during their formation. This data can further be used in reconstructing the brittle tectonic evolution of the Precambrian crust of southern Fennoscandia.

The International Continental Drilling Program (ICDP) – status and prospects for Nordic drilling projects

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During the last years, the International Continental Drilling Program (ICDP - https://www.icdp-online.org/profile/) has developed its activities and now includes 21 nations, including Finland, Sweden and Norway, working together in high-profile science projects based on drilling in terrestrial environments. UNESCO serves as a Corporate Affiliate. So far, a large number of planning workshops, and many successful drilling projects have been supported by ICDP.
ICDP has recently decided to professionalize and modernize the program structure. From 2019, each panel is led by a chair and a co-chair, whereas the daily operations are managed by an Executive Director hosted by GFZ Potsdam. There is also a clear ambition to increase the number of member countries, as well as forming closer partnerships with other organizations, especially IODP.
ICDP has also initiated a review of its science plan with the aim to present a revised version for the 25th anniversary of ICDP in 2021. The drilling projects will still contribute to our understanding of issues of great scientific and societal importance, such as environmental changes, geo-hazards, earth resources, and the origin and evolution of life through Earth's history.
Currently, two Nordic projects are approved by ICDP. The COSC-2 drilling project (Collisional Orogeny in the Scandinavian Caledonides) will undertake drilling as a follow-up of the COSC-1 drilling at Åreskutan, which was successfully completed in August 2014. Complemented with the core from the planned COSC-2 project, drill core will become available through many key sections of the Caledonian Nappe stack, immediately east of the Swedish-Norwegian in Trøndelag. ICDP has also decided to support a drilling proposal (DAFNE – Drilling Active Faults in Northern Europe), aiming to intersect and investigate the tectonic and structural nature of a postglacial fault near Kiruna, Sweden. Prominent post-glacial faults are widely distributed in northern Fennoscandia, and given their relatively recent movement history, a better understanding of these fault systems has great scientific and societal relevance.
Using the ICDP infrastructure as a platform, the Nordic earth science community will have an opportunity to develop drilling projects of global importance that will contribute to a better understanding of processes that have shaped the continental crust.

PFOS-sorption in the groundwater fluctuation zone

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Several sites contaminated with PFOS in groundwater aquifers show rapid transport of PFOS locally at the source area, but at greater distances, lower concentrations and transport rates have been documented. Previous work has described sediments showing a higher binding capacity with PFOS where there are air bubbles in the formation pores. The unsaturated zone and the tidal-/groundwater fluctuation zone have more air-filled pores than the constant saturated zone.
Our lab experiments were to find the distribution coefficient of PFOS in pure water-saturated sand, in sand in the groundwater fluctuation zone and in the capillary zone. This was done in three experiments: (1) water-saturated column (water-saturated Kd), (2) column with some pore air in the column (Kd with pore air), and (3) sand-filled glass tank with fluctuating water levels partially filling the tank.
The results of the column experiment under water-saturated conditions (1) gave a PFOS-saturation before two pore volumes of concentrate had flowed through. Calculated distribution coefficient (Kd) for the saturated column based on concentration in the eluate and in the sand masses

was 0.12-0.16 L/kg, with a retardation value of 1.6-1.8.
Even after 6 pore volumes, the column with air/water filled pores (2) had not been saturated with PFOS. Absorbed PFOS gradually increased for each pore volume but the eluate was still below 80% of the concentrate. Hydraulic conductivity had been reduced by bubbles from approx. $6.7x10^{-4}$ m/s in the water-saturated column to approx. $1.7x10^{-4}$ m/s, i.e. four times lower than in the water-saturated column.
Eluate concentrations increased from the glass tank to high levels in the last experiment (3), but never reached full initial concentration, even after 5 months with a continual tidal cycle. The pore-water samples showed the highest concentration in the lysimeter within the upper tidal zone (filter 5.5-11.5 cm), approx. 81% less in the lower filter (2-8 cm) and least in the top filter (capillary zone, 16-21 cm) by 2 orders of magnitude relative to the middle interval. All three elevations showed however concentrations in sand exceeding concentration found in water-saturated column, supporting the hypothesis that soils with air bobbles have a higher Kd than water saturated soils. PFOS-concentration will therefore be higher in the upper groundwater fluctuation zone of the aquifer. This has substantial consequences for PFOS transport and successful remediation actions.

The Seljord Quartzite, Telemark supracrustals, South Norway: A Mesoproterozoic shallow lake in a cratonic basin

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The Seljord Quartzite (Group), being about 5000 m thick and of c. 1200 Ma in age, has excellently preserved ripple marks, desiccation cracks and raindrop imprints, distributed at various stratigraphic levels. Preliminary studies of the quartzite at Tunhovd, in Rødberg and in the Gausta Mountain, together with previously published observations from various localities in Telemark, have revealed that this association of sedimentary structures are common in a wide region defined by the outcrop area of the Seljord Quartzite. The recorded ripple marks in the studied areas are all wave ripples with dominant orientation of crest line within the sector NW-NE (corrected for structural rotation) and with an asymmetry indicating palaeowind direction from west to east. Sedimentary facies, indicating shallow-water to drying-up environments, is present for at least about thousand metres stratigraphic thickness in the Rødberg area. The quartz arenitic composition, large thickness and uniform sedimentary facies indicate that there must have been a delicate balance between rate of weathering, erosion, deposition, and tectonic subsidence, lasting some millions of years with stable semi-arid to semi-humid climatic conditions. The basin of the Seljord Quartzite might have been a continental basin comparable with this type of basins in present Central Asia. The basin may represent a post-rift stage of a large rift basin or, preferentially, a pure cratonic sag basin superimposed onto an older rift basin.

Neoproterozoic gold mineralization in southwestern Ethiopia - A Norwegian-Swedish revisit

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One hundred years ago Christian Thams, the Norwegian industrialist who rebuilt Løkken Mines, became involved in Ethiopia, a near- mythic country that was the supplier of gold and incense to ancient Egypt, the birthplace of *Homo sapiens*, and was also the homeland of coffee. Besides establishing the first brewery in the country, in Addis Abeba, Thams was heavily involved in mining and mineral exploration. His involvement included platinum mining at Yubdo, and gold exploration in the western parts of the country, an area known to have supplied the pharaohs of Egypt with gold.
About 20 years ago, the Geological Survey of Norway continued the legacy of Norwegian involvement within the Ethiopian mineral sector. The Norwegian Survey did extensive field work over a period of 5 years within the context of a capacity building project with the Geological Survey of Ethiopia. Funded and initiated by NORAD, the goal for Ethiopia was to develop a mineral resources sector that would be as self-sufficient as possible. The project, EthioNor, involved extensive work within the Neoproterozoic rocks of western Ethiopia, which included exploration and gold deposit investigation.
Today the Norwegian company Abyssinia Resources Development, (now Norwegian-Swedish Akobo Minerals AB), continuous the Norwegian-Ethiopian legacy, actively exploring for gold and other mineral resources in the southernmost part of the same geological domain. The rocks of interest are part of the Arabian-Nubian Shield, which represents the northernmost segment of the Neoproterozoic East African Orogen.

Our presentation gives an overview of the geology of this highly gold bearing area, including some preliminary zircon U-Pb and Ar-Ar white mica ages from the various gold deposits. At the time of presentation, a Norwegian drilling company, Arctic Drilling, will be core drilling two of the most promising gold deposits.

Middle Triassic syn-tectonic coarse-grained tidal influenced deposits in Svalbard and close to Finnmark Platform; cross-shelf sediment supply fairways

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The Lower and Middle Triassic basin fill in the Barents Sea is dominated by large-scale, northwestward prograding heterolithic shelf margins of very fine to fine-grained immature sandstone and mudstone. These sediments were sourced from the denudation of the Uralian mountain chain to the southeast. In addition, coarser grained and more mature sandstones were sourced from Fennoscandia throughout the Triassic. In the Anisian to Early Ladinian Kobbe Formation these coarser-grained deposits are up to 50 m thick in the Goliat area, and are confined by the Troms Finnmark Fault Complex. These deposits were mainly point-sourced from the Finnmark Platform, and are interpreted as estuarine valley fills representing northwards cross-shelf sediment supply fairways. We suggest that the expanded sedimentary sequence seen in the Goliat area is controlled by tectonic activity, likely controlling the limited extension of the sand fairways.
Coarse grained tidally-influenced deposits are also seen in the southernmost part of Spitsbergen, where a 30m thick massive medium to very coarse-grained sandstone of the Anisian-Ladinian Karentoppen Member is underlain by an Anisian organic-rich marine offshore mudstone and overlain by upper Ladinian highly condensed inner shelf deposits. At Karentoppen, the Karentoppen Member is interpreted as delta front and stacked subtidal dune deposits. The subtidal dunes occur as semi-tabular cross bedded sandstone with set thicknesses up to 1.5 m thick with tangential foresets. The dunes indicate unidirectional paleocurrents to the north east and are suggested to migrate along the axis of a north east trending valley. 20 km to the northwest of Karentoppen, the middle part of this member records decimeter scale tidal dunes of finer grained and well-sorted sandstone. These are bounded below and above by inner shelf storm deposits. Approximately 45km to the north this member passes in 4 to 5 m thick, more isolated sandstone tidal bars. The member becomes progressively shale dominated to the northeast and correlates with the organic-rich Botneheia Formation. Current provenance study (Czarniecka et al.) shows a western source of the Karentoppen Member with evidences of drainage from basement rocks with affinity to Greenland and Arctic Canada.
The proposed Middle Triassic tectonism in the studied areas is suggested to have created localized cross-shelf sediment supply fairways, so that coarse-grained sediments are present only in very specific areas of the Barents Sea. This tectonism could be linked to a Late Permian-Early Triassic rifting episode, located to the western margin of the Barents Shelf and East Greenland.

You learn as long as you drill. Surprising results from the drilling campaign of the Mesozoic in Adventdalen, Svalbard, Norway for possible storage of CO_2 in unconventional reservoirs

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In the years 2007 to 2015 eight wells were drilled and fully cored to test the feasibility of storing CO_2 emitted from the local coal-fuelled power plant in Longyearbyen, Svalbard. The drilling campaign has identified three water-bearing unconventional sandstone reservoirs as aquifers; with the lower and middle aquifers representing potential storage units (reservoirs) for CO_2. While storage units ideally should be high porosity and permeability rocks, we show that fractured sandstones beneath Adventdalen may be clearly defined as unconventional reservoirs. In spite of low-moderate matrix porosity and low matrix permeability, water injection tests have confirmed injectivity and storage capacity. The lower and middle aquifers are characterised by a surprising level of underpressure of 50 bar and are overlain by a c. 400 m thick mudstone-dominated, Middle Jurassic to

Lower Cretaceous succession capped by a slightly over-pressured upper aquifer. The contrasting pressure conditions therefore show that the mudstone dominated succession in between is an efficient top seal for buoyant fluids. An approximately 100 m thick zone of permafrost which includes both bed rock and Late Quaternary marine deposits in the uppermost 70 m towards the present day valley floor also provides an additional seal.

Nearly all disciplines within geology and geophysics have benefited from the data obtained from the Longyearbyen CO2 Lab and, so far, over 70 peer reviewed papers have been published in international journals. Apart from the primary objectives related to characterizing the CO_2 storage and cap rock system, the project resulted in several surprising spin-off results, including:

- An unexpected gravity flow of Hauterivian age in the middle part of the Rurikfjellet Formation. This unit represents the remains of a previously unknown Hauterivian clastic wedge in Svalbard, probably of deltaic origin.
- Biogenic gas was expected and was struck below the permafrost, while a surprising producible thermogenic gas was encountered at 640 to 700 m, probably shale gas.
- Core data and wireline logs from the wells provided new insights into the age and depositional environments of the succession.
- Improved identification of key sequence stratigraphic surfaces which are valid throughout Svalbard and nearby Arctic basins.
- Based on core data an Aptian organic rich marine mudstone (OMM) unit linked to the early Aptian Oceanic Anoxic Event 1a (OAE1a) can now be followed throughout Spitsbergen.
- Well preserved bentonite in middle part of the Helvetiafjellet Formation give an absolute age of 123.3 ± 0.2 Ma, this combined with biostratigraphy question the age of the Barremian-Aptian boundary.

Deep weathering and geomorphology in Mid Norway

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It is generally accepted that southeastern Norway represents a Mesozoic paleosurface that was exhumed during the Cenozoic. Most of the deep weathering products (saprolite) of this Triassic-Jurassic palaeosurface were eroded while the linear weathering extending to large depths is still preserved in fractures and faults. It has also been suggested that the Trondheimfjord and Fosen areas are part of this sub-Cretaceous etch surface (Lidmar-Bergström et al., 1999). In the Coop project (Crustal onshore-offshore project) we have studied remnants of deep weathering in Mid-Norway using digital topography, resistivity profiling, core drilling, XRD, XRF and K-Ar dating. The palaeosurface can be found at an altitude of 200-500 m in the Fosen-Trondheimfjord area and rises to 500-700 m farther inland in the Brungmarka-Hølonda area. The old weathering remnants are characteristically containing smectite and can be found at large depths (>100 m). Weathered coarse-grained magmatic and metamorphic rocks are frequently found in a state of arenisation ("gravel"), while the weathering products of greenstones are usually fine-grained and clay-rich (2-14 wt%). Mica schists disintegrate into splinters and chips (fløssberg) with a low content of clay. K-Ar dating of clay weathering products most frequently yields Jurassic and Triassic ages but Permian and Eocene ages also occur. The weathering is generally youngest at the coast and older in the inland. The saprolite is eroded along the strandflat at the coast and in valleys such as Gauldalen. We interpret these valleys in terms of 'superimposed valleys' similar to the Nittedal and Lågendalen valleys in southern Norway (Reusch, 1902). The course of these rivers was outlined in the palaeotopography in the overlying, soft sedimentary rocks of Mesozoic age. Hence, no deep weathering zones were encountered during the construction of the new road tunnel in Sokndal. Construction of tunnels close to sea level in the Trondheim area has for similar reasons few problems with clay-infected bedrock.

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Estimation of geothermal reservoir quality by diagenesis modelling of the Gassum Formation sandstones

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The effects of mechanical compaction and chemical diagenesis on the porosity and permeability of the Upper Triassic – Lower Jurassic Gassum Formation vary greatly across the Norwegian–Danish Basin due to variations in burial histories and initial mineralogical compositions. Hence, an integrated approach is necessary to estimate the reservoir quality and to establish where the Gassum Formation sandstones are suitable for geothermal energy exploitation prior to drilling campaigns. Diagenesis modelling of the sandstones is conducted for this purpose and the applicability of the modelling approaches in this setting is tested. Results of organic and mineralogical temperature constrains such as vitrinite reflectance, fluid inclusions in quartz cement, and oxygen isotopes in carbonate cement give comparable temperatures that are used to calibrate the basin modelling using PetroMod. Thermodynamic modelling of the mineralogical reactions by SURP provides important knowledge about the conditions for dissolution and precipitation of carbonate minerals, which result in low reservoir quality when pervasive carbonate cement is formed. The Mg availability in the pore water dictates where ankerite can precipitate, and the largest amounts of ankerite cement are able to form when both calcite and siderite are available for dissolution. Integration of petrographic observations, mineralogical compositions, reservoir properties, depositional environments, and burial histories in the calibration of compaction and diagenesis modelling by Touchstone produces results that are in good agreement with test samples and analog data. The calculated quartz cement volumes correlate acceptably with the measured values, showing the reliability of the modelled burial histories given that quartz precipitation is strongly dependent on the temperature evolution. The initial mineralogical composition and grain size distribution vary in relation to depositional environments and sediment source areas. Therefore, individual model scenarios need to consider each of these settings to obtain a detailed estimate of the reservoir properties. In this way, we were able to establish a robust model for estimation of geothermal reservoir quality of the Gassum Formation, which can be used to make pre-drill predictions in light of the burial history and depositional setting for sites of interest.

Shaken, not stirred: Mosaic sand – a semi-liquefaction phenomenon originating from strong earthquakes

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The formation of mosaic sand, here as exemplified from a 0.23 km^2 sand field at the coast of Nordland in Northern Norway, is thought to be related to earthquake induced shaking, re-mobilization and partial (semi-) liquefaction of water-saturated, stratified fine and medium sand. The process may best be described as 'shaken, not stirred', because the individual parts of stratified sands are apparently not totally removed from their original position. The layers are rather broken, fragmented in pieces or ball-like structures, which are deformed, partly rotated and then settled in a complex mosaic mixture. The structure developed resembles those of a dense conglomerate, or as pudding balls (armored sediment balls) cemented by sand. The mosaic sand formations are so far recorded at 19 sites in middle and northern Norway and are thought to originally have been a series of water-lain, shallow marine alternating fine to medium sand layers. Water-saturation during formation likely indicates an environment close to sea-level, and the sites' elevation may thus, where high-resolution sea-level records are available, yield a relative dating method for the associated earthquakes. An implication of occurrences of mosaic sand is that it may record periods of relatively high postglacial seismicity. For example, the presented mosaic sand in Nordland is located, together with several similar sites, in an area with recorded active seismicity today, and future earthquakes of relatively high magnitude in this area should be expected.

Dating of the Stuoragurra Fault at Finnmarksvidda, northern Norway

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The Stuoragurra Fault (SF) is located on Finnmarksvidda, northern Norway, in the northernmost part of the Lapland province of postglacial faults, occurring in large tracts of northern Sweden and northern Finland. The SF is a reverse fault trending SSW–NNE, and it was previously assumed to be a response during rebound after melting of the last inland ice sheet. The SF is separated in three major segments and its total length is 80 km with a c. 20 km wide gap without any apparent faulting in the central part of the fault. The

maximum scarp height is 7 m. The dip is 50–60° implying a maximum reverse displacement of approximately 10 m, which together with the length of the fault indicate an associated earthquake magnitude of 7–8. Trenching across the SF was first performed in 1998 in the southern segment south of Masi, in a location that did not include buried organic materials usable for ^{14}C-dating. The till above the SF was folded forming a blind thrust. New trenchings across the SF were carried out in 2018-2019, this time in three locations (Guovziljohka, Masi, Fitnajohka), one in each of the northern, middle and southern fault segments, where basin sediments with peat and gyttja were supposed to have pre-existed and thus predated the fault event. The trenching at Masi showed gyttja and peat layers, buried and deformed during the main fault event, and ^{14}C-dates of macro plant remains from the buried organics and from the base of the undeformed modern surficial peat indicate an age between 900 and 700 cal years BP of the youngest fault event there. If true, faulting occurred c. 10 ka after deglaciation and is not a direct result of rapid, initial rebound following deglaciation. In addition, ^{14}C datings from Guovziljohka and Fitnajohka indicate that the fault event may have happened at different times in all three fault segments, youngest at Masi and slightly before 1280 cal years BP at Fitnajohka and after 4000 cal years BP at Guovziljohka.

Cenozoic sedimentary environments of the Vesterålen continental margin

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The Cenozoic strata of the Vesterålen continental margin are studied using multi-channel 2D seismic data. The study area encompasses the Loften and Harstad basins and lies along a particularly steep and narrow segment of the Norwegian margin. The early Cenozoic evolution of the margin comprised rifting and opening of the Norwegian-Greenland Sea, which created accommodation space on the continental slope and in the newly formed ocean basin. In the earliest Eocene, igneous processes dominated in the eastern part of the basin, resulting in the deposition of lavas, tuffs and possibly some intrusions, observed as discontinuous high-amplitude seismic reflections.

In the early Eocene to mid-Miocene strata, a chaotic seismic facies on the slope indicates mass wasting activity, while parallel-layered continuous reflections in the basin indicate hemipelagic deposition and/or turbidity currents (unit A). Parts of the basin succession show a mounded onlapping relationship to the underlying sediments, characteristic of contourites. This might suggest that restricted oceanic circulation began in the newly formed basin during the early Cenozoic. Contourite development shifted onto the slope later in the period.

From mid-Miocene, widespread contourite build-up, both on the slope and in the basin, indicate intensified oceanic circulation (unit B). This is likely a result of the opening of the Fram Strait and subsidence of the Greenland-Scotland Ridge, allowing for a fully ventilated Norwegian-Greenland Sea, i.e. with connections to the North Atlantic in the south and the Arctic Ocean in the north. Focused mass transport activity to the basin indicates that canyons on the slope developed shortly after the mid-Miocene.

During the Quaternary, glaciers traversed the shelf forming glacial troughs. Material eroded from ice streams in these troughs was delivered directly into the canyons, which efficiently transported sediments into the basin where they accumulated as submarine fans at the canyon outlets. The slope, thereby acted as a sediment bypass zone. Contourites continued to develop on the slope and in the basin throughout the Quaternary (unit C).

Provenance on the Lange-Lysing megasequences on the Dønna Terrace: stratigraphic variability and lateral sandbody connectivity

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We demonstrate how stratigraphic variability and lateral connectivity of turbiditic megasequences can be identified with provenance research. This is exemplified with a combination of traditional core logging, petrographic and whole-rock geochemical investigations coupled with *in situ* U-Pb and Hf isotope analysis on zircon from Cenomanian to Coniacian-Turonian Lange-Lysing megasequences

on the Dønna Terrace in the Norwegian Sea. The sandstone represents marginal-marine, upper slope, lower slope and basinfloor gross depositional environments. Previously, only single-grain isotope analysis has indicated stratigraphic variability. Porosity data unravels a trend from good to bad reservoir quality from the marginal-marine environment (subarkose petrofacies) towards the basinfloor environment (quartzarenite). The marginal-marine environment shows low recycling and weathering patterns (Th/Sc=0.8 and chemical index of alteration, CIA, is 65), whereas the basinfloor environment has higher Th/Sc (3) and CIA values (90), pointing to a higher degree of recycling and weathering. This points to stratigraphic variability among the different megasequences. The decrease in reservoir quality also defines a lateral connection between the marginal-marine and lower slope environments. For the different megasequences, four main sediment transportation directions from seven provenance regions were deduced by a dominance of zircon ages of 350-1850 Ma, and subordinate 90-300 Ma and 2000-3300 Ma ages in different parts of the system. These ages are in accordance with protosources in the Western Gneiss Region, Lofoten-Vesterålen and the West-Troms Basement Complex on the Norwegian mainland. Subordinate juvenile (positive eHf) Phanerozoic (90-350 Ma) and mature (negative eHf) Archean zircon (2500-3300 Ma) suggest additional protosources in the High Arctic Large Igneous Province, Spitsbergen, and Novaya Zemlya and the Varangerfjord in the Barents Sea. A dominance of negative eHf for the Early Proterozoic and Archean zircon and a lack of Phanerozoic and Late Proterozoic zircon ages in the northwestern part of the study area correspond to protosources in northern Greenland. Thus, the different megasequences are sourced from different but clearly definable areas. Finally, this study emphasizes the importance of incorporating provenance methods, and stresses the use of U-Pb and hafnium isotope analysis to comprehend the stratigraphic variability of complex turbidite systems and to predict their lateral extent.

Detection of hydrothermally extinct seafloor massive sulfide deposits using combined high-resolution imagery and geophysical dataset

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The self-potential (SP) method detects naturally occurring voltages that may result from seafloor massive sulfide deposits (SMS) acting like an electrically conductive body. Recently, the interest in applying this method to explore seafloor massive sulfide deposits in marine environments has increased. To detect active hydrothermal vent sites, we are typically looking for chemical traces produced by a plume in the water column. However, this is not useful for detecting extinct vent fields. The use of AUVs that carry a range of geophysical sensors seems today to be the most promising technique for detecting hydrothermally extinct seafloor massive sulfide deposits. The aim of this study is to use multiple sensors including imagery, acoustic and electro-magnetic datasets to enhance detection and characterization of hydrothermally extinct seafloor massive sulfide deposits. This study is based on a data set collected by AUV's along the Mohns Ridge by K.G. Jebsen Centre for Deep Sea Research and the Norwegian Petroleum Directorate (NPD). These AUV survey data include SAS, magnetic and self-potential measurements from both active and extinct vent fields located at around 73°N.

Emplacement mechanisms and channelised magmatic flow at a high yielding Ediacaran mantle plume: Evidence from the Seiland Igneous Province, N. Norway

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Dyking is a fast mechanism for transferring melts that generates self-organised networks of permeable pathways. The Reinfjord Ultramafic Complex (RUC) comprises a unique deep-section through a mafic-ultramafic intrusion in the Seiland Igneous Province, displaying an exceptionally well-preserved dyke swarm. The dyke swarm from the RUC is essential in understanding how large volumes of sub-alkaline and alkaline melts intruded the lower crust and how these melts changed during ascend to higher crustal levels. The RUC dyke swarm consists of several generations of hornblende-bearing dykes. Mineralogically, the dykes range from diffuse wehrlites, formed by grain-boundary migration of picritic melts intruding the un-consolidated ultramafic cumulates, to late basaltic dykes with sharp margins. The dykes have chaotic cross-cutting relations and in areas constitute up to 50% of the outcrop volume. The textural-, major- and trace-element characteristics of the dykes indicate that they are products of fractional crystallization. Therefore, estimates of melt composition

were obtained from the trace element composition of the minerals. EPMA and LA-ICP-MS data were used in various thermo-barometric calibrations, to answer questions about the PT-conditions of dyke emplacement. Observations indicate that the earliest dykes were emplaced by the migration of picritic melts along grain boundaries, followed by the formation of ductile fractures accommodating pyroxenite forming melts, which finally reaches a critical length that allows for brittle-elastic dyking. The near-ubiquitous presence of dolomite shows that the migrating melt had a significant CO2 component. Dyke emplacement coincides with large-scale CO2 driven deformation, which indicates that the dykes supplied CO2 to this tectonic process. The mineral-chemistry shows that the dykes are formed by enriched mafic-ultramafic melts, comparable to those that initially created the RUC and indicating a mantle reservoir maintaining enriched compositions throughout the formation of the ultramafic complexes. Previously it was interpreted that P increased from 6 to 10 Kb during the formation of RUC. Our studies imply that P was 10 Kb throughout the formation of the RUC and the dyke complex. The gradual consolidation of the central conduit and variable input of melts led to a complex network of dykes that enforced and catalyzed extensional tectonics.

Quaternary pockmark distributions informed by 3D seismic interpretation above the Horda Platform, northern North Sea

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Pockmarks in offshore settings record the expulsion of fluids sourced from the subsurface. The northern North Sea hosts one of the words largest seafloor pockmark fields above the Horda Platform where Troll hydrocarbon fields and prospective CO_2 storage sites are located. Previous workers have used data from multi-beam bathymetry surveys, shallow boreholes, and ocean-bottom sediment samples to better understand the distribution, timing, and potential causative mechanisms related to the seafloor pockmarks directly above Troll East field. It has been proposed that these seafloor pockmarks formed ~10 ka during the latest deglaciation period, possibly by gas expulsion from destabilized methane hydrate paleo-accumulations in underlying strata, but little has been done to characterize the greater affected area or to determine if there were earlier pockmark-forming events. We expand on previous work by using 4,770 km^2 of conventional 3D seismic data to 1) map the regional extent and density of the seafloor pockmarks, and 2) to investigate other potential fluid-escape structures preserved within Quaternary strata below the seafloor. Over 35,000 seafloor pockmarks are interpreted inside the study area, where they abruptly appear and gradually cease from west to east. All mapped seafloor pockmarks lie within the Norwegian Channel, where the highest densities are above the hanging wall of the Tusse fault zone and the Troll West field underneath the regional Quaternary unconformity (URU). More novel is that we have identified a prominent seismic reflector roughly 200 ms below the seafloor hosting more than 2,500 buried pockmarks confined to a thin and discontinuous intra-Quaternary deposit along the eastern side of the study area. Interestingly, the location of seafloor pockmarks seldomly overlap those that are buried, suggesting that the two populations formed during separate expulsion events, although we are currently unable to determine if they formed by the same proposed mechanism. The present arrangement of Quaternary sediments and underlying geologic features correlate with pockmark distributions, demonstrating possible stratigraphic and structural controls on their distribution. Furthermore, while the original source (microbial or thermogenic) of methane thought to have been frozen and expelled from the destabilized paleo-hydrates remains unresolved, we discuss how the pockmark distributions and other observations constrain up-dip paleo-fluid migration routes from possible thermogenic sources and surrounding hydrocarbon fields (e.g. Troll). If the source is indeed thermogenic, evidence of paleo-fluid expulsion through the Quaternary interval has implications towards buoyant fluid flow regionally, as it indicates that deeply sourced fluids have migrated through it over time.

Trap and seal geohistory informed from integrated overburden interpretation, Texas inner shelf

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Characterizing fault and seal potential is imperative for derisking the presence of subsurface hydrocarbon accumulations in faulted siliciclastic reservoirs. Although several notable techniques are often used to evaluate both fault and top seals at

depth, special attention should also be given to features within the overburden sediments. Gas chimneys and deep-rooted faults propagating into the overburden strata above a prospect can imply both local hydrocarbon presence and recent movement along trap-bounding faults, respectively. With regard to trap and seal performance, however, gas chimneys and near-surface faulting also provide important details about geohistory and can indicate that an accumulation may be compromised. Conventional 3D seismic data is often capable of imaging these features, yet high-resolution 3D seismic (HR3D, e.g. P-Cable) and chirp data acquisition allow for more accurate interpretation of the overburden stratigraphy where conventional acoustic datasets may be lacking sufficient fidelity. This study supports the acquisition of nested seismic datasets of variable resolution together with wireline data for inspecting the overburden geology and assessing trap and seal potential. We present local HR3D seismic data that resolves features above a faulted Early Miocene structure with recent slip history along the Texas inner shelf, which are unapparent from available conventional seismic data. Vertical gas chimneys appear to emanate from the trap where wells tested the prospect and were deemed dry, suggesting that hydrocarbons within the Early Miocene reservoir have migrated vertically into the overburden strata. The primary fault bounding the trap (Fault A) is thought to have had significant influence on breaching the containment system, but results from static fill-to-spill, juxtaposition, SGR, and top seal analyses predict that the closure could have withheld gas column heights up to 300 m. Nevertheless, imagery from the HR3D data indicates that Fault A and accessory faults displacing the Early Miocene reservoir have propagated through Late Pleistocene strata near the seafloor, suggesting progressive fault slip may have compromised the trap and seal. Overall, our results demonstrate the potential value of comprehensive overburden interpretation when investigating the geohistory of traps and seals, and the usefulness of high-resolution datasets for reducing uncertainty in exploration.

Arrangement of top and across-fault seal intervals within the Horda Platform: implications towards CCS in Viking Group sandstones

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Effective traps require seals to be vertically and laterally continuous around the hydrocarbon reservoir or CO_2 storage formation. Moreover, traps that require faults to laterally seal the closure must be scrutinized adequately enough to draw confidence in its seal quality. Although useful, techniques for predicting the presence and quality of low-permeability fault membrane seals or fault rocks are speculative. Across-fault juxtaposition seal analysis remains a more simplistic, yet effective means of determining lateral seal presence. Upper Jurassic Viking Group sandstones of the Horda Platform in the northern North Sea contain large quantities of trapped hydrocarbons, particularly within the greater Troll field. The Viking Group also possesses sufficient quality and high CO_2 storage potential along the eastern Horda Platform. This study focuses on the Alpha CO_2 storage prospect within the Smeaheia fault block 5 km east of the Troll East gas field. The trap is a large three-way closure with unproven seals and is bound by the Vette fault zone on its western flank. This structural configuration draws similarity to the adjacent Tusse fault zone, which seals the >200 m Troll East gas column. Equivalent fine-grained Upper Jurassic through Lower Paleogene strata overlie the Alpha and Troll East traps and are also juxtaposed along the bounding Vette and Tusse fault zones, respectively. This relationship provides a useful analogy for CO_2 top and lateral seal quality at Alpha since comparable seals hold hydrocarbons at Troll East. However, thickness changes occur regionally among individual sealing intervals, especially within the Cretaceous growth strata in the hanging walls of the bounding fault zones. We use 3D seismic data and wireline logs to map the distribution of four top and lateral seal intervals between the Tusse and Smeaheia fault blocks in an effort to derisk CO_2 containment within the Alpha closure. Regional thickness maps indicate several areas where individual top seals are absent, while across-fault juxtaposition maps (Allan diagrams) establish the arrangement of top and lateral seals along the Tusse and Vette faults. While a combination the four seal intervals appears to trap the hydrocarbons at Troll East, only the two lowermost intervals would be required to trap CO_2 at Alpha. Overall, if lithological properties are laterally consistent, we find that the possibility of CO_2 leakage at Alpha due to unfavorable top seal or across-fault juxtaposition conditions is low given that similar seals at Troll East are proven.

Tectonic controls on basin styles at rifted continental margins

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From orogenic collapse to continental breakup, syn-rift basin styles depend on the structural and rheological evolution of the lithosphere. We divide the stratigraphy of the Mid-Norwegian margin into successions that record the progressive evolution and migration of crust- and lithospheric scale deformation during the margin evolution. In the proximal margin, stacked syntectonic successions record the transition from orogenic collapse to continental rifting and a range of corresponding basin styles from supradetachment basins to deeply rooted half-graben. Successions related to lithospheric scale necking and subsequent hyper-extension contain both syn- and post-kinematic geometries, consistent with migrating deformation and basin formation. In the necking and distal margin domains, each succession can be sub-divided into a range of basin types that occupy distinct locations in the margin and that record specific processes related to the large-scale tectonic controls. The 3D evolution of basins records lateral variations in tectonic control at the different stages of margin formation, including complex reactivation of previous structures as well as the growth and propagation of large-magnitude extensional faults.

EPOS-Norway WP3: Improved monitoring in the Arctic

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The work package 3 of the EPOS-Norway project aims to improve the monitoring in the Norwegian Arctic. The main tasks of this work are: 1) establish integrated seismic and GNSS monitoring stations on Jan Mayen, in the Nordland area and on Svalbard; 2) establish a seismic array on Bear Island; and 3) collect aeromagnetic data between Svalbard and the Knipovich ridge. The monitoring infrastructure is planned to answer different specific research questions. However, EPOS-Norway being an infrastructure project, the research still needs to be financed through other initiatives. The project has completed four of five years and many of the objectives have been achieved. However, delays in the permission process have resulted in the work on Svalbard to begin in the summer of 2020. The seismic and GNSS data are openly available through the EPOS-Norway portal as well as the common discipline-based ways of sharing data. The aeromagnetic data will be made available in early 2020. The poster will give an overview of the achievements so far and present the plans for the final phase of the project.

Comparisons between multi-scale extractions of fracture networks in south-eastern Finland

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Fracture and lineament traces in the bedrock can be extracted with many different methods and in varying scales. Traces can be mapped from e.g. topographical data, photographic images, geophysical methods and in situ field mapping. All methods have their own constraints, costs, time requirements and inaccuracies and most methods can be employed in varying scales.
A research project at the Geological Survey of Finland was established to develop fracture and lineament extraction methods in different scales. Target areas for such a study of methods requires exceptionally well exposed outcrop surfaces which can in Finland be found on the southern seashores. My study area is in south-eastern Finland within a crystalline rapakivi batholith. This Wiborg rapakivi granite batholith (Haapala, 2005) is a plutonic rock which intruded after the major orogenic events of Southern Finland. Thus, major tectonic ductile deformation is absent. The batholith can overall be considered a very homogeneous rock mass and therefore it is a great study area for testing extraction methods of brittle deformation in different scales. I compared four different extraction scales with each other: Two scales of extraction used LiDAR topographical maps to extract lineaments and the other two used UAV imagery to extract outcrop fractures. Both lineaments and fractures were extracted with similar workflows. Target areas for different scales of extraction varied to acquire representative sample sizes of lineaments and fractures. All extractions were analyzed similarly as traces and fracture networks. Both trace properties such as length and orientation and the topological properties of the fracture networks

(Sanderson and Nixon, 2015) were compared between different scales of extraction.

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Meteor craters re-interpreted as iceberg pits in Härjedalen, Sweden

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Scepticism about the so-called "impact crater" known as the Tor structure, a tourist attraction at Torsbygget, Härjedalen, led to an examination of the area using detailed elevation models. Previous investigations together with old stories about this place have led to the suggestion that this crater was created when a meteor crashed into the Earth surface about 2000 years ago, creating a semi-round depression. The results of our investigation clearly indicate that the feature was formed by a grounded iceberg scouring the bed of an ice-dammed lake during deglaciation.

Using LiDAR-derived elevation data, provided by the Swedish National Land Survey, the geomorphological traces from ice-dammed lakes and grounded icebergs at Torsbygget and its vicinity were mapped.

Geomorphic evidences of an ice-dammed lake are consistent with earlier mapping efforts in the area. Furthermore, an abundance of geomorphological imprints of iceberg activity was mapped inside these paleo-ice-dammed lakes. Based on this we suggest that the depression at Torsbygget is not an impact crater but formed by a grounded iceberg.

These findings show what the environment, with glacier(s) calving into an ice-dammed lake, may have looked like during deglaciation. The crater is a beautiful feature, easily reached by a 200 m walk from the highway, and the fascinating story about deep glacial lakes and floating icebergs will continue to promote this geotourism location – it is well worth a visit.

An assessment of Grindalsmoen Aquifer, Elverum, Norway – Field observations and groundwater modelling

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The water supply of the city of Elverum depends on the waterworks of Grindalsmoen that is based on groundwater extraction. The waterworks is situated at the banks of Glomma river. Due to the high background concentration of iron and manganese, an in-situ treatment (Vyredox) is installed at the waterworks, improving the quality of the water supply. The municipality plans to expand the pumping rate due to the increasing population that will require a better knowledge of the aquifer from where water is being extracted.

The properties and the geometry of the Grindalsmoen phreatic aquifer were studied and a groundwater flow model was developed in MODFLOW. The catchment was manually delineated. Groundwater table and depth to bedrock were defined by using information from wells, geotechnical ground investigations, geological maps and fieldwork observations. Additional constrains are from geophysical data (ERT, GPR and seismic refraction). All the data were gathered in QGIS and were analysed in order to construct a groundwater flow model.

Near surface geophysical surveys and data from geotechnical drillings showed that the sediment thickness of the western part of the catchment ranges between 2-7 m while the thickness close to the Glomma river banks is up to 35 m. Therefore, the upper western part of the catchment was cut and only the eastern part was modeled. The calculated flux from the cut area due to recharge associated with precipitation, was distributed to the western border, with more strength at the northern part, because of the greater amount of water ending to it. The observed groundwater table data were used in PEST for the calibration of the model.

Different scenarios were tested on the model to predict future changes associated to human uses, as well as a possible flux entering from the northern boundary of the catchment. The results showed that during the extraction of groundwater there is a significant amount of recharge from the river Glomma that could have an impact in the chemical properties of groundwater. The flux from the northern boundary appeared to be rather small, because of a small aquifer thickness, and very low gradient.

A synchronous change of mid- to late-Holocene hydroclimate and prehistoric population in coastal East Asia indicated by pollen and XRF data

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A relationship between climate change and prehistoric civilizations is a topic of growing interest. Here, we present a 6,000-year-long pollen and X-ray fluorescence (XRF) data of the core STP18-03 from the southern Korean peninsula, spanning the mid- to late- Holocene. Terrigenous erosion indicators (such as titanium) and tree pollen ratio show synchronous change throughout the period. Relatively low titanium content and high tree pollen percentage indicate wet climate and reduced erosion during ca. 7.8-7.5, 7.0-6.5, and 6.0-4.9 cal ka BP. The opposite trend is found during ca. 8.0-7.8, 6.5-6.0, 4.9-3.0 cal ka BP, reflecting drier climate and subsequent enhanced erosion. The former is coincident with warmer Western Pacific Warm Pool (WPWP) sea surface temperatures (SSTs) and/or reduced El Niño–Southern Oscillation (ENSO) activity, while the latter is with cooler WPWP SSTs and/or enhanced ENSO. This implies that oceanic force was an important factor modulating Holocene hydroclimate in coastal East Asia. Furthermore, sudden increases in erosion indicators occur strikingly at the same time with the dropping points in summed probability distributions (SPD) of archaeological radiocarbon dates, ca. 4.9-4.6, 4.4-4.2, and 4.0-3.7 cal ka BP. Though smaller in amplitude, similar trends are also found at around 5.8, 5.5, 5.3, 5.1, 3.3, 3.1 cal ka BP. These periods coincide with diminished arboreal pollen ratio, supporting that past human societies responded sensitively to hydroclimate changes in the southern Korean peninsula during the Holocene.

Plant mutations and ecosystem disruption induced by toxic metals and climatic warming during the end-Permian extinction

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The investigation of mass extinction events is paramount for understanding the resilience of ecosystems to a range of abiotic stressors, such as climate change and environmental toxicity. Insights gained from such research may provide the means to mitigate the risks of analogous anthropogenically-driven crises in the modern World. At the end of the Permian Period, rapid climatic change and oceanic acidification triggered by Siberian Traps volcanism resulted in the most severe mass extinction in Earth's history. The event culminated in a major biotic crisis in the marine realm, but its impact on terrestrial ecosystems, particularly plant communities, remains poorly known. While a mass extinction in plants at the Permian-Triassic Boundary (PTB) is debatable (e.g. Nowak et al., 2019), there is mounting palynological evidence for mutation among various plant lineages. Recent geochemical studies of several PTB localities globally have revealed an abrupt increase in the levels of various volcanically-derived heavy metals, including As, Co, Hg, and Ni. Despite being well-documented as mutagenic agents among modern plants, their role as potential mutagens during the end-Permian has not been previously assessed. Here we present the results of a high resolution palynological and geochemical study from the PTB in the Norwegian Arctic. Our data shows the transient disruption of plant communities without significant turnover in species or decrease in diversity, consistent with other records from the Boreal Realm (e.g. Schneebeli-Hermann et al., 2017). However, the abrupt appearance and high abundance of aberrant spores and pollen, coinciding with elevated concentrations of As, Co, Hg, and Ni, is interpreted as the first evidence for heavy metal-induced mutagenesis during the EPE. We propose that biomagnification of these elements may have been a significant yet unrecognised driver for the end-Permian biotic crisis.

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Hydrothermal activity and marine mineral deposits in the Norwegian-Greenland Sea

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Twenty years of deep sea exploration and research has revealed the presence of large hydrothermal and hydrogenetic mineral deposits in Norwegian waters and an understanding of the spreading ridge system and the deep sea environments that are hosting them. Presently, eight active hydrothermal venting areas and a large number of active and extinct venting sites have been located at the Arctic Mid-Ocean Ridges that extends from Iceland through the Norwegian-Greenland Sea and into the Polar Basin. The active vent fields that have been visited and sampled range from black smoker vent fields at 2000 to 3000 m water depth to shallow, epithermal systems at 100 m water depth. The character of the hydrothermal activity and the associated mineral deposits varies with depth and tectonic setting, and the sizes range from small, insignificant deposits to large mounds that are several 100 meters across and that contains millions of tons of hydrothermal deposits. As a result of more capable robotics and monitoring technology, and the gradual development of more efficient exploration techniques, our understanding of the active venting areas is now rapidly developing, and we are gradually establishing the knowledge base needed to assess the metal inventory of mineral deposits in the Norwegian-Greenland Sea.

In-situ shaped landscapes in old mountains

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Substantial controversy surrounds the origin and recent evolution of high topography along the passive continental margins that fringe the North Atlantic – particularly for the western Scandinavian margin. An important aspect of this controversy relates to the formation of the margin's characteristic landscape, with deep fjords and intervening high-elevation landscapes of relatively low relief. These high-elevation low-relief landscapes have traditionally been interpreted as remnants of a Mesozoic peneplain, elevated and dissected during several phases of uplift in the Paleogene and especially the Neogene. In this case, the topography in Scandinavia is an old dissected landscape that predates the younger mountains.
Here we focus on an alternative hypothesis for the formation of the high topography and the characteristic landscape elements in western Scandinavia. In essence, this hypothesis suggests that the high topography in western Scandinavia predates the Cenozoic and that the landscape has been shaped continuously, although with renewed intensity in the Quaternary. In this case the topography in Scandinavia is an in-situ shaped landscape that postdates the older mountains.
In this contribution we combine offshore sediment volumes and cosmogenic nuclide data with results from numerical modeling of physical processes, in order to assess the recent Quaternary landscape evolution in Scandinavia and the effects glaciations have had on the pre-Quaternary topography.

CollapsEX- A forward modelling tool for cave collapse

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During the past years paleokarst has been in the focus of the scientific community mainly due to the fact that these relict landforms have the potential to act as major hydrocarbon plays. Paleokarst reservoirs are essentially old caves that are inactive and partially or totally collapsed under the overburden. Forecasting the spatial distribution of these old cave systems is a prerequisite for their prospect evaluation, production planning, and exploitation by the oil industry. In this study, we present a forward modelling tool that can be used to forecast the shape and geometry of a collapsed cave system. To this end, we are using a simple approach where the geometry of cave passages is described by 3D vectors in a cartesian system. The inclination and the direction of the vectors remain unchanged whereas the length of the vector is weighted based on the cross-sectional shape of the cave corridors. Our approach is based on the assumption cross-sectional shape of cave corridors can be used as a proxy for the structural setting under which speleogenesis took place. In order to validate our modelling results we use a cave survey from an active karst system to run our forward

model and compare the model output with field constraints.

The proximal domain of the Mid-Norwegian rifted margin: the Trøndelag Platform revisited

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Standard rifting models often assume homogeneous lithosphere, normal faulting and very moderate amounts of crustal thinning for the first phases of rift-related deformation. This is not representative of the offshore mid Norwegian basement geometries which attest to a profoundly different structural context with a previously underreported deformation phase.
Located along the coast of Norway, the Trøndelag Platform area corresponds to the proximal domain of the Mid Norwegian Vøring rifted margin. We investigated its architecture and structural evolution based on interpretation of a dense network of high-resolution seismic reflection profiles, supplemented by potential field modelling and comparison with local onshore analogues.
The entire area is floored by major basement ductile shearing and regional-scale core complexes. The series of core complexes form a corrugated surface with basement culminations that are flanked and sometimes cut by detachment faults. The latter are sub-segmented suggesting long-lived and complex tectonic activity. The observed geometries are directly comparable to the ones mapped onshore in the Devonian so-called 'Old Red Sandstone' sedimentary basins in western and south-western Norway.
The combination of intensively sheared basement, core complexes, flanking and cutting detachment faults and chaotic to organized stratigraphic filling is interpreted as the offshore record of the last phases of the orogenic collapse and of the first phases of rifting. However, the amount of crustal thinning recorded by these structures exceeds what is normally associated with orogenic collapse as well as the moderate extension commonly assumed for the stretching phase preserved in proximal margins.
The observations highlight the need for a revision of conceptual rifting models. Alternative modes of deformation must be considered, including intense ductile shearing and major detachment faulting, resulting in extensive crustal thinning and thick sedimentary records even very early in the rifting history.

How the use of designated geological conservation values has influenced on the assessment of nature-protected areas according to IUCN standards - an example from a Danish project

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In Denmark an in-depth analysis was made in relation to the IUCN's standard for a specific type of protected nature areas called Conservation Areas (in Danish called *Fredninger*) was carried out for the first time in 2018. The analysis was requested to be carried out by the Danish Minister for Environment and Food on the basis of criticism of parts of the Danish reports to the EU and the UN, reports that provide a status of the overall Danish nature protection. There was a suspicion that the Danish data was not accurate – a suspicion which could apply to a large number of other countries.
This is the first important message to be carried forward here; When we measure on our achievements in accordance to SDG's and Aichi Biodiversity Targets, we need to use the same ruler – otherwise we compare/or add apples and oranges when we measure on how we have achieved our goals on a global scale. I.e. in order to obtain data on how much area we have reserved as protected (nature) areas (PA's) at a global level, we need to use the same measurements on assessment on PA's. IUCN has developed a standard for this.
When we talk about – and measure on – nature conservation/protected areas we often take into account biological values (e.g. habitats and species) where the abiotic values are not particularly included, if at all. In the Danish example, designations of sites of special geological value have been included as an expression of natural values. This is the second important message; to inspire and demonstrate how abiotic values have been used in relation to assessing natural values, an area of

which there is an increased awareness of the importance of – also within IUCN.
At the same time, it is a struck a blow for a systematic application of the IUCN management categories to all established national protected areas.

Equifinality or a unifying theory of drumlin formation? - The Stargard Drumlin Field, NW Poland

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Drumlins are landforms vital to our understanding of ice sheet movement over soft beds, advection of sediment at the ice/bed interface, and the formation of a wide range of subglacial deposits. Although investigated more than any other glacial landform, the origin of drumlins remains contentious leaving some fundamental questions regarding the interaction between ice sheets and their beds open. The Stargard drumlin field is one of the biggest drumlin fields in the North European Lowland - it consists of over 1300 drumlins and related streamlined bedforms nested in the terminal part of a major Weichselian palaeo-ice stream (Hermanowski & Piotrowski 2019, Hermanowski et al. 2019). The drumlins are typically 600-800 m long, 200-250 m wide, 3-6 m high and have elongation ratios of mostly around 2. They are composed of a great variety of either undisturbed or heavily deformed glacial deposits including various types of tills and meltwater sediments. The spatial characteristics of the drumlins are unrelated to the drumlin deposits and the landform surfaces often truncate these deposits suggesting that the drumlin shaping post-dates the deposits inside the drumlins.
Numerical modelling of subglacial groundwater flow during the drumlin-forming ice advance shows a total re-organization of groundwater dynamics to a depth of up to ~200 m. A mosaic of intervening groundwater recharge and discharge areas originates whereby some areas experience multiple shifts in groundwater flow directions. A prominent time- and space-transgressive pressure pump recharges groundwater in a subglacial zone up to about 20 km within the ice margin and releases it in front of the ice sheet. Simulations suggest that the drumlins occur preferentially where groundwater upwells from the bed and discharges at the ice/bed interface.
The proposed drumlin-forming mechanism involves an excess of pressurized water at the ice/bed interface. The drumlin field was likely generated by some combination of direct glacial erosion and erosion by turbulent subglacial meltwater flows removing antecedent material from the inter-drumlin areas and streamlining the resultant bumps. Our data yield support to the quest for a unifying theory of drumlin formation and suggest erosion as the most plausible single mechanism generating drumlin landscapes, which also explains the enigmatic diversity of drumlin deposits and the frequent lack of obvious deposit/landform relationships.

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Emergent and invasive magmatism of the Siberian Traps in a wet forest environment

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The end-Permian Siberian Traps large igneous province is temporally associated with the major extinction event at the Paleozoic-Mesozoic boundary. The extinction was likely triggered by massive eruption of carbon gasses released from metamorphic aureoles around sill complexes in the Tunguska Basin. Additional environmental pollution was likely associated with magma degassing, forest fires, and extensive tuff formation during magma-water interaction. We have been conducting detailed field work in the Norilsk area in northern Siberia since 2006 to study the environment during the initial lava eruptions in the Siberian Traps. The field work included mapping, photogrammetric drone surveying, sampling, and subsequent inorganic geochemical and petrographic analyzes. The sediment-lava transition is particularly well exposed in the Norilsk area. In the Kajerkan quarry, shallow basaltic igneous intrusions were emplacement into the coal-rich upper

part of the Tunguska Group of Late Carboniferous to earliest Permian age. These intrusions are present as tubular, sub-horizontal bodies of c 10 m thickness. The coals have partly been assimilated into the intrusions and have transformed the magma to light-grey graphite-like rocks with abundant breccia fragments. In the Ore Brook and Red Rocks localities, more than ten near-vertical tree trunks have been mapped and sampled in the lowermost lava flow. The tree trunks contain petrified wood of end-Permian age. Pillow lavas are found at the same levels, showing that the lavas were emplaced in a wet environment. However, no pillows are present in the uppermost part of the lava flows. Ropy pahoehoe structures are found at the top of these flows suggesting that the uppermost part of the lava flows were emplaced in a subaerial environment. We propose a model where the eruption of the lowermost lava flow caused damming of local rivers, forming lakes and partly drowning the forest. These shallow lakes were subsequently in-filled by lava during the same eruption. Pillow lavas were formed when the lava entered the lakes, whereas later inflation of the lava flow lead to subaerial emplacement of the uppermost part of the flow unit. The presence of shallow water prevented the burning of the lower part of the tree trunks. Elsewhere, the lava may have intruded unconsolidated sediments, forming invasive flows. This study documents that the Siberian Traps was locally erupted in a wet forest environment and that it caused forest destruction.

Åknes drainage project – An investigation program to evaluate drainage as mitigation at the Åknes rockslide, western Norway

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The Åknes rock slope is located in the county of Møre and Romsdal in western part of Norway. Due to its location above a fjord and potential of creating a large tsunami, it is recognized as one of the most hazardous rock slopes in Norway. It has an estimated unstable volume of 54 million m^3 in the largest scenario.
Åknes is the most investigated unstable rock slope in Norway. The rock slope has 12 cored boreholes totalling 2400 m and extensive geophysics including 11 resistivity profiles and 3 seismic profiles. It is monitored by an automated total station with 30 prisms, rod extensometers, differential GPS, instrumented boreholes, lasers, periodic laser scanning, satellitebased InSAR and a seismic network of geophones.
The movement at Åknes is at present limited to a maximum of 6-10 cm per year. If Åknes was to destabilize further and cause long-term evacuations of thousands of inhabitants and eventually a major landslide it would not only pose a risk to human life but also cause a substantial economic impact. Therefore, an investigation program, started in 2017, aims to answer if drainage of groundwater can stabilize Åknes. The method is implemented with success in several locations including Dutchman's Ridge and Downie Slide in Canada and Mt. de La Saxe in Italy.
The investigation program includes a research project with Schlumberger to build a dynamic 3D model collecting all data from Åknes, requiring special adaptations to their well-tested methods from the oil industry. The Norwegian Geotechnical Institute is analysing the stability of Åknes and the approximate quantity of drainage that needs to be implemented in order to achieve sufficient stabilizing effect. The University of Oslo conducts extensive hydrogeological testing of groundwater and streams, with the aim of building a complete hydrogeological model of Åknes. The project also includes four new boreholes, which have been logged and tested for hydraulic properties, instrumented with multi packer instrumentation from CSG Italy and measured with fiberoptic temperature measurements. Preliminary results from all parts of the project will be presented. The aim of the study is to provide a thorough recommendation if drainage is a viable method of stabilizing the Åknes rockslope.

Untangling transient groundwater mixing and travel times using noble gas time series and numerical modeling

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The quality and quantity of alluvial groundwater in mountainous areas are particularly susceptible to the effects of climate change, as well as increasing pollution from agriculture and urbanization. Understanding groundwater mixing and travel times in such systems is thus crucial to sustain a safe and sufficient water supply. We used a novel combination of real-time, in-situ noble gas analysis to quantify groundwater mixing of recently infiltrated river water (Frw) and regional groundwater, as well as travel times of Frw during a two-month groundwater pumping test carried out at a drinking water well-field in a prealpine valley in Switzerland. Transient groundwater mixing ratios for a pumping well were calculated using the ratio of helium-4 to argon-40 concentrations combined with a Bayesian end-member mixing model. Having identified Frw consequently allowed us to infer its mean travel time to the pumping well estimated based on radon-222 activities. Additionally, we compared and validated our tracer-based estimates of Frw using a calibrated surface water-groundwater model. Our findings observed at the investigated pumping well show that (i) mean travel times of Frw are in the order of two weeks, (ii) during most of the experiment, Frw is substantially high (70%), and (iii) increased groundwater pumping only has a marginal effect on groundwater mixing ratios and travel times. The high groundwater fraction of Frw and its short travel times emphasize the vulnerability of mountainous regions to present and predicted environmental changes.

Multi-scale influence of topography on depositional architecture of long-term transgressive successions (Jurassic, Neuquén Basin, Argentina)

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Shallow-marine successions deposited during long-term transgressions are considered to develop relatively thin and well-sorted deposits. Thick transgressive successions are rarely preserved in the stratigraphic record, although a few examples are described in subsurface and outcrop studies of rift basins.

An outcrop example from the Jurassic of Neuquén Basin (Argentina) is presented here, with the aim to a) refine the model of long-term transgressive deposition in early post-rift settings and b) constrain controls on stratigraphic architecture and lateral facies variability. To do this, a <300 m-thick succession has been studied along a >10 km continuous exposure, with detailed mapping, sedimentary logging and physical correlation of stratigraphic units, integrated with subsurface, biostratigraphic and ichnological data.

The lower part of the succession lies unconformably above syn-rift deposits, and comprises laterally-discontinuous (10's m-long), coarse-grained deposits, dominated by 10's m-thick coarsening-up packages and discrete m-scale erosive conglomeratic lenses, and interpreted as mouth-bars and distributary channel-fills. The rest of the succession shows a retrogradational fining-upward development, with several minor order regressive units. They cover the entire outcrop length (>4.5 km) and thicken southwards, although subsurface data reveals a fault-controlled regional extension. They comprise laterally-continuous (>100's m-long), <1m-thick fine-grained structureless and highly bioturbated tabular muddy sandstones and sandy mudstones, with locally-preserved HCS and bioclastic-rich levels. They are interpreted as storm-dominated lower-shoreface to upper-offshore deposits. Internal characteristics and bed boundaries are diffuse, suggesting recurrent periods of seabed oxygenation and colonization of organisms.

The coarse-grained nature and lithology of the lower succession are consistent with a proximal sediment source, associated with erosion of intrabasinal highs. Its variable thickness, lateral distribution, and marked onlap termination against underlying syn-rift deposits, demonstrates the partial infill of localized higher-accommodation areas. The rest of the succession shows more extensive, well-defined parasequences internally composed of laterally-continuous bedsets, preserving original stacking patterns. However, the vertical thickness variability of parasequences is interpreted to reflect their transgression over a larger-scale ramp-step and underfilled rift topography. The overall good sorting and fine-grained nature of sandstones indicates a mature, distal source of sediment, which was redistributed alongshore by storm/wave-dominated processes, and accumulated in inherited post-rift depocentres, where intensive biogenic reworking was favored.

This study offers new insights in how to interpret transgressive systems based on both primary depositional mechanisms and postdepositional processes, and provides useful tools to understand and predict the nature and potential preservation

of these deposits in limited subsurface datasets, especially in syn-rift to early post-rift transitions.

Master seminar series for geoscience master students: the way to support geoscience graduate students and prepare them for professional employment?

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To write a master thesis is a big undertaking. The geoscience master students at the University of Oslo work on their theses for the better part of 2 years. In that time they are supposed to master and apply skills in the geosciences, but also professional skills such as time management, literature searches, writing and data management, while staying motivated and productive. With the implementation of the InterAct project at the Faculty of Mathematics and Natural Sciences at the University of Oslo, more emphasis has been put on supporting the students in acquiring these professional skills.

The Science Library at Oslo University has a well-established collaboration on education with the Department of Geosciences. Inspired by the InterAct program, a new concept has been developed to support the geoscience students through their masters, the *Master Seminar*.

The *Master Seminar* is a series of seminars that runs parallel with the candidates' master studies over the course of four semesters. The aims of the seminars are to i) support the students in achieving their goals with their master studies ii) develop the candidates' professional competences iii) inspire and support them in carrying out their research, and iv) provide an arena for the students to interact with their peers.

The seminars are built on the philosophy of *active learning* and include hands-on practices, discussions, invited lecturers, social activities, help desks and more. The invited lecturers are drafted from both the academic staff, academic librarians and technical staff.

Subjects that are addressed include literature search, scientific writing, research data management, reference tools, publication, scientific poster design, motivation, master thesis evaluation and more.

The second corner stone of the *Master Seminar* is the *just in time* principle. We believe that the students need to be introduced to (or reacquaint themselves with), and work with, different tools at different stages of their master thesis. This principle is implemented by tailoring the seminars to follow the natural progression of most theses; finding a relevant topic, planning the thesis work, doing background research, managing research data and so on. The seminars are continuously evaluated by the students, and their wishes are used to tailor and modify the seminars.

This presentation will focus on the seminars' goals, set up and content, but also address some of the challenges and student feedback.

(Dis)similarities in the distributions of the shapes of large fresh impact craters on Mercury, Moon and Mars. What can we learn from them?

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The morphology of impact craters on terrestrial planetary bodies have been often generalized as either being simple (bowl-shaped) or complex (broad flat floors, central peaks and terraces) in shape. The transition from simple (craters smaller than approx. 15 km in diameter D on the Moon, characterized by minor collapse) to complex craters (D > 15 km on the Moon, large collapse) D_t depends strongly on a temporary weakening mechanism, the acoustic fluidization [1], and the surface gravity g of the planetary body [2,3]. The transition D_t is gradual, occurs over several kilometers and depends on factors such as the geology (porosity, strength, layering, inhomogeneities), volatile content (presence of ice), impactor properties (diameter and velocity) and the morphometric parameter used to characterize this transition [2-7]. In reality, a large number of crater morphometries falls in between this generalized description of crater shapes, e.g., bowl-shaped with flat floor, central-mound, concentric, conical, flat-bottomed, flat-bottomed with pit and scalloped-walled craters [5,6]. The cratering mechanisms behind the formation of those transitional morphologies and the influence of factors on D_t are yet not well understood [1,8]. In order to fill this gap of knowledge, we here investigate the distributions of five transitional morphologies of relatively large fresh impact craters on Mercury, Moon and Mars, similar to what was done for the Moon in [4]. By conducting this study on several planetary bodies, the influence of: i) impact velocity (increase in averaged impact velocity inward in the Solar System), ii) volatile content (presence of permafrost on Mars) and iii) geology (different geological activity through geological activity) on the impact cratering processes will be able to be studied in detail.

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Petrophysical interpretation of public data indicates deep groundwater potential in Somalia

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Predominantly, hydrogeological studies have been limited to shallow depth characterization due to a lack of technology and resources in the water industry. Depending on the geology, some formations are likely to be saturated with freshwater at depths that could be out of the water industry scope.
To overcome this constraint, a new approach is proposed by taking advantage of the already acquired oil and gas data and, afterwards, apply petrophysics and seismic interpretation towards deeper groundwater resources identification. Seismic profiles allow for better structural modeling while well logs provide information for rock and fluids characterization.
Some arid and semi-arid countries, in which the population is continuously facing a lack of water resources, have been the focus of different oil and gas exploration campaigns. For instance, in Somalia about 80 oil and gas wells have been drilled and, to date more than 40.000 km of seismic lines have been acquired.
Somalia has a total area of 637,657 km2 and an estimated population of 14.7 million. Approximately, 95 % of the total population use shallow groundwater for human and agriculture consumption and only less than 45% have access to safe drinking water. However, demand increases with increasing population, resulting in a drop of the water table that, in most cases, leads to wells to run dry.
According to the oil and gas literature from certain areas of Somalia, a Drill Stem test of the lower Jesoma formation in a well indicated low-salinity water saturation. Since the resistivity profile indicates conductive mud invasion, a positive deflection on the static spontaneous potential in freshwater saturated zones is expected.
Using the available logs and the geothermal gradient of the same well, this study applies the SP method to determine the mud filtrate resistivity from the 18 inches section. Afterwards, using the same SP method, water resistivity from the upper intervals showing a positive SP deflection was calculated assuming that the 18 inches section was drilled with the same mud filtrate salinity.
Results from this study reveal intervals in the Auradu formation with low salinity values. This strengthens previous hydrogeological studies that suggest the Auradu formation to be one of the main water reservoirs based on the water samples analysis of springs and water wells in outcrops from this formation in certain areas of Somalia.

Integration of geological field observations and geophysical data: The El Manzano Sill Complex (Argentina) as a showcase of igneous intrusions emplaced in active petroleum systems

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Igneous intrusions are present in many sedimentary basins with ongoing hydrocarbon production and exploration around the world. Such intrusions may affect all parts of a petroleum system, i.e. charge, migration, reservoir, trap, and seal. A large part of our understanding of such intrusive complexes stems from geophysical studies, especially seismic interpretation studies, as well as field studies. Although the importance of integrated studies has been acknowledged, challenges arise from the scale gap between of seismic and field studies as well as the lack of availability of both types of data from the same study area. Therefore, holistic analogue studies addressing both geological observations on the outcrop scale as well as the geophysical signature of intrusions are very rare.
Here, we present the El Manzano field locality, which allows us to address the issues mentioned above. It includes an extremely well exposed, kilometer-scale sill complex emplaced in organic-rich shale, close to the Río Grande Valley in the northern Neuquén Basin, Argentina. The sill complex is a direct outcrop analogue to subsurface sills acting as oil reservoirs in the Río Grande valley oil fields, only some few kilometers east of El Manzano. To illustrate the physical processes around magmatic intrusions, we present outcrop and well data of thermal maturation aureoles, widespread large bitumen filled fractures interpreted as efficient migration pathways for hydro-

carbons, and sulphide mineralization within the aureoles, likely stemming from hydrothermal fluid circulation. Additionally, we present a seismic modelling study form the same outcrop that illustrates the variability in seismic signature of sill complexes resulting from the effect of these processes on the geophysical rock properties, such as velocity reduction through fracturing. By integrating datasets at different scales addressing different aspects of the system, we are able to create a case study that has high educational value for the understanding of various aspects related to sill complexes emplaced in organic-rich shales.

How do upper secondary students construct a geological time line of their local area?

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This study investigates how upper secondary students in geoscience use field observations from their local area to construct a geological timeline during classroom-based follow-up work. Educational fieldwork in geoscience comprises classroom-based preparation, field activities and follow-up work in the classroom. During follow-up work, students connect observations collected in the field to conceptual frameworks in the discipline. However, few studies investigate students' learning processes during follow-up work. Therefore, we investigated how students use field observations during follow-up work to construct a geological timeline of the area in the school's surroundings.
Data from the students learning processes consist of videos of two small groups during follow-up work, as well as students' written products (e.g., geological timelines). The student learning processes were analysed by three frameworks derived from the literature: scientific practices, argumentations and teacher support.
Findings indicate that both student groups constructed timelines that were consistent with the geological events in the actual area. Asking questions and using evidence found in digital maps or field observations appeared to be critical in the process. The students developed arguments by using principles for relative dating when interpreting their field observations. However, the analysis revealed differences in the students' processes towards the conclusion of a timeline. One of the groups received more teacher support, which influenced the group's concluding geological timeline. The teacher's questions was particularly important. This study provides a window into how students apply field observations and connect them to theory during follow-up work, which can be important for teachers in upper secondary school and university when planning follow-up work after educational fieldwork in geoscience.

Caprock quality of potential CO_2 storage site Smeaheia

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The Smeaheia area is suggested for a potential large-scale CO_2 storage site in the northern North Sea. The area is located east of the Troll field in the Horda platform and is bounded by the Øygarden Fault Complex in the east and the Vette Fault Complexe in the west. The Sognefjord Formation Sandstone is the main reservoir in the area capped by the Draupne and Heather Formation Shales. Failure of these caprocks during injection and post-operation is the major risk of the site besides other factors such as reactivation of faults and juxtaposition of reservoir sandstone in Øygarden Fault with fractured basement. A careful investigation of caprocks can warrant any CO_2 leakage risk.
The caprocks of Draupne and Heather Formations were deposited in a marine environment and consist of dark grey-brown to black, usually non-calcareous, carbonaceous, occasionally fissile claystones. The fractions of brittle and ductile minerals were estimated from XRD, SEM and thin section analysis using core and cutting samples from two exploration wells 32/2-1 and 32/4-1 from the study area. Synthetic Vs logs were predicted for both wells using a machine learning algorithm (random forest) for calculating geomechanical and elastic parameters of Young Modulus (E), Poisson's Ratio (n), MuRho (μr) and lambdaRho (λr). Seal rock brittleness Indices (BIs) were computed using empirical relations based on mineralogy and elastic parameters. Moreover, we performed a comparison between mineralogical- and elastic parameters-based brittleness indices (BIs). The Draupne Formation in the area has a higher percentage of ductile minerals (e.g. clays) than the brittle minerals (e.g. quartz, feldspar & carbonate) compared to the Heather Formation. Moreover, within the same formation, well 32/2-1 has a higher content of ductile minerals than well 32/4-1. Mineralogical brittleness calculations reveal that increase in dolomite as brittle mineral along with quartz does not change the brittleness much due to low dolomite percentage. However, calcite and feldspar increase the brittleness of Heather formation

significantly. According to the mineralogical brittleness results, the caprock in well 32/2-1 shows less ductile while in well 32/4-1, the seal rock properties range from less ductile to less brittle. We observed a significant difference between mineralogy and elastic parameter based brittleness indices. Our results suggest that the assumption of the linear relation between rocks brittleness and elastic parameters is somewhat questionable, and the influence of other factors such as diagenesis, temperature, fluid composition, and tectonic history must be taken into account when evaluating caprocks.

Relationship between magnetotelluric and seismic geophysical observations and mantle viscosity

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An important physical property that can control the motion and dynamics of Earth's lithosphere and asthenosphere is viscosity η (the ratio of stress σ and strain rate έ). Mantle viscosity cannot be measured directly, but can be inferred from strain rate, for example as observed by ground uplift following deglaciation. Empirically, mantle strain rate is mainly controlled by stress, temperature, grain size, and composition (water content and partial melt). The influence of these controlling parameters can be investigated from geophysical observations such as seismicity and magnetotelluric (MT) measurements, which are useful ways to image the subsurface of the Earth, but do not directly constrain viscosity. We aim to establish (mathematical and/or scaling) relationships between the geophysical observations and the aforementioned controlling parameters to get the best possible viscosity estimate. This involves a two-way conversion process from geophysical data to viscosity: (1) the gathered MT sounding is to be converted into composition and temperature by combining the electrical resistivity with the experimental mineral physics data, and seismic data with surface heat flow; then, (2) convert the calculated thermal and compositional structures to a constrained viscosity structure. In each conversion process, we can assess and quantify the involved uncertainties. We expect to decrease uncertainty by jointly interpreting the MT and seismic data, as both are highly sensitive to temperature and partial melt.

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Optimal utilization of groundwater for heating and cooling in Melhus and Elverum – Lessons learned and some recommendations

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The main objective in the research project called *Optimal Utilization of Groundwater for Heating and Cooling in Melhus and Elverum* (2015-2018) in Norway has been to provide a sufficient and sustainable base of knowledge for optimized utilization and management of the aquifer in the two city centers. In addition to mapping of the groundwater and energy potential, the technical knowledge for using groundwater for heating and cooling purposes has increased significantly in every level in the value chain.

Many open loop ground source heat pump (GSHP) systems in the center of Melhus have challenges with clogging of the injection wells due to iron and manganese precipitations, and/or filling of the wells with particles of sand and silt pumped with groundwater. Precipitation of iron and manganese reduce the well capacity, pumps, pipes and heat exchangers. The infiltration capacity is gradually reduced by the filling of well screen part of the infiltration well. The solution to many of these problems are better documentation, maintenance and system design ensuring simple and routinely maintenance. Based on this, some lessons learned and specific recommendations for open loop GSHPs for heating and cooling purposes will be presented.

The Asker 800 m energy wells in Norway with two types of coaxial collector – planning, installation and operation

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The two energy wells at Føyka in Asker close to Oslo Norway are now in operation. The process from the initial idea and planning to operation has been long and given valuable experience for further development and operation of deeper energy wells in crystalline bedrock. The most important aspects of the Asker energy wells are the improved knowledge on deeper drilling in crystalline bedrock and the use of two principle concepts of coaxial collectors (open and closed) and distributed temperature sensing (DTS) in deep boreholes and in ordinary operation.
The project is a demonstration project for geothermal energy and deeper energy wells in Norway financially supported by Enova and Innovasjon Norge, the Norwegian state enterprises for financing the green shift in Norway. The main goal has been to test the potential for profitability of the concept of deeper wells and coaxial collectors in general, and specific as the preferred heating source for the expected real estate development of the Føyka area in Asker. Asker municipality is the project owner with the project partners Båsum boring AS and Asplan Viak AS, drilling and ground source heat pump consultant, respectively.
Originally, a closed coaxial collector was planned, but installation challenges and leakage issues changed the collector for the second borehole to an open coaxial collector with a submersible pump in the borehole. Ground water is the circulating medium, and coaxial collectors were necessary to keep the pressure drop low. Two fiber optical cables for DTS-measurements are installed in the center pipe (upwards) and annulus (downwards flow direction) in the borehole with closed collector. Differences in the operation experiences for both collector types are compared. The energy wells supply a 100 kW heat pump for heating the soccer field at Føyka. Results from planning and design process as well as installation, testing and operation will be presented from this unique cooperative project in Asker Norway.

Thorium – the national element of Norway. Communicating the 1828 discovery in Gea Norvegica UNESCO Global Geopark.

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The Periodic Table was celebrating its 150 years anniversary in 2019 and in connection to the celebration Thorium was elected as the national element of Norway. The element was discovered in Gea Norvegica UNESCO Global Geopark and the geopark is using the opportunity to establish a new geosite in Porsgrunn municipality.
In 1828 a brownish mineral was found on a small island outside the town Brevik. The brownish crystal was found by a priest, Morten Thrane Esmark. He was son of Norwegian geologist and mineralogist Jens Esmark and together these two decided to send this for them new mineral to the Swedish chemist J.J. Berzelius.
Not only was the tiny brown crystal proven to be a new mineral, it was also containing a new element. Berzelius named the mineral thorite and the new element was called thorium. Both names were given as an honor to the Nordic god Thor.
The small island Løvøya is close to the border of the Permian Oslo Rift volcanic province. This area is well known among mineralogists as the Langesund Fiord mineral province, an area famous for the richness of different minerals. Several minerals are found for the first time here, some are even found exclusively in the area. The rocks are mainly larvikites and nepheline syenites.
The hosting rock, a nepheline syenite pegmatite is a very typical occurrence in the surroundings of Løvøya. Several of the pegmatites in the vicinity bear evidence of an intensive hunt for the newly found brown treasure – the thorite containing thorium. In the late 1890ties something like a Klondike situation developed, since thorium showed to be valuable for the improvements of gas lamps. The introduction of electricity brought the mineral hunt to an abrupt stop. Today the interest for the radioactive element thorium is growing, due to the research for a possibly “cleaner” atomic energy production.
The planned geosite will be aimed towards local population and visitors, with a mix of geoscience information, history and myths in different panels. The island is accessible by private boats and a seasonal ferry and is an exotic, new locality in our geopark, developed in cooperation with the municipality of Porsgrunn and the local branch of Norwegian Chemical Society.

Geochemistry of the hydrothermal systems of the Askja and Kverkfjöll volcanoes, Iceland

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We present preliminary gas and water chemistry data for a sample set collected between 2017-2019 at hot springs and fumaroles from the Askja and Kverkfjöll volcanoes, located in the Northern Rift Zone of Iceland. The aim of the study is to understand the geochemical characteristics and hydrogeology of these rarely visited volcanic hydrothermal systems.

The geothermal activity at Askja is mostly restricted to a caldera that formed following a VEI-5 eruption in 1875 and today hosts Lake Öskjuvatn, a 217 m deep caldera lake covering an area of 10.7 km^2. The fumarole discharge at Askja is among the most gas-rich in Iceland (i.e., the proportion of non-H_2O gases is > 3 mol.%) with high CO_2/CH_4 ratios (7000-35000). High SO_4^{2-} contents (> 400 ppm) in Lake Öskjuvatn water suggest a considerable input of H_2S from fumaroles on the lake bottom. A vigorous geothermal system at Kverkfjöll is manifested on the surface as: (1) the high-altitude (1550-1700 m.a.s.l), vapour-dominated geothermal area Hveradalur, with relatively wet fumarole discharge, at 98-99.5 mol.% H_2O and intermediate CO_2/CH_4 ratios (400-4000), and (2) two thermal rivers - Volga (up to 24°C) and Hveragil (up to 60 °C) that flow out of the mountain at about 1000 m.a.s.l. The Hveragil water is alkaline (pH up to 8.9) with low SO_4^{2-} contents (17-44 ppm) and high ΣCO_2 (up to 583 ppm), likely representing variable mixing between non-thermal water and boiled deep geothermal reservoir fluid with a temperature of 300 ° C, estimated with a silica-enthalpy mixing model.

We propose a conceptual hydrogeological model where the steep topographic gradient at Kverkfjöll facilitates the separation of a rising one-phase reservoir fluid into a gas phase that rises through caldera faults to exit at high elevation, and a liquid fraction that flows out laterally to the two hot rivers Hveragil and Volga at lower elevation. In contrast, the topography surrounding the geothermal upflow zone at Askja is relatively flat, preventing the boiled reservoir water discharge to the surface, which results in the observed acid-sulfate springs and fumarolic activity.

In the next phase of the project, we will use major element data in conjunction with isotopic data of the fluids (δD, $^3He/^4He$, $\delta^{13}C$, $\delta^{18}O$, $\delta^{33,34,36}S$) with the ultimate goal of identifying the shallow and deep sources of volatiles, and to constrain and relate the contribution of hydrothermal systems in Iceland to the volatile fluxes between different Earth reservoirs.

Reconstructing Fennoscandian paleo-environments during the two last glacial -interglacial cycles: Does sequence stratigraphic approach help?

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The development of Fennoscandian paleoenvironments during the Saalian and Weichselian glacial cycles must be reconstructed from regionally restricted, isolated glacial and interglacial deposits. The situation is different to marine basins, where sequence stratigraphy has mainly been applied and where base level changes control the accommodation. In Fennoscandia we have a more complicated system with regionally much varying subglacial, proglacial or interglacial erosional and depositional history. This has led to a relatively thin depositional record, which is also spatially differentiated in age and origin. In this type of depositional record, we have to look carefully on the lithofacies associations, depositional trends, nature of unconformities and include all available micro- and macrofossil data to be able to give the best possible sequence stratigraphic interpretation of the different systems tracts and glacial sequences (cf. Corner 2006, Räsänen et al. 2015). In the presentation, examples are given from several field localities in Finland and Sweden, where the sequence stratigraphic interpretation of the origin and age of the strata differs from the earlier published interpretations. The new results raise the question; how much we can thrust on the sequence stratigraphic interpretations? These are based on the repeatedly in many localities occurring depositional trends in certain systems tracts or should we thrust more on the radiocarbon- and OSL-dates, which are often in conflict with the sequence stratigraphic results.

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The northward tilt of the Icelandic plume as traced by olivine chemistry

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Basalts erupted in Iceland have geochemical characteristics, which reflect mantle-source heterogeneity. However, the cause and characteristics of the heterogeneity remains unsure. High-forsteritic olivine (high Mg to Fe ratio) is an ideal proxy for primary source characteristics and several studies have used the minor- and trace element composition of olivine to evaluate mantle heterogeneity in Iceland (e.g., Sobolev *et al.*, 2007; Nikkola *et al*., 2019). However, these studies lack regional coverage which limits the spatial resolution. We present a study of 53 samples of high-forsterite olivine from the neovolcanic rift and flank zones, as well as Tertiary crust in Iceland. Using high-precision *in-situ* methods to measure their minor and trace elemental compositions we find, that the source feeding the neovolcanic rift zones, along with the off-rift regions; Öræfajökull and Snæfellsness, are dominated by peridotitic melting. Signs of melting from a more pyroxenite-like lithology (resulting from the incorporation of a subducted oceanic crust at depth) are captured in olivine from South Iceland. The trace elemental results are furthermore combined with previously published $^{3}He/^{4}He$ analysis for the same set of samples which show, that olivine with low Mn/Fe and high Ga/Sc values, indicative of a more pyroxenite-dominated source lithology, is characterised by high $^{3}He/^{4}He$. High $^{3}He/^{4}He$ is also found in peridotitic-derived olivine. Because $^{3}He/^{4}He>8R_A$ (where $1R_A$=air) is a primordial plume-source feature, this suggests, that the Icelandic plume is lithological heterogenous.
The presence of a high $^{3}He/^{4}He$ plume in central and South Iceland with pyroxenitic-like melts constrained to the south is best explained by a northward tilt of the Icelandic plume stem which has previously been advocated based on geophysical studies. A similar tilting plume-model has been suggested for Hawaii, implying that the plume geometry might be a common controlling factor for the preferential tapping of lithological heterogeneous source components beneath ocean islands.

Tracing the final deglaciation of the Scandinavian Ice Sheet - ice-dammed lakes and a catastrophic flood

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We present geomorphological evidence of large early Holocene ice-dammed lakes in the northern Scandinavian Mountains. The lakes extent indicate that the last remnants of the Scandinavian Ice Sheet were located east of the mountain range, in contrast with the prevailing view of final deglaciation in the higher mountains. Our results indicate that a larger system of ice-dammed lakes existed in this region than previously thought. The lakes were dammed between the main water divide to the west and the retreating ice sheet margin to the east. Further, we have compiled Lateglacial and Holocene shoreline data along the Norwegian coast and from within the Baltic Sea basin and reconstructed the isostatic uplift along a 1400 km long northwest-southeast transect from the Norwegian Sea to Lake Ladoga. By comparing the measured ice-dammed lake shoreline gradients to previously dated marine shorelines, we infer that they formed shortly following 10.2 cal ka BP. We also describe large deposits and extensive erosive features, which demonstrate that a catastrophic glacial lake outburst flood took place eastward along the Pite River Valley. Based on cross-cutting relations to raised shorelines developed in the early Holocene Ancylus Lake (Baltic Sea basin) we conclude that the flood and thus the final phase of deglaciation took place within the time interval 10.3-9.9 cal ka BP.

Skåne - a geological boundary region and (hopefully) a future UNESCO Geopark

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Skåne is the southernmost county in Sweden. It is of medium size in the Swedish context, but houses over 1 million people and is the most densely populated county in Sweden together with the Stockholm and Uppsala regions.
The geodiversity in Skåne on the other hand, is unprecedented in Sweden. Straddling the Tornquist zone the area has experienced a long and comparably young geological evolution. The first protoliths were formed ~1.7 Ga ago in an Andean margin setting together with most of the rest of Sweden. A second event of active margin magmatism formed the eastern parts of Skåne around 1.45 Ga ago and a continent-continent collision at around 1 Ga subjected the western parts of Skåne to high-grade metamorphism and deformation. The Paleozoic was characterized by sedimentation and incipient block movements. A soft docking event with Avalonia in Ordovician times left only faint, but never the less important marks in the geological record. Mesozoic deposits are rare in Scandinavia, but Skåne has an almost uninterrupted record from the Triassic to the Cretaceous,

from dry deserts deposits to anthracite seams harboring lush forests and dinosaur tracks. The aftermath of climatic conditions during this period have had an immense influence on many different aspects much later in Skåne history. Tectonic movement along the Tornquist zone have resulted in a plethora of fault related phenomena including large scale breccia formation and volcanism, whereas recent converging ice-sheets resulted in unique depositional environments during the last Ice Age.
The geology of Skåne have also been a plentiful resource for people inhabiting this part of the country, yielding a rich geocultural heritage. All this is the fundament of an initiative to establish a UNESCO Geopark in Skåne. A brief resumé of the Skåne geotourism case history up to this point will be given.

Pockmarks within a stratigraphic framework from the Witch Ground Basin, central North Sea

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One manifestation of focused fluid migration at the seafloor are circular to semi-circular depressions known as pockmarks, which form in response to vigorous venting of fluids from the seafloor. Here, we use 2-D and 3-D seismic reflection, multibeam bathymetric and sedimentological data to map and describe pockmarks in the Witch Ground Basin (central North Sea) and characterize associated sedimentological and fluid migration structures. More than 1500 pockmarks of two distinct morphological classes spread over an area of 225 km². Large pockmarks (> 6 m deep, > 250 m long, and > 75 m wide), show active venting, and are located above vertical fluid conduits that hydraulically connect the seafloor with deep methane sources. Smaller pockmarks (0.9-3.1 m deep, 26-140 m long, and 14-57 m wide) are limited to the soft, fine-grained sediments of the Witch Ground Formation. The larger pockmarks are sourced by biogenic methane through seismic pipe structures which hydraulically connect deeper strata with the surface. The smaller pockmarks are independently formed by another source of fluids. Paleo-pockmarks within the Witch Ground Formation document distinct phases of pockmark formation, likely triggered by externally-induced pressure and temperature changes.

Pervasive cold ice within a temperate glacier – implications for glacier thermal regimes, sediment transport and foreland geomorphology

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Ground penetrating radar data indicates that cold-ice processes at the temperate glacier Midtdalsbreen, an outlet of the Hardangerjøkulen icefield (Norway), may be more widespread than previously assumed. Results show a 40 m wide cold-ice zone within the majority of the glacier snout. We interpret ice to be cold-based across this zone, consistent with basal freeze-on processes involved in the deposition of moraines. We also find at least two zones of cold ice within the ablation area, occasionally extending to the glacier bed. There are two further zones of cold ice in the accumulation area, also extending to the glacier bed. Cold-ice zones in the ablation area tend to correspond to areas of the glacier that are covered by late-lying seasonal snow patches that reoccur over multiple years. Subglacial topography and the location of the freezing isotherm within the glacier and underlying subglacial strata likely influence the transport and supply of supraglacial debris. The glacier margin contains several landforms and associated sediments that relate to a process-form continuum caused by concentrated supraglacial debris, leading to the formation of controlled moraines and subsequent de-icing of these controlled moraines into hummocky moraine. With predicted continued warming in future decades, areas of cold ice may decrease due to reduced or disappearing late-lying seasonal snow patches. Conversely, continued thinning of the icefield and its outlet glaciers and probable reduction in ice flow velocity, as well as glacier retreat to higher altitudes, may promote more widespread cold ice and processes such as basal freeze-on in the short

to medium term at least. The most striking implication of this study is the possibility that temperate environments with primarily temperate glaciers could become polythermal, similarly to recently reported high-Arctic glaciers transitioning from polythermal to entirely cold-based.

Revising the national curriculum for Geoscience specialization in Upper secondary school in Norway

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This presentation describes the revision of the national curriculum for optional geoscience specialization in upper secondary school in Norway – Geoscience X, Geoscience 1 and Geoscience 2. The background is the new national curriculum reform for Grades 1-13, called Kunnskapsløftet 2020, which involves revising and renewing the reform Kunnskapsløftet 2006. As stated by the Norwegian education authorities, the new curriculum comprises the following components: relevance of the subject, connection to core curriculum values, contribution to transdisciplinary topics (sustainable development, democracy, and public health), literacy, core elements, competence goals, and formative and summative assessment. In this presentation, we describe the first draft of the new geoscience curriculum published by the authorities in November 2019, focusing on the relevance of the subject, core elements, i.e., the most important parts of the geoscience subject that students should learn, and literacy, i.e., reading, writing, verbal skills, mathematical thinking and use of digital resources. We also discuss how the curriculum draft aligns with geoscience topics in other subjects, such as General science in Grade 1-11 and Geography in Grade 11. The new curriculum for geoscience specialization will be implemented in schools from the school year 2021/2022.

Murtoo – geomorphometry, associated landforms, positioning, and cross-cutting relationships

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Recently a new, roughly triangular, mesoscale glacial landform called “murtoo” was discovered during LiDAR surveys in Sweden and Finland. By using a LiDAR-based digital elevation model to identify and describe murtoos, their morphometry and the landscape in which they are situated, we characterized this newfound landform and provide a statistical basis for future research. The perimeter of 35 murtoo fields and 1465 individual landforms were mapped. Three axes of the individual murtoos were mapped as well: the l-axis (from the apex to the break of the slope), the a-axis (from the end of the l-axis along the natural elongation of the landform), and the b-axis (perpendicular the a-axis, at the widest part of the landform). The l-axis lengths were found on average to be 6–12 meters, with slopes varying between 19° and 33°. For the a -axis, on average lengths varied between 10 and 75 meters with 4°–9° slopes, and the b-axis lengths varied between 28 and 84 meters with 5°–12° slopes. Murtoos were observed in two main landscape positions (valley settings and flat landscapes) and in geographic association with subglacial and glaciofluvial landforms. The most frequent cross-cutting relationships observed in this study are that between ribbed moraine and murtoos and drumlinization of the murtoo field. Murtoo orientations parallel to the local ice flow direction with general but slight deviations was also observed. These findings support a subglacial, in-part fluvial formation setting for murtoos, and indicates a relationship between the orientation and meltwater flow direction. Studying the morphometric properties of murtoos together with their geographic distribution may serve to propel research in multiple fields forward. In addition to being of interest for geologists, murtoos and their provenance could prove relevant for glaciologists, hydrologists, and climatologists.

Tidal effect on pressure in upper and lower aquifer of the Svelvik Ridge

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CO_2 emissions must decrease to ensure global temperature staying below two degrees by 2100. Carbon capture and storage (CCS) will likely become a necessary climate mitigation measure. Between 2009 and 2013 a small-scale CO_2 field laboratory was established in Svelvik, Norway, which has been upgraded in summer 2019. Injection experiments are conducted to test and improve CCS monitoring methods.

The objective of our study, funded by the UiO:-Energi summer programme, the ICO2P project and ECCSEL Svelvik CO_2 Field Lab, is to investigate pressure responses in upper and lower parts of a stacked aquifer system. The Svelvik ridge comprises unconsolidated, Quaternary sand deposits. The uppermost part holds a fresh water, unconfined aquifer, while lower strata comprise stacked, saline aquifers in hydraulic connection with seawater.

We have investigated and compared the tidal pressure response in the upper and lower aquifers, using data from two wells (6.5 and 64-65 m depth), i.e. time series of P, T from submerged loggers. The data set from Svelvik CO_2 Field Lab represents natural background variations before CO_2 injection starts in October. We used Fast Fourier Transformation to analyse the frequency spectrum of the pressure data and compared these to tidal data from Kartverket. We find the deep saltwater aquifer to be in strong communication with the Drammensfjord. The tidally-induced pressure response in lower aquifer is delayed by 1.4 hours. The shallow freshwater aquifer is almost insensitive to the tidal forcing.

Continued monitoring will allow us to analyse the aquifers' reaction to water and CO_2 injection during fall 2019. Improved understanding of aquifer boundary conditions, connectivity and pressure response is essential to ensure CO_2 containment and reduce risks of CO_2 storage reservoirs.

The formation of clay-poor regoliths (grus) from granites in the Sila Mountains, Calabria, Italy.

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The storage of hydrocarbons in weathered and fractured crystalline rocks is a relatively new play concept on the Norwegian Continental Shelf. The recent discoveries by Lundin Norway and partners at the Utsira High in the Rolvsnes, Goddo and Tellus prospects have established the commercial potential of basement reservoirs.

When crystalline rocks are exposed at the surface of the Earth, fractures and joints will allow the infiltration of rainwater and plant roots into the rock. Biochemical reactions between the percolating fluids, the rock, fauna and flora may dissolve the primary minerals and replace them with new mineral phases. The result is a weathered material (regolith) that differs in composition and physical properties from the original and unweathered parent rock.

Recent studies from the Utsira High have shown that the reservoir potential is impaired in clay rich regoliths, as clays clogs pores and fractures. The best reservoir properties have been observed in clay-poor regoliths, so-called grus. The properties of the regolith is to a large degree controlled by the prevailing climate under which the regolith formed.

As an analog to the Utsira High weathering sections, we have studied weathering of granitoids under a Mediterranean type of climate in the Sila Massif, Calabria region of southern Italy. The metamorphic and plutonic terranes of the Sila Massif consist of rocks of Paleozoic intrusive and metamorphic rocks, locally with an unmetamorphized Mesozoic sedimentary cover.

The studied profile represented a ~35 m thick profile demonstrating the process of complete disintegration of a coarse-grained, two-mica, granite that displayed an upwards increase in degree of alteration, culminating in an interval of about 2 m grus and 0.6 m soil cover. Compared to the unweathered granite, the plagioclase/(plagioclase+quartz) ratio in the grus had been reduced by 50%, resulting in a clay content of about 5% kaolinite of the total rock. Furthermore, the vermiculization of biotite resulted in a volumetric expansion of biotite that probably was contributing to the disintegration of the rock during weathering. The chemical index of alteration (CIA) increased from around 55 to 60, suggesting intermediate degrees of chemical weathering. Density estimations indicated a reduction from around 2.66 g/cm^3 to 1.61 g/cm^3 and thin section analysis demonstrated an increase in well-connected porosity from negligible in the fresh rock to around 30-40% in the grus. Together, the analyses showed that weathering in the Sila Mountains produced a highly porous and permeable regolith with excellent capacity to store fluids.

Textural and chemical characterization of sulphide minerals for improved beneficiation and exploration at the Rävliden Norra VMS deposit, Skellefte district, Sweden

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The Rävliden Norra VMS deposit, represents one of the most important new discoveries in the Skellefte district (SD) in this decade. The mineralization is hosted at the transition between Skellefte group rocks (SG), dominated by coherent rhyolitic and dacitic meta-volcanic rocks, and the Vargfors group (VG), composed of metasedimentary graphitic shale interbedded with crystal-rich, monomictic to polymictic, clast-supported mass flow deposits. The ore lenses contain massive sphalerite + galena + pyrite + pyrrhotite + chalcopyrite ± Ag-Sb-Pb-sulphosalts, structurally and stratigraphically above chalcopyrite + pyrrhotite stringer mineralization. The hanging wall rocks (VG) host pyrite + pyrrhotite ± arsenopyrite mineralization. Alteration in the footwall rocks, consists of sericite, chlorite, quartz, pyrite, tremolite, actinolite, carbonate and talc. The hanging wall is less altered with limited sericite or chlorite associated with minor carbonate alteration. Post ore modifications occur as, e.g. sulphides in pressure shadows, infilling of syntectonic tension gashes, "durchbewegung" texture, and sulphide-rich veins that crosscut hanging wall rocks. Significant changes in the distribution and deportment of trace and precious elements within the deposit are evident, however the implications of these on mineral processing performance and exploration vectoring has not previously been assessed in other VMS deposits in the SD. To this end, the presence of pyrite and remobilised sulphides in both hanging wall and footwall of the Rävliden Norra mineralizations, provides an opportunity to evaluate enrichment or depletion of elements hosted in the sulphide lattices or as inclusions using LA-ICP-MS. In-situ SIMS analyses in sulphide phases will allow discrimination between sedimentary and hydrothermal sulphur in the system. An investigation into the deportment of In, Ga and Ge in sphalerite and galena, will be the first assessment of these critical elements in a VMS deposit in the SD. Ultimately, integration of elemental distribution and mineral features, such as modal mineralogy, liberation degree, and grain size, with processing variables, e.g. mineral recovery, grade or flotation kinetics; will provide a better understanding of the ore performance during concentration and beneficiation.

Early Holocene establishment of the Barents Sea Arctic front

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A main feature of the Barents Sea oceanography is the Arctic front. The Arctic front marks the transition between the dominating water masses of the Barents Sea: Atlantic Water in the south and Arctic Water in the north. Presently, the Barents Sea Arctic front is directed by the topography of the Bear Island Trough and to some degree the location of the sea ice boundary. During the last glacial maximum, the Svalbard-Barents Sea and Scandinavian Ice Sheets covered the Barents Sea. Hence, no water entered the Barents Sea, neither from the south nor from the north. Following the deglaciation of the Barents Sea, the present-day ocean circulation developed. The evolution of how the present location of the Barents Sea Arctic front established during the early Holocene is documented by foraminiferal relative assemblage data from six core sites along the western Barents Sea margin and opening. The relative abundance of Arctic front indicator *Turborotalita quinqueloba*, in combination with the cold, polar *Neogloboquadrina pachyderma* and warm, Atlantic *Neogloboquadrina incompta*, are used to infer the location of the Barents Sea Arctic front relative to the individual core sites. Until ca. 11 ka BP, the Barents Sea Arctic front followed the western margin of the Barents Sea. All sites along the Barents Sea margin where still dominated by Arctic Water between ca. 11 and 10.2 ka BP, however, the Barents Sea Arctic front turned eastwards into the southwestern Barents Sea. From ca. 10.2 to 8.8 ka BP, the Barents Sea Arctic front moved eastward and was located right above most sites as it followed the Barents Sea margin. The northwestern Barents Sea Arctic front was close to the present location from ca. 8.8 to 7.4 ka BP, however, it was still confined to the southwestern Barents Sea. From ca. 7.4 ka BP, the Barents Sea Arctic front has been located close to the present position, along the margin southwards from Svalbard, turning eastwards along and beyond the northern Bear Island Trough margin.

The Early Triassic 'Grippia' bone bed of Spitsbergen and its implications for taxonomy and palaeobiogeography of vertebrates after the P-T extinction event

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Five expeditions to Flowerdalen in central Spitsbergen have resulted in the discovery and excavation of several tonnes of bone bed material from the Early Triassic. This bone bed is interpreted to be at the same level as the historical 'Grippia' bone bed and is referred to as such. The fossils have been sorted and contains bones in multiple size classes, from large bone elements and fin spines (<10 cm) to microscopic bones, teeth and scales. The resulting material includes elements from ichthyopterygians, amphibians, chondrichthyans, teleosts and possibly sauropterygians. The significance of this discovery is that the bone bed supplies a significant amount of data regarding the understanding of recovery and diversification after the Permian-Triassic mass extinction. The fossils were deposited in the Boreal Ocean, an embayment of the Panthalassa Ocean, on the northern rim of the super-continent Pangea. At approximately 40-50° palaeolatitude, the 'Grippia' bone bed, and three other Early to Middle Triassic bone beds in central Spitsbergen are the only large high-latitude localities for Early Triassic marine vertebrates in the world, as the majority of fossiliferous localities are deposits from the Tethys Sea. Here we present the preliminary taxonomical identifications of the material and their implications for understanding the evolution and biogeography of Early Triassic marine reptiles. The reptilian material includes bone elements from different ontogenetic stages, which is incredibly valuable when examining the taxonomy and palaeoecology of the bone bed.

News about the Aptian and Albian of the Longyearbyen area (Spitsbergen)

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While describing Aptian ammonite faunas of Spitsbergen, Stolley (1912) provided figures and / or descriptions of ammonite specimens, mainly collected from the Innkjegla Member of the Carolinefjellet Fm near Longyearbyen, or from the 'Westseite der Adventbai'. Later Aptian ammonites were also figured from other parts of Spitsbergen, but surprisingly both the ammonite succession and zonal subdivision of the Aptian here are unclear yet. Very recently Carolinefjellet Fm of the Longyearbyen area became in focus of glendonite studies (Vickers et al., 2018). Glendonite specimens recorded by Vickers et al. were found in the well-exposed cliffs and stream-cut section located along the road to the airport (so-called Airport Road section). However, their age remained unclear due to the absence of any age-diagnostic fossils. During the field works held in the year 2019 numerous ammonites were recorded in this section. More than 20 specimens assigned to either Tropaeum or Tonohamites came from the lowermost 35 m of the Innkjegla Member, where they occur along with Theganoceras. Just above the glendonite-bearing level, which is perhaps corresponding to those indicated by Vickers et al. (2018, 2019) a little below 120 m from the base of the studied succession (or ca. 70-75 m above the base of the Innkjegla Member, and 20 m below the highest glendonites) ammonite Grantziceras was found, indicating an early Albian age of these rocks. Interval with Tropaeum here is corresponding to the Upper Aptian, but the significant thickness of rocks lacking ammonites above the Tropaeum-bearing unit make the position of the Aptian / Albian boundary in this section unclear.

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Lower Volgian ammonites and ammonite-based stratigraphy of Spitsbergen

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In the Upper Jurassic interval of Spitsbergen the lower Volgian substage remains especially poorly known. Although presence of the lower Volgian ammonites here was at first reported by Pchelina (1965) and later confirmed by Ershova (1983), all figured specimens referred to lower Volgian taxa (Birkenmajer et al., 1982; Rogov, 2010) should be re-determined as middle Volgian taxa. New data about the lower Volgian succession were derived during the study of the famous Janusfjellet

succession. Here just above the first appearance of reddish siderite concretions the following succession of ammonites has been found: (1) *Virgatosphictoides* spp., including ammonites closely allied to *V. woodwardi* Neav. and *V. grandis* (Cope); (2) *Pectinatites* spp., including *P. eastlecottensis* Salfeld and piece of big smooth body chamber of macroconch; (3) *Paravirgatites* spp., with coarsely-ribbed, small to moderately sized ammonites. These ammonite occurrences permit to recognize preliminary succession of zones: *Virgatosphinctoides wheatleyensis* zone below, and *Pectinatites pectinatus* zone (with *P. eastlecottensis* and *Paravirgatites paravirgatus* subzones) above. Nearly the same succession of ammonites can be recognized throughout the Arctic, from the famous Dorset and Yorkshire coasts in the west to the Lena river lower flows in the east.

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The nature of trace elements in speleothem calcite

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Variations in trace element concentrations in a speleothem record reflect corresponding changes in the surrounding environment. For instance Mg/Ca and Sr/Ca have been used as indicators of temperature and drip rate. It is therefore of interest to map such variations of a wide range of elements and to understand the way trace contaminants are incorporated in the calcite. Using an XRF core scanner, we have investigated two stalagmite sequences from North Norway and South Africa for a selection of trace elements (Sr, S, Se, Fe, Br, Cl, Cu, Pb, Zn) and compared them with stable isotope and known climatic variations. Trace elements can be incorporated in several ways; within the mineral lattice and in defects, adsorbed to detrital particles, or reside in fluid inclusions. In order to find out how various elements are attached to the material, a series of treatments were done in order to *remove* the signal, and thereby deducing the nature of bonding. Testing for lateral consistency along growth layers can reveal localised concentrations, i.e. particles or fluid inclusion vugs. Heating and etching the calcite surface with various reagents also reveal information on bonding. Successive heating removed Br down to a constant background, suggesting that Br resides in fluid inclusions (volatile) and in part within the crystal lattice (stable signal). Yet other elements (S) increased in concentration upon treatment with water or weak acids, suggesting a “dirty snow” effect where insoluble particles accumulate on an ablated surface.

The role of intrusive volcanism in the origin of Venus' crust and its age distribution

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Compared to the Moon, Mars or Mercury, the surface of Venus is presumably young (0.3–1.0 Ga) given its low cratering density. Moreover, its age is rather uniform compared to its sister planet, the Earth, as suggested by the nearly random distribution of Venusian craters. These peculiar characteristics provide a window into Venus’ tectonic and volcanic evolution on a geological time scale as the production and preservation of crust, and thus its age, are tightly linked to the planetary interior as well as to the tectonic and magmatic regime and its temporal changes. Understanding these links is important for understanding planetary evolution in our solar system and ultimately why Earth is so special.

Since direct data from Venus is difficult to obtain and sparse, we use numerical simulations of mantle convection to address these issues. We employ the code StagYY in 2D annulus geometry and compute the evolution of Venus from 4.4 Ga until present. The model predicts where melt is generated in the mantle and where it may rise to the surface and form new crust. Previously, we used this framework under the assumption that all interior melt reaches the surface, which typically leads to very thick and very young crust. It is known from terrestrial settings, however, that most volcanism is intrusive and does not reach the surface.

Here, we investigate in a stagnant-lid regime of mantle convection how the partitioning into intrusive and extrusive volcanism affects the characteristics of Venus' surface by varying the intrusion-extrusion ratio and the mantle reference viscosity. Both parameters impact on the predicted present-day crustal thickness and surface age via reducing average crustal thickness and increasing average surface age. In a next step, we will test improved melt-related heat transport and models featuring episodic tectonic overturns.

Recent results from coring coastal lake basins in western Finnmark

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During field campaigns 2018-19 we retrieved long sediment sequences from over 20 lakes spread along the Altafjord in northernmost Norway. The work is a collaboration between NGU and archaeologists at University of Tromsø and was motivated by need for a better chronology for the postglacial shoreline displacement in the region. Altafjorden hosts widespread uplifted archaeological sites that once were shore-bound, including the famous UNESCO world heritage rock art. In addition, the visually striking, raised and tilted shoreline levels along the fjord were described already in the mid-19th Century during the La Rescherche expedition, and later used by De Geer as evidence for glacio-isostatic adjustment and the ice-age theory. The cored lakes are located below the marine limit and thus hold records of relative sea level change. Transitions between marine and lacustrine sedimentary units have been determined based on the macrofossil biostratigraphy, and robustly radiocarbon dated using series of samples of plant macrofossils. Our new relative sea level data span the entire postglacial period (Late glacial to the latest Holocene), and unveil intriguing differences in rates of relative sea level change across the region. Two of the basins also hold records of the Storegga tsunami. We also obtained several minimum-limiting ages for regional deglaciation and thus for local marine limits. Radiocarbon dating results were received just in time for the Nordic geological winter meeting, where preliminary interpretations and possible implications of the results will be discussed.

Records of ice-sheet and relative sea-level history, gathered from uplifted lakes near Tvedestrand at the Skagerrak coastline in southern Norway

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Extensive archaeological excavations were conducted prior to construction work for a new E18 highway between Tvedestrand and Arendal in southern Norway. The excavated sites, mainly representing shore-bound and marine oriented human activities, are located at various elevations between the postglacial marine limit at c. 83 m asl and the present sea level. The falling relative sea level (RSL) has caused an ever-changing configuration of islands, sounds and bays. This, in turn, has caused changes to fishing grounds, travel routes and suitable locations for dwelling sites.

A detailed knowledge of the local RSL is hence crucial for understanding Stone Age settlement patterns and landscape use in this area. Moreover, organic matter suitable for radiocarbon dating is often lacking on early Stone Age sites and a well-dated RSL curve provides an alternative tool for precise dating of shore-bound settlement sites. Archaeologists thus teamed up with geologists from NGU to produce a new RSL reconstruction. The cragged, Skjaergaard-type coastline in this part of Norway is dotted with isolation basins, i.e. small and deep lakes and bogs below marine limit. This is therefore an extremely well-suited area for detailed studies of past RSL changes. We cored in total 24 isolation basins near Tvedestrand, from which we recovered 10-15 m long sequences. Sedimentary facies transitions representing the time of disconnection from the sea, were determined using biostratigraphy, and radiocarbon dated using series of multiple samples of terrestrial plant macrofossils. We also radiocarbon dated shells from basal layers to obtain age constraints for Lateglacial ice-sheet oscillations and final deglaciation. The main scientific output from the work is two-fold; (1) a high-resolution RSL reconstruction, covering the entire Holocene and revealing unexpected variability in emergence rates, and (2) new age constraints for the Younger Dryas ice-sheet oscillation at this coastline, including a revised age for the famous Ra moraine.

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Jølster landslide event July 2019: predisposition, trigger and consequences

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On July 30th, 2019, over 50 landslides were triggered by an extreme heavy precipitation event in Jølster, Norway. This localized and prolonged rainfall exceeded the magnitude 200-year 24-hour precipitation event at the two nearest precipitation weather stations, Botnen and Haukedalen, in the neighbouring municipality of Førde. The landslides resulted in damage to infrastructure, private property and the death of one man whose car was swept into the lake.
This study aims to answer the following questions, focussing on the three largest debris flows at Vassenden, Slåtten and at Årnes; (1) What was the predisposition of the locations to landslides? (2) What was the trigger? (3) What can be learnt from the events at Jølster that can be applied to similar settings in Western-Norway?
The predisposition to slope failure was analysed qualitatively. This included obtaining a historical landslide inventory, geological maps, digital terrain models (DTM) and conducting field observations in August and October 2019. Based on these investigations, a volume estimation and geologic profile were completed. These were used in a slope stability analysis in order to verify the presumed trigger.
Discrepancy between older satellite images and the landslides inventory shows an incomplete record of landslide events in Jølster due to the lack of historic data. Although landslide hazard mapping was conducted in the region in 2018 by NGI for NVE, Slåtten, the area of the largest debris flow from July 2019, was not identified and mapped as a potential hazard. In this case, the debris flows occurred on slopes with shallow soil cover, consisting of compact moraine and colluvium, with a cover of spruce forest. The analysis of the three largest debris flows gives estimated volumes in the order of 10-25,000 m^3 and a factor of safety below one, given the maximum observed rainfall of 113 mm/24h (Meteorologisk Institutt, 2019).
The stability analyses confirm the extreme rainfall appears to be the trigger of slope failure. A significant amount of loose material remains on the slopes, which could be reactivated in future heavy rainfall events. Climate change is rendering extreme precipitation events likely to become more frequent due to a warming climate. Such storms present a risk of failure on slopes which do not have a known history of landslide activity.

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The destruction of the Nubian Sandstone Aquifer System (NSAS)

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The NSAS aquifer systems under Libya is comprised of 5 main reservoirs, presently exploited by the Ghadames, Hassouna, Sarir, Tazerbo, Jaghboub and Kufra (water) wellfields, respectively. To varying extent most of these reservoirs also contain salt and fresh water aquifers as well as oil and gas facies. The total volume of fresh water contained within the NSAS is in the order of 500.000 - 1000.000 km^3, i.e 3-6x10^{15} bbl of water (1). At a market price of 1USD/m^3 for water, the corresponding value will be roughly 2 orders of magnitude higher than the value of all oil of the North Sea reservoirs combined, past and present. - Or probably more correctly: *was*.
A characteristic trait of the Libyan reservoirs is the unusual corrosiveness of these waters. Coupled with a pronounced tendency of crossflow in poorly completed, abandoned and/or corroded wells, fresh water, salt water, oil and gas will migrate vertically within wells. Left unattended and unregulated, such a 'rogue' oil well will have the potential to destroy an infinite volume of surrounding pristine fresh water of these highly permeable sandstones. The Libyan Petroleum Institute served as the regulatory body in this respect.
The Nato-led aerial bombardment of March-November 2011 dropped nearly 1000 bombs on Libyan infrastructure. According to Norwegian pilot's statements (2), about 75% of all missions were of the 'SCAR' category (Strike Coordination and Reconnaissance), meaning these missions were implemented without ground intelligence 'quality control'. A victim of the random bombing included the Libyan Petroleum Institute, whose regulatory functions safeguarded all petroleum activities,

including the NSAS, - but only until 2011. After this date, all wells will be classified as 'rogue'.
The legacy of the 2011 Libyan bombing campaign will have lasting, irreversible and devastating impacts due to the ensuing crossflow contamination; with no remedies in sight. The destruction of NSAS, the World's largest aquifer system, will forever be linked to the destruction of Libya's infrastructure. The consequences will go down in history as an environmental disaster of epic proportions, and Exxon Valdez and the Gulf of Mexico episodes as mere footnotes. No one will ever be held accountable. The hydrogeology community remains silent.

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Kvalitative tiltak for å evaluere effekten av lokale inngripende tiltak på energibrønner (eneboliger)

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I forbindelse med bygging av infrastruktur i undergrunnen (f.eks. tunneler for VA, strømkabler, T-bane/tog, vei, etc.) vil det kunne oppstå tilfeller hvor eksisterende energibrønner blir ødelagt (direkte påtreff) eller at de mister ytelse. Redusert ytelse er primært knyttet til redusert grunnvannsnivå og/eller påvirkning (reduksjon) i tidligere grunnvannsstrømmer rundt og i energibrønnen. Redusert ytelse for energibrønnen gir en lavere energibesparelse for varmepumpen.
Det er omfattende og kostbart å dokumentere nøyaktig effektivitet av en boligvarmepumpe med energibrønn, både med tanke på omfang av målere, måleusikkerhet, variasjoner i klimaet, brukeradferd, etc.
Logging av tur/retur-temperatur i kollektorvæsken er en enkel metode for å avdekke evt. betydelige *endringer* i ytelsen for en energibrønn, ifm. f.eks. et tunnelprosjekt. Ved redusert ytelse for energibrønnen vil tur/retur-temperatur i kollektorvæsken være lavere, sammenlignet med referansemålingen før infrastruktur tiltaket. Temperatursensorer tilkoblet en logger, festes mot tur/returrørene, og isoleres godt. Loggeperioden bør være minimum to uker. For de fleste boligvarmepumper er sirkulasjonen i kollektoren konstant, så målinger av sirkulert mengde er ikke nødvendig (pumpe starter og stopper med varmepumpen). Brønnpumpe (også dersom denne er frekvensstyrt) bør settes i fast posisjon (kontinuerlig drift) når referanse- og etterkontrollmålinger utføres. Logging bør fortrinnsvis gjennomføres i vinterhalvåret, og ved ca. samme tid på året for hhv. referanse- og etterkontrollmåling.
Sweco Norge har gjennom samarbeid med Futurum Energi AS erfaring fra prosjekter hvor de har utført følgende tiltak:

- Referansemålinger (logging, ca. to uker) på energibrønner før oppstart av tunnelarbeider
- Utkobling av energibrønn samt andre beskyttende tiltak når tunnelarbeider er ca. 100 meter fra energibrønn. Omprogrammering av varmepumpe/system til kun elektrisk drift.
- Når tunnelarbeider har passert med ca. 100 meter: Sjekk av tilstand for kollektor, tilbakestilling og igangsetting av varmepumpeanlegg.
- Forslag til tiltak dersom energibrønn er ødelagt, plassering av erstatningsbrønn, mm.
- Evt. etterkontrollmåling ved mistanke om redusert ytelse.

Eventuelle endringer i grunnvannsstrømninger i en energibrønn er svært vanskelig å dokumentere. Endringer i grunnvannsnivået er noe tunnelprosjektene prøver å unngå (injisering), da dette kan få mer omfattende uønskede effekter (setningsskader, mm). Veldig få varmepumpeeiere har dokumentert grunnvannsnivået i energibrønnen før tunnelarbeider, men dette er viktig informasjon som i større grad må rapporteres fra brønnborer til NGU ved etablering av energibrønner. For brønner med mistanke om, eller påvist redusert ytelse, kan det være aktuelt å injisere termisk masse i den tørre delen av brønnen, slik at energibrønnen kan hente energi i hele sin dybde.

Remnants of old saprolites in Norwegian tills

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Few studies of tills in southern Norway have demonstrated with certainty remnants of pre-Quaternary saprolites; e.g., Rosenqvist (1975). Two large geochemical data sets of tills and bedrock samples in Mid-Norway have been investigated to detect such old saprolite material. The datasets include 7,000 till samples in addition to samples of all the bedrocks in the area. The studied area is divided into two regions; Region A: dominated by Precambrian granitic gneisses; and Region B: dominated by ophiolitic rocks. All the till samples

(finer than 2 mm) and the rock samples are ground to pass a 180-micron sieve and 1.0 gram of each sample is treated with 7N HNO_3 at 110 ° C for 3.5 hours. The extracts are analysed for a comprehensive number of chemical elements. Unfortunately, the datasets do not include any mineralogical data. Here, some selected elements from the two subsets are investigated to identify correlations that may exist between the till samples and the underlying rocks; rocks that have contributed to the composition of the tills. Large differences were found between the acid-extractable elements from tills and the underlying rocks. The minerals which are preferentially dissolved in the strong acid are, with some exceptions, the same as those dissolved by weathering. For this reason, the data is investigated by applying methods commonly used to study weathering profiles; e.g. Chemical Index of Alteration (CIA = Al / (Al + Ca + Na + K)). The CIA values are used as "proxies" for comparing the chemical extracts from the tills and bedrock samples. It is found that the ratio of average values of CIA for tills and bedrocks is close to 0.5 in both regions (A and B), indicating that the tills are "diluted with ~50% inert material", which is assumed to be quartz. High contents of quartz in tills was also detected by Dekko (1973). The high contents of quartz in the tills may be remnants of old saprolites, eroded during the Quaternary.

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Remnants of old saprolites in marine clays, Mid Norway

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It is commonly assumed that the Quaternary tills onshore Norway contain a significant amount of powdered bedrocks eroded by the glaciers. A large portion of this fine material was washed out of the till material by melt water during the retreat of the glaciers and deposited as marine clays. This view is supported by the apparent absence of saprolite material in the clays.

During the last two decades, remnants of paleo-weathering have been found in faults and fractures in most parts of Norway, where the weathered material was protected from glacial erosion (e.g. Olesen et al., 2013). The clay minerals in the paleo-weathered zones are dominantly smectitic, indicating weathering in a sub-tropical to tropical climate. But smectite is rarely found in marine clays, where the dominant clay minerals are illite and chlorite (Roaldset, 1972; Hilmo, 1989).

Here, a new approach is made to identify the possible presence of old saprolite minerals in the marine clays. Marine (quick) clays were sampled at two localities in Mid Norway; Snåsa (Agle) and Trondheim (Tiller). Detailed XRD analysis of the fine fractions (<0.1; 0.1-0.4; 0.4-2; 2-6; and 6-10 µm) of the clays was carried out to ensure a good overview of the mineralogy; focusing on the types of illites that dominates the fine fractions. These fine fractions were also dated by the K-Ar method established at NGU. The combined XRD and K-Ar data show that the coarser fractions (6-10 µm) contained K-bearing phases of Caledonian age, whereas the finer fractions (<0.4 micron) are highly enriched in younger illites, of late Permian to Triassic ages; i.e. the <0.1 µm fractions from Tiller clay 210.6 (+/-3.3) Ma and Agle clay 262.9 (+/-3.6) Ma. These ages are comparable to the corresponding fine fractions of the saprolite clays found in Mid Norway and it is therefore suggested that the youngest illites in the marine clays are derived from remnants of old saprolites formed during post-Caledonian time.

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Hydrothermal ore-forming processes in the deep-seated parts of a continental rift system and implications for hydrothermal processes in rift-related systems on the Norwegian continental shelf

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The Reinfjord Ultramafic Complex (RUC) in Northern Norway is a deep crustal volcanic conduit system consisting of layered dunites, wehrlites, and olivine clinopyroxenites emplaced into gabbro-norite and metasedimentary gneiss through a series of magmatic recharge events. The RUC is a part of the Seiland Igneous Province, which comprises over 20,000 km^3 of mafic, ultramafic, alkaline and silicic rocks. The various melts were emplaced into the lower continental crust under an extensional regime between approximately 560 –

570 Ma. This study uses detailed field studies, EPMA analysis, and thermodynamic modeling to describe the formation of hydrothermal alteration and subordinate sulfide mineralization in a specific metamorphic and structural geological setting. We find that sulfide mineralizations formed at particular intervals during the development of the RUC, both at the magmatic stage (Ni + Cu + PGE) and during the infiltration of hydrothermal fluids (Cu + Ni + Zn + Au) through the reaction of mixed aqueous fluids at 550 – 650°C and approximately 6-10 kbar, related to talc-magnesite veining and other mixed volatile alteration assemblages. The hydrothermal alteration is closely related to a kilometer-scale north-south trending shear zone with a down-to-the east transport direction, exemplifying the complex interplay between tectonic, hydrothermal and mineralizing processes. The genesis of sulfide mineralizations in the RUC has implications for mineralizing processes in the lowermost continental crust, where structurally controlled fluid flow and the transport of volatiles may affect mineralizing processes at higher crustal levels, particularly along hyperextended continental margins where mantle derived fluids ascend into the uppermost continental crust and associated sedimentary basins.

Investigating Tear Faults in the Oslo Region

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The Lower Paleozoic units of the Oslo region have undergone two major tectonic events, SE-directed thrusting and folding during the late Silurian Caledonian orogeny, and E-W extension during the creation of the Oslo graben in late Carboniferous and Permian time. The Oslo graben is divided into several segments, and in the assumed transfer zone between the Vestfold and Akershus segments, sub-vertical faults with strike-slip and oblique-slip movements are commonly assumed to belong to the Permo-Carboniferous extensional phase. Alternatively, some such faults could represent Silurian tear faults, accommodating lateral differences in displacement between segments of thrust sheets; such faults have previously not been the focus of systematic investigation in the Oslo region. An attempt has been made to identify and characterise Silurian tear faults in the assumed transfer zone through detailed fieldwork. The fieldwork reveals that tear faults are a common feature in the field area and contribute significantly to the complexity of the mapped outcrops. The identified tear faults yield consistent SE directed strikes parallel to the direction of thrusting (i.e., no rotation of the tear faults has taken place during thrusting and folding). These directions match the local Caledonian grain, and could potentially explain some of the previously reported strike-slip vectors from the Oslo region. The poster shows detailed mapping and interpretation of Silurian tear faults on Bygdøy and in the Slemmestad area.

Normal faults and shear bands in unconsolidated sands: Properties and mechanisms

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Extensional deformation in loose sands tends to be along discrete, thin shear bands and faults, hardly affecting porosity and permeability. This deformation may be very challenging to see, both in the field and in the well core, if the sands are homogeneous with few markers. In contrast, deformation in consolidated and cemented sands is much more eye-catching with grain crushing, brecciation and slickensides, considerable effecting porosity and permeability.
Jurassic rifting in the North Sea took place prior to consolidation of the main reservoir sands. The mechanical behavior of a typical Jurassic Brent Group sand is investigated in a sand box experiment subjected to a stress regime that simulates the Jurassic rifting (Rykkelid & Skurtveit 2017). Some observations are listed below:

- Sand can deform very little before strain localize to very thin shear bands and faults. The critical strain state increases progressively by burial depth, from 1.2% at 10 m simulated burial to 5% at 800 m simulated burial depth.
- The Initial homogeneous-strain-phase involves strain hardening that, strangely enough, is associated with a bulk rock porosity increase. Stiffening despite higher porosity is caused by reorientation of sand grains into vertical force chains. A progressive porosity increase can however not go on forever, and instability with local collapse of the force chains result in a following strain softening phase with formation of thin shear bands. When these shear bands start to form, they take up all the progressive deformation. It is anticipated that wall rocks that has intact force chains will stiffen by aging whereas the looser sands in deformation bands are weakened by each reactivation. The result is a high degree of

strain localization, observed also over time.
- Adding clays and silts to the sand experiments make the sand stronger and less prone to strain localization. Both factors suggest that a fault will start in the sand and ultimately migrate into enveloping silts and clays where they link and overlap with a more complex deformation pattern.
- By high strain rate (seismic rate), the strain localization occurs faster compared to what observed in a slow creep experiment, and shear resistance is less in the steady state shear phase. Both processes add to preserve intact wall rocks.

Conclusion: The sand box experiments seem to explain the general high degree of strain localization in unconsolidated sands.

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Triassic – Jurassic boundary in the Barents Sea: A regional retake on tectonic controls and sediment routing

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Strata of Late Triassic – Middle Jurassic age contain significant reservoirs in the SW Barents Sea. Whereas terrestrial/marginal marine conditions persisted across the Triassic – Jurassic (T/J) boundary, a very distinct reduction in accommodation space occurred during latest Triassic, resulting in a widespread unconformity across the Barents Sea and Svalbard and subsequent deposition of a stratigraphically condensed, sandstone-dominated Jurassic succession. Furthermore, a change in provenance area, from the southeast (Urals) during the Triassic, to the south (Fennoscandia) during the Jurassic, is well established, particularly to the west.

Recent studies have linked the basal Jurassic unconformity to contemporary forebulge uplift induced by compression in the Novaya Zemlya fold and thrust belt to the east. The loss of accommodation space across the T/J boundary is however not unique for Barents Sea and Svalbard. On the contrary, similar relative condensation of Jurassic strata can be observed along the entire Norwegian shelf as far south as the North Sea, raising the question if not additional controls, perhaps involving North Atlantic rift-related tectonism, should be considered.

The provenance change at the T/J boundary is primarily recorded from petrography data, showing dominantly fine-grained and feldspathic sandstones in the Triassic, overlain by coarser and quartz-rich Jurassic sandstones. New well data from the Norwegian – Russian boundary zone, however, testify to sediment routing from the Uralian hinterland well into the Early Jurassic. Accordingly, the petrographic turnaround is diachronous, with the southeasterly sediment flux reaching into the NE part of the Norwegian Barents Sea sector at least through Pliensbachian times.

Paleocene Play in the Deepwater Norwegian Sea – Plenty of Opportunity?

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The deep Vøring and Møre basins cover large areas of the mid-Norwegian shelf. Exploration drilling in these basins has led to the gas discoveries in the Ormen Lange and Aasta Hansteen fields, in the Møre and Vøring basins, respectively. Significant Upper Cretaceous - Danian reservoirs occur in the NW Vøring Basin. These are deposited in submarine fans derived from westerly source areas (Greenland) and tend to pinch-out towards east and south. Further east in the greater Vøring Basin, a thick Paleocene submarine fan system occurs in the inner part of the Træna Basin, being derived from an easterly source area. This system too shows relatively rapid pinch-out towards the south.

In the Møre Basin, significant Lower Paleocene (Danian) submarine fan sandstones occur to the east in the Ormen Lange field. The fan is clearly sourced from uplifted parts of Norway but does not seem to extend far into the basin. A limited Danian reservoir unit has also been drilled in the western part of the Møre Basin but cannot be confidently tied to a specific provenance area. Otherwise, wells drilled in the southern Vøring Basin and in the Møre Basin show a systematic paucity of reservoir quality sandstones, both at the Upper Cretaceous and Paleocene levels. For the Paleocene this reservoir deficiency may relate to the contemporary growth of basaltic volcanic highs along the western basin margins, effectively blocking for sediment flux from the west.

Whereas source rocks for petroleum appears throughout the Upper Cretaceous, continued exploration need to establish new reservoir fairways, and additionally consider possible reservoir units preserved both within and below the volcanic marginal highs.

The importance of dyke evolution in the Upper Layered Series of the Reinfjord Ultramafic Complex in understanding the intrusive history of the Central Series and other mantle derived magmas

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The Reinfjord Ultramafic Complex (RUC) is part of the lower crustal Seiland Igneous Province (SIP), a mantle derived magmatic conduit system comprising the most deep-seated parts of the Ediacarn Central Iapetus Magmatic Province (CIMP). SIP consists of several ultramafic intrusive centres hosted by layered gabbros, and are considered to be the de facto conduits transporting melts from the the asthenosphere to the lithosphere. The Upper Layered Series (ULS) and the Central Series (CS) comprises most of RUC. The ULS consists of dunitic as well as wherlitic cumulates, and rare olivine clinopyroxenites which all features a primary magmatic layering, providing information about early magmatic processes in RUC. The younger CS consists mainly of dunites and wherlites, which show similar magmatic processes to the ULS. Comparing the magmatic and geochemical evolution of the CS and the ULS, as well as studying the contact between the two magmatic series provides insights regarding the emplacement of the CS and other mantle derived magmas.
The Southern plateau of the RUC contains consecutive generations of dykes covering a continuum of compositions including picritic, basaltic and alkaline affinities. The mineralogy, geochemistry and structures of these dykes is studied in order to gain a better understanding of the magmatic amalgamation and intrusive chronology of RUC. It may also be possible to better understand the dynamics and composition of parental melts in a high yielding magmatic system such as those observed in SIP. The different generations of dykes display different degrees of deformation, which appears to be a function of composition rather than age. The oldest ultramafic dykes are primarily affected by late brittle deformation, while the younger mafic dykes are strongly deformed by magmatic shear zones with high degrees of strain localization, as well as late brittle deformation. Studying the petrological variations, orientations and styles of deformation in both the dykes and the host rock is imperative in understanding the emplacement of giant volumes of asthenospheric melts from the deep Earth to the shallow crust.

New High Quality 3D Seismic Data in the far southwest of the Barents Sea

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The far southwest Barents Sea is one of the few remaining frontier basins. There is little exploration activity and the data coverage is sparse. Until now, almost all existing seismic data was 2D, of variable data quality and as a result, the geology and hydrocarbon potential of the area is not fully understood.
PGS has now covered parts of this area with the first 3D GeoStreamer MultiClient 3D broadband seismic dataset to enhance the geological understanding of the area and as a tool for unlocking new potential in this virtually unexplored and exciting part of the Norwegian Barents Sea. Through advances in data acquisition and imaging, and building on experience of acquiring data in the Barents Sea, this newly acquired dataset illuminates the geology and the exploration potential.
The multicomponent seismic survey was acquired in 2017 and is processed with an innovative workflow using complete wavefield inversion (CWI). CWI is a processing flow developed by PGS which integrates advanced technology for high-resolution velocity model building and depth imaging using reflections, refractions and multiples. This new high resolution 3D seismic data is revealing geological details never seen before in this unexplored area thanks to the acquired broadband data and the state-of-the-art imaging workflow.

Distribution, age, geochemistry and origin of "anorogenic" granites in the Baltic Sea region

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The Palaeoproterozoic Svecofennian Domain was intruded by truly anorogenic granites, represented by the 1.70-1.67 Ga Dala suite and the 1.64-1.50 Ga rapakivi batholiths of e.g. Åland, Wiborg and Riga, which are temporally and spatially associated with mafic dykes and clastic sedimentary basins emplaced within a back-arc basin. Wiborgitic

rapakivi textures (K-feldspar phenocrysts rimmed by plagioclase) are common. Slightly younger granites (e.g. the 1.52-1.44 Ga Götemar, Karlshamn and Geluva plutons) were emplaced in a variety of TIB 1 units in SE Sweden, in the Baltic Sea region (cf. Salin et al., 2019) and Lithuania. They show no wiborgitic rapakivi textures and are neither associated to mafic dykes nor to sedimentary basins, suggesting major differences in tectonic conditions. Two percussion drilling samples from the Precambrian basement beneath the Phanerozoic cover in the Baltic Sea region were collected from the archives of the Geological Survey of Sweden and dated using the U-Pb zircon method. The Hamra granitoid (southern Gotland) was dated at 1471±7 Ma, while the Kvinnsgröta granitoid (southern Öland) was dated at 1442±7 Ma. Both ages are compatible with those of the younger granitoid group south in the TIB 1 units.

A compilation of geochemical data for the classic rapakivi granites in the Svecofennian Domain shows that they are metaluminous to marginally peraluminous with high Fe/Mg, K/Na, Ga/Al, Zr and F, low CaO and Sr, and a distinct negative Eu anomaly. The granites in the TIB 1 units (and in Lithuania) have also A-type affinities due to high contents of HFSE and Ga/Al ratios, but only the Götemar and Blå Jungfrun plutons can be considered anorogenic. All other granites in the TIB 1 sector are metaluminous, have lower Fe/Mg and K/Na ratios as well as rather gentle REE trends with low negative Eu anomalies typical for I-type granites.

The differences in chemical composition and mode of magmatism of these two groups can be explained by a major difference in geological settings; the classical rapakivi granites were emplaced in very thick continental crust of the Svecofennian Domain while the second group intruded into thinner crust of arc sequences intrusions belonging to the TIB 1 units.

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UpDeep standard reference material bank for the top soil and plant geochemistry in mineral exploration

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Quality control is an essential part of the geochemical research process. Typically it covers laboratory pre-processing, field sampling, sample delivery but equally important is external monitoring of laboratory chemical analyses. Standard reference materials (SRMs) are commonly utilized to monitor the laboratory accuracy, i.e. bias, and laboratory precision but also trends and breaks in laboratory analytics performed on geochemical sampling media including surface geochemical materials. SRMs withdrawn from a SRM bank are inserted within certain intervals into the regular survey sample sets in the field or before sending samples to a laboratory. The analytical results are then compared to the predetermined analytics of the homogenized bank material.

Recently, there has been increase demand on development of new, environmentally friendly sampling and analyses techniques. Simultaneously a lack of surface geochemical SRM samples relevant to Europe is identified. To solve this problem, practical sampling and immediate sample preprocessing procedures were demonstrated to produce guidelines for a surface geochemical SRMs sample material bank. The work was conducted in the UpDeep project: Upscaling deep buried geochemical exploration techniques into European business in 2017-2020 (EIT Raw Materials KAVA project number 16329). The reference sample materials include both mineral soil and plant biogeochemical sample materials for the purpose of mineral exploration on glaciated terrains. The ultimate goal in the UpDeep project was to produce the specifications how to produce SRMs and to construct a small example bank of the materials for EU market. The same protocols can also be used in producing certified reference materials site/study/project reference standards or in-house standards.

In this presentation, we describe the sampling procedures and sample pre-processing prior to dispatching aliquots of the bulk reference sample materials to be analysed using different leaching techniques in different commercial geochemical laboratories. Two known mineralization (Au and Au -REE) were chosen as sampling sites. Sample materials were chosen based on existing soil and vegetation types observed in the field. The aim was to collect several material types to demonstrate the idea of producing a reference material bank applicable to commercial production. The expertise and the facilities of required laboratory procedures including milling, homogenization and subsampling were established at GTK Mintec. The certificates of the UpDeep SRM bank samples can be found on the project web site (http://projects.gtk.fi/updeep/).

Danish Paleogene supersize glendonite gives possible keys to an old enigma

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The fine preservation of Danish Early Eocene supersize glendonite assist in understanding historic papers on the enigmatic "pseudogaylussite", later named glendonite (Dana 1884). The study also offers a plausible explanation as to why early masters of crystallography remained baffled by glendonite, which appears similar to gypsum but yet differs in key features of symmetry. Gypsum has the same monoclinic M/2 symmetry, is similar in shape and has some parallels in genesis (Cody and Cody, 1988).
First described by Freisleben in 1827 it remained an enigma to the early crystallographers, who have studied pseudogaylussite in details. Today it is thought the precursor mineral is ikaite, calcium carbonate hexahydrate ($CaCO_3{\cdot}6H_2O$), originally identified in a laboratory study by the chemist Pelouze (1865). Naturally occurring ikaite was only found in 1962, as submerged spectacular mineral pillars in Ikka Fjord of SE Greenland (Pauly 1963). In natural environments, ikaite is a metastable mineral that precipitates in cold conditions and spontaneously dehydrates at temperatures above 6 – 8 °C, a temperature limit that can be extended depending on sediment chemistry (Marland 1975). Several papers have described the characteristic petrography of glendonite and related it to the transformation process from ikaite, whilst other glendonite-like euhedral ikaite crystals that have been retrieved from marine sediments. Direct petrological comparison of ikaite-generated calcite from Sea of Okhotsk (Greinert and Derkachev, 2004) to glendonite matrix. The Danish site supports the observation that ancient glendonite sites often display a horizontal distribution, suggesting an ikaite formation zone, as seen in modern marine settings.

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First analysis results from the new seismic array BEAR on Bjørnøya

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NORSAR received from the Research Council of Norway funding for a new regional seismic array on Bjørnøya (Bear Island) in the European Arctic as part of the EPOS-Norway infrastructure project.
After a long planning phase, this new six-element array was installed by NORSAR staff in August 2019 and has been providing data to NORSAR in near real-time since then. Data are also copied to the Norwegian node of the European Integrated Data Archive (EIDA), which has been installed as part of the same infrastructure project at the University of Bergen in cooperation with NORSAR.
This talk will report on the installation of the array and on the first results from analysis of the array data. We will try to answer the following questions: How are the seismic monitoring capabilities in the region changing? What seismicity can be observed in the Barents Sea? How are data from this new installation complementing data from the seismic arrays (ARCES, SPITS and Apatity) already installed in the European Arctic?

Groundwater recharge and discharge in the Åknes rockslide – constraining uncertainties for the development of a numerical groundwater flow model

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Åknes rockslide, located in Storfjorden (Northwest Norway), is one of the priority sites monitored since 1986, with an automated monitoring system installed in 2004.

In 2008, groundwater springs were reported at three elevations: Lower Spring Horizon (LSH, 100-120 masl); Middle Spring Horizon (MSH, 360-460 masl); and Upper Spring Horizon (USH, 640-840 masl).

Here, we present the results of the NVE-UiO collaboration, initiated in 2017, which aims to assess the groundwater recharge, discharge and flow patterns, and ultimately develop a hydrogeological model of the Åknes rockslide.

Monitoring of springs and streams discharge, physico-chemical parameters (pH; Electrical Conductivity, EC; temperature), and dissolved inorganic components took place in the Spring-Summer of 2018 and 2019. In addition, detailed structural geology mapping of the area above the backscarp was carried out in the Summer 2018 to assess the groundwater recharge processes.

Groundwater flow in Åknes is laminar to turbulent, partially occurring along perched aquifers above the local water table. Contributing to this high-velocity groundwater flow regime are (i) the permeable structures of the rock mass – slope cover (soil and rock debris), steep fractures interconnected to slope-subparallel undulating fracture corridors in biotite-rich and feldspar-rich gneiss, and crushed rock membranes; and, (ii) the high steepness of the slope (30-40^{o}).

Groundwater recharge occurs indirectly through infiltration of surface runoff and subsurface flow produced above the backscarp, and directly through infiltration of precipitation and snowmelt from the backscarp to the toe zone. On the East side of the unstable slope, perched aquifers and surface runoff feed the ephemeral Eastern Stream. To the West and South, the perennial discharge and water chemistry reveal a groundwater reservoir with an important storage capacity discharging at the bottom of the fastest moving rock mass (West part of the MSH). An even larger reservoir feeds the LSH, at the rockslide's toe zone.

Felsic MASH zone in southernmost Finland

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Melting, assimilation, storage and homogenization of mafic magmas are known to occur in lower crustal MASH zones, but similar processes also occur in the middle crust, where the melts are more felsic. In these felsic or mid-crustal MASH zones, melts from different crustal sources interact with each other, crystal mushes, restites and fluids. In MASH zones, fluids are often active in inducing partial melting.

Migmatites in the mainland southern Finland were formed in the Svecofennian orogeny at 1.9-1.8 Ga, mainly through dehydration melting of metasedimentary rocks. Intrusive granite plutons related to the anatectic event are common amongst high-grade metamorphic rocks of the mainland. Migmatites in the southernmost part of Finland, around the Hanko peninsula and Ekenäs archipelago, were formed in the same orogenic sequence but differ considerably from the mainland migmatites. The protoliths to these migmatites are mainly amphibolites and a wide variety of K-feldspar bearing gneisses, resulting in many different compositions of anatectic melt. Additionally, the morphology and mineral composition of these migmatites indicate formation in a water-fluxed environment rather than through dehydration melting.

Even-grained granites associated with the migmatites also occur in southernmost Finland. The granites range from grey, magnetite-flecked granite west of the Hanko peninsula to red granite to the south and southeast of the peninsula. Some even-grained red granites differ from others in mineralogy and geochemistry, appearing more evolved. Xenoliths of amphibolites and K-feldspar bearing gneisses are commonly found in the granite bodies, occasionally displaying signs of assimilation. In contrast to the intrusive granites in mainland southern Finland, these granites appear to be stored at the site of the anatexis.

Chemical equilibrium between the leucosomes and metatexite migmatites indicates that homogenisation has occurred. All the MASH processes are thereby prominent in the southernmost Finland granite-migmatite belt, making it a good example of a mid-crustal MASH zone.

Svalbard Rock Vault: Let us safeguard Svalbard's geoscientific heritage!

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Geology, in particular the presence of coal-bearing strata, has determined the location of where Svalbard's settlements are located, and its history is closely linked with the exploitation of its natural resources. Coal exploration has resulted in hundreds of boreholes and tens of kilometers of core material. Much of the core material and data are globally unique and may be used, for instance, in climate reconstructions. Petroleum exploration onshore Svalbard resulted in eighteen deep boreholes drilled between 1961 and 1994. In recent years, research drilling targeting local CO_2 subsurface storage generated unique data sets, including core material from most of the Mesozoic succession. But how are geological data from Svalbard organized? Where are the cores, the samples, the well reports, the geophysical data sets and other geoscientific data? Unfortunately, some of the material is lost forever: thrown away or left exposed to the outdoor elements of Svalbard. Some material has been preserved in the numerous data repositories in Svalbard, in Norway or abroad, but it is often hard to locate. In contrast to routines on the Norwegian continental shelf, well reports are never officially released and thus hard to access. Through the Svalbard Rock Vault (SRV) initiative, we strive to lay the foundation for a safe geoscientific data archive, especially important in today's turbulent times and the rapid decrease in coal mining activity. SRV comprises both a physical core storage facility in Longyearbyen and a geodata portal to facilitate locating and accessing the data for research and education. Furthermore, we envision SRV to be an active repository with customized non-destructive analytical tools and sampling procedures that can be used to characterize relevant sections of existing drill core material, to contribute to ongoing research projects.

Erupting large volumes of basalt: Lessons learned from three most recent caldera collapses on Earth

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The three most recent caldera collapses on Earth occurred at Kilauea in 2018 (Hawaii), Bardarbunga in 2014-2015 (Iceland) and Piton de la Fournaise in 2007 (Réunion). Monitoring of these events, and their comparison sheds light on processes responsible for erupting large volumes of basalts to the surface. The link between caldera and rift was important in all cases. Mechanical models suggest a very different behavior of volcanoes before and after onset of localized movements on caldera faults (caldera failure). After establishment of a stabilized magma channel to the surface during eruption, the pressure drop in the magma body will be governed by interplay between properties of the magma body, elastic behavior of the host rock, and the properties of the magma channel. The geometry of the magma body plays a major role determining how fast its pressure drops. In exceptional cases, if sufficient magma drains, the conditions in the roof the magma become critical, and slip on caldera faults begins (caldera failure). At this time the mechanical model behavior changes, and pressure drop in a magma body scales in a different manner than before caldera failure. After onset of caldera failure, it relates to the average rate of subsidence of the caldera floor. Pressure may drop at a much lower rate, and larger volume of magma drains for each unit change of pressure. Therefore, caldera collapses driving lateral eruptions can drive out much larger volumes of basaltic than when no caldera collapse occurs. The three most recent caldera collapses shed light on this process. At Bárðarbunga caldera failure occurred 8 days after the onset of magma flow, when about 0.3 cubic kilometers of magma had flowed into a regional dike. In a simple model the associated pressure drop depends on magma body geometry, the compressibility of the magma and the shear modulus of the host rock. The results of mechanical models for Bárðarbunga are compared to lessons learned from the Kilauea and Piton de la Fournaise collapses, to evaluate the general role of caldera collapses to drive large volume basaltic eruptions through caldera-rift interaction.

Candidate prospects for a novel keyhole mining system with minimal environmental footprint

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Northern Europe is littered with the reminders of a mining industry that exploited small, high grade deposits for centuries. Many such deposits were

characterized by thin, more-or-less structurally continuous orebodies. As the industry shifted emphasis to larger deposits that could exploit favourable economies of scale in the first half of the 20th century, exploitation of this type of deposit ceased . Ravel AS is re-enabling the development of these types of prospects with a novel telerobotic mining system that operates with minimal environmental impact and capital cost. In this talk we will review the geological and technical rationale behind the selection of several sites the company is using to guide development of the system.

Detrital zircon inventory of the Triassic Greater Barents Sea Basin: sediment transport and geodynamics

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The intra-cratonic Greater Barents Sea Basin (GBSB) represents one of the last underexplored petroleum provinces in the world. It is believed to contain most of the yet-to-find hydrocarbon resources on the Norwegian continental shelf, and significant resources are also present within the Russian sector of the Barents Sea (e.g. Shtokman discovery). Several of the hydrocarbon reservoirs within the Barents Sea are of Triassic age (e.g. Goliat field). The reservoir properties are influenced by the mineralogical composition, and the reservoir quality is therefore also strongly linked to the source area for the sediment. Within the GBSB, c. 2200 U-Pb detrital zircon ages from 26 Triassic samples have provided information on the provenance for the Triassic reservoirs (e.g. Omma, 2009; Soloviev et al., 2015; Fleming et al., 2016; Klausen et al., 2016; Flowerdew et al., 2019). These analyses indicate two main sources for the Triassic succession in GBSB: a south-southwestern source related to the Fennoscandian Shield and the Caledonides contributes with mature sediments with favorable reservoir qualities, while an eastern source from the Urals and the Siberian Traps provided immature sediments with poor reservoir properties. Using U-Pb analyses on detrital zircons for pin-pointing the source area and understanding their geodynamic evolution is therefore useful for predicting the reservoir quality.
Decades of hydrocarbon exploration in the GBSB have made it possible to obtain detrital zircon data from time-equivalent formations over large areas. The GBSB is therefore an ideal basin for a large-scale source-to-sink study of an intra-cratonic basin. By combining the previously published U-Pb data with new U-Pb analyses on stratigraphic intervals and geographic areas with low sampling density, we obtain a holistic view of the Greater Barents Sea Basin throughout the Triassic, with respect to temporal and spatial variations in sediment influx. This will provide information on the relative contribution from the different sediment sources in the basin, and furthermore, we will use these data to gain insight into the geodynamic evolution of the source areas.

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Glacial erosion estimates for the Dronning Maud Land Mountains, based on low-temperature thermochronology

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The Dronning Maud Land Mountains are regarded as one of the key nucleation sites for the 34 Ma East Antarctic ice sheet, as the high coast-parallel mountain range most likely attracted significant precipitation prior to the glaciation. The subsequent 34 million years of glaciation have certainly altered the landscape significantly. However, many ice sheet models use the present-day topography, isostatically relaxed to ice-free equilibrium, as an input parameter for models of the growing ice sheet. In order to improve estimates of glacial erosion and the resulting landscape changes since 34 Ma, we re-evaluate 55 previously published thermal models, based on low-temperature thermochronological data (apatite fission track, apatite and zircon (U – Th)/He), from western and central Dronning Maud Land. Our estimates of pre-glacial overburden amount to c. 0.2 – 1.5 km in western Dronning Maud Land and up to c. 2.4 km in central Dronning Maud Land. The ice sheet changed from being wet-based and

erosive, to cold-based and preservative at c. 15 Ma. Assuming that most of the erosion took place during the Oligocene to middle Miocene, we calculate mean glacial erosion rates of c. 10 – 80 (western Dronning Maud Land) and up to c. 125 m/Myr (central Dronning Maud Land). Most areas show moderately good correlations between elevation and erosion rate. Along the E – W-trending Dronning Maud Land escarpment, the highest erosion rates are found in the escarpment foothills, interpreted to be a result of escarpment retreat since the Jurassic Gondwana rifting. Variations along the NE – SW trending mountain range in western Dronning Maud Land are attributed to the proximity to present-day fast-flowing glaciers, or a combination of fast-flowing glaciers and escarpment retreat.

International Earth Science Olympiads: inspiring a new generation of geoscientists

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Since 2007, the International Earth Science Olympiads (IESO) have been held with participants from more than 30 countries. The Olympiad is aimed at stimulating the interest of upper secondary school students to discover the possibilities for further studies and professions in the natural sciences in general, and geoscience in particular. Each country is represented by four students and two mentors; during three days of competition, the students increase their knowledge in a range of geoscientific disciplines, such as geology, hydrology and meteorology, as well as other science subjects such as mathematics, physics and chemistry as integral parts of geoscience. Working and interacting with international students with a range of backgrounds, the participants broaden their horizons and develop an appreciation for the international aspects of the geosciences. IESO is arranged by the International Geoscience Education Organisation (IGEO). The 2019 IESO took place in South Korea where 26 countries were represented. Next year's Olympiad will take place in Russia. IESO are considered very prestigious in many countries, and the level is somewhat more advanced than what Norwegian students are taught in their upper secondary school curriculum. Norway participated for the first time in IESO in Santander, Spain, in 2014, and again in 2015 in Pocos de Caldes, Brazil; 2016 in Tsu, Japan; 2017 in Nice, France; 2018 in Kanchanaburi, Thailand and 2019 in Daegu, South Korea. The participants were selected based on competitive tests during local qualification rounds as well as a four-day national training and qualification session at the Department of Earth Science at the University of Bergen (UiB). Our students demonstrated that they meet the required standards as a silver medal was won in Thailand, and bronze medals have been won in all the Olympiads where Norway has participated. In several Olympiads Norwegian students have scored both silver and gold medals in international group-based fieldwork. In Norway, the interest for IESO has increased from 22 participating schools and 208 students in 2014 to 33 schools and 1001 students in 2019 as part of the qualification rounds. In Norway the recruitment for natural science education has been low for several years. Through the participation in IESO, the intention is to incentivize and stimulate the interest in the natural sciences. Even more essential than reaching the four students that qualify for the Olympiad, are the big number of students that participate in the qualification and especially the 16 that go on to the national final and training session in Bergen. At the training camp at UiB, the secondary school students meet university students and young researchers, and they get an introduction to field and laboratory methodology. Through national and international publicity on the achievements at the Olympics, it is our hope that more students will be inspired to pursue a career in natural sciences, and geoscience in particular.

Artificial groundwater injection/infiltration in large Swedish infrastructure projects

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This abstract summarizes a Master Thesis from the department of Environmental Engineering and Sustainable Infrastructure at KTH and was conducted on behalf of the Swedish transport administration (STA) to investigate the STAs usage of artificial groundwater injection/infiltration (AGWI). More specifically, it was conducted to align the AGWIs usage with the current and future climate situation/scenarios to view how the technique was and/or can be fit for a changed future climate.
The goal of this thesis was to increase the knowledge of AGWI. Firstly, a literature review was conducted which provided the theoretical background of the relevant science. Thereafter, several methods were utilized. Insight in the industry were gained through interviews, the cost perspective was provided by a cost analysis, generalizability through case studies of large infrastructure projects and finally a numerical model in MOD-

FLOW catered the theoretical computation of a generic AGWI context.
The results showed that the AGWI technique in Sweden has developed and is currently a subject of increased focus and demand from a legislator and designer perspective. Some of the reasons found for this development indicated tougher requirements of concrete in combination with increased urban subsurface development, such as the Stockholm City Line project, in conjunction with old infrastructure of lower groundwater stability requirements. With increased requirements, the cost of concrete has increased leaving AGWI to take the place of a fully sealed tunnel due to the relative low cost of an AGWI facility. The older infrastructure, such as the metro in Stockholm, is according to the interview, leaking more water resulting in the need of mitigating both the old and new infrastructure. More results show that the preconditions of the AGWI is changing, both geographically and temporally. Precipitation patterns, increased temperatures and groundwater levels, especially in the south East Sweden, is sinking. The cost analysis showed that the reinjection of the water used is 300 million SEK or 43% percent less expensive than the tap water alternative which oppose the common idea of tap water being the cheapest alternative.
The results lead to a recommendation to increase the demand of reinjection facilities, that the STA should view the operation and maintenance in a more sustainable way and to demand calculations of the AGWI costs in relation to water use and sustainability utilizing the future climate change estimation.

TeachOUT – an educational application to get kids into the outdoor classroom

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TeachOUT is a useful tool for teachers in all subjects, but especially in Natural Science. In Magma Geopark we provide trails based on our natural- and cultural heritage for the local schools. The application is GPS-based, and educators can create trails in an area of interest and attach tasks for the pupils/students. The educator can choose to add points to each task to get a winner, or he/she can choose to set a time limit to the trail if they have got limited time.
Magma Geopark use this educational application in their teaching in the geopark. We have used it on pupils in the range of 11 years old to grownups. We have also had several workshops with local teachers/schools, and TeachOUT is now being used all over the geopark.
The main benefit of TeachOUT is that you can educate people based on what is actually in your area, both natural- and cultural heritage. The pupils appreciate that the teaching is interactive, and the educator can provide assistance and guidance along the trail instead of trying to gather all pupils at designated posts to educate them as a group. It is also an advantage that when a lot of teachers use this application in an area you will get the possibility to share trails with each other. This results in more sharing and more knowledge transfer within the area. Thus, enlightening in the spirit of UNESCO.
Teachers all over Norway, and basically all over the world can get access to TeachOUT if they contact one of the founding geoparks.

Dating ore mineralizations in the Precambrian Varena Iron Ore deposit, SE Lithuania: baddelyite, zircon and monazite ages

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The Varena Iron Ore deposit (VIOD) in the Paleoproterozoic basement of western East European Craton, S Lithuania, is situated predominantly in former dolostones, that accumulated in a shelf environment along an older continental margin, established after ca. 1.84 Ga (Bogdanova et al., 2015).
High-grade skarns (forsterite, enstatite, spinel and diopside) were produced during metamorphism at 750^{o} C and 5-6 kbar. Mineral analysis indicate silica, magnesium, iron, calcium and alkalis transportation between carbonates and alumina-silicate rocks. The high-grade skarns were followed by fluid reactions and formation of amphiboles (tremolite, actinolite, anthophyllite etc) and phlogopite during subsequent uplift. Magnetite, sulphide, apatite, zircon, monazite and baddeleyite mineralizations are associated with the skarns. Although some magnetite was produced due to the higher-grade reactions, large amount of iron was brought or remobilized at low temperatures (ca. 300-400^{o} C) together with serpentinization and iddingsite formation.
A LA ICP-MS study was applied to the skarns in order to determine the age of mineralization. Sample 982-3 consists of thin, magnetite-rich and carbonate-dominated (with rounded serpentine and iddingsite grains) layers. Baddeleyite and monazite grains are in textural equilibrium with magnetite and other minerals. Both baddeleyite and monazite yielded ages of approximately 1730 Ma. The D8-1 phlogopite-rich serpentinite is impregnated by magnetite and crosscut by

magnetite, sulphide and carbonate veinlets. Irregular-shaped zircon grains intergrowing with magnetite produced somewhat ambiguous and scattered age results, with a main age group yielding ca. 1700 Ma.

The consistent monazite and baddeleyite ages indicate ore mineralization ca. 1.73 Ga, probably related to the second skarn formation event. It is semi-simultinious with ca. 1.73 Ga metamorphic reworking recorded in the neighbouring Lazdijai area and metamorphic overprint recorded by hornblende 40Ar/39Ar ages (Bogdanova et al., 2001). These events may be related to the TIB magmatism further west.

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Voluminous 1.54-1.40 Ga magmatism and metamorphism in the western East European Craton, Lithuania and Poland: are they manifestations of Danopolonian or other orogenies further west?

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Data obtained from the western East European Craton over the last few decades have recorded numerous Mesoproterozoic events in the crystalline basements of Lithuania, N Poland and NW Belarus. The 1.54 – 1.50 Ga Mazury AMCG complex crosscuts older complexes and extends hundreds of kilometres from the Baltic Sea through N Poland and S Lithuania to NW Belarus. Voluminous heat and fluid influxes resulted in extensive metamorphism and hydrothermal reworking of surrounding rocks at 1.55-1.43 Ga, as recorded by zircon, monazite and $^{39}Ar/^{40}Ar$ hornblende ages (cf Bogdanova et al 2001). Those intrusions host Ti-Fe deposits (N Poland) and are responsible for iron ore remobolization in the Varena Iron Ore deposit (S Lithuania) etc. A chain of younger ca. 1.46-1.44 Ga (cf Motuza et al 2006), granitoid intrusions lies along E-W trending shear zones in W Lithuania,reaches the surface on the Danish island of Bornholm (Zarins et al 2009) and are more or less contemporaneous with the 1.46–1.44Ga Stenshuvud and Taghusa intrusions in south-central Sweden. The most plausible scenario for those Mesoproterozoic events in previously consolidated crust is that, after the Gothian orogeny, rotation of the Craton triggered extension and voluminous magmatism in the E-W trending shear zones (Bogdanova et al 2008). The shearing, magmatism, following migmatization of the host rocks, metamorphism, hydrothermal reworking and ore remobilization can be attributed to a Danopolonian orogeny at 1.55-1.40 Ga (Bogdanova 2001). It overlaps with the Telemarkian (1.52 -1.48 Ga, Norway, Bingen et al 2001) and Hallandian (1.47 -1.38 Ga, Sweden, Hubbard 1975) orogenies to the west of the Baltic Sea.

This presentation is in memory of Svetlana Bogdanova who recognized and named the Danopolonian orogeny.

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Dynamic changes in fault permeability – How can experimental work provide support for fault seal integrity?

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Implementation of large-scale CO_2 storage will require utilization of a wide range of storage reservoirs including faulted reservoirs with structural traps, e.g. Smeaheia fault-block area. Within faulted reservoirs, both bounding faults and faults intersecting the caprock layer may act as seals. The flow properties of faults are challenging to predict, moreover, along-fault flow and dynamic changes due to reservoir pressure increases are poorly understood.

In this ongoing work, heterogeneities in fault rock properties and flow within faults are studied. Experimental data addressing intact and deformed rocks are re-visited to quantify the uncertainties related to static and dynamic fault rock permeability and provide input for numerical simulations addressing fluid migration within fault zones. The

analysis of experimental work addresses three main categories; (i) Stress dependent changes in permeability of intact rocks, (ii) Opening and closure of tensile fractures in low permeable units comparable to cap rock and (iii) Shear deformation along distinct slip-surfaces and related effects on permeability. The results indicate that stress conditions and dynamic change in pore pressure plays an important role for the flow properties. Tensile fractures with a good mating are observed to close under application of normal stress, and the permeability approaches that of intact rock permeability for silty sandstone. Fractures within clay rich formations, e.g. the upper Jurassic Draupne Formation, are found to be difficult to keep open for flow measurements using in-situ stress conditions. More dedicated work on this is needed, and it remains to be addressed to understand if this behaviour also holds for in-situ field conditions. The experimental data analysis on flow properties will be combined with detailed information on fault architecture from seismic interpretation of Smeaheia fault-block area. Together this will provide input for improved reservoir simulations to verify fault seal integrity and its impact on the CO2 storage capacity.

The patterns of fractures associated with fault terminations and step-overs within isotropic Mesoproterozoic Rapakivi granites, SE Finland

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Detailed mapping and analysis of brittle structures within the Mesoproterozoic Rapakivi granites of South-Eastern Finland aims at improving our knowledge about the patterns of secondary fractures related to narrow discrete faults with known geometries and kinematics. In specific, we aim to characterize the fracture patterns within contrasting types of damage zones such as i) adjacent to the fault surfaces, including curvatures of continuous faults (wall and fault bend damage); spatially associated with ii) fault terminations (tip damage), and iii) step-overs and intersections (interaction damage). The studied target is optimal as the rock is completely isotropic, has not been affected by the complex Svecofennian deformation and provides continuous high-quality glacially polished outcrops. The mapping utilized newly acquired drone-based orthophotographs upon which the fracture traces were digitized, followed by field mapping focusing on recognition of the kinematic sense of the fractures and fault zones. Moreover, detailed observation of the fracture patterns and topologies beyond the resolution of the drone-images was conducted and dip measurements for the planar structures were collected. As a result of the study, we found that the dominant structures of the area comprise two sub-parallel sets of sub-vertical faults with trace lengths up to 250 m. The faults with dextral and sinistral lateral movement senses but unknown displacement magnitudes strike 010 to 020 and 350, respectively. The results further indicate that the i) wing-crack type fractures defining the tip damage zones and ii) fractures at fault step-overs have significantly gentler dips than the approximately coevally developed sub-vertical background fractures outside the fault zones. Moreover, strikes of the fractures at fault step-overs are controlled by the step-over type, with largest angles between the developed fractures and the controlling faults observed at overlapping steps. The results of this study provide important insight into fracturing of crystalline rocks and may be applied for delineating and characterizing unexposed faults from regional fracture patterns. Moreover, the results may be further utilized in understanding how brittle faults contribute to the development of contrasting fracture domains at variable scales.

A new LiDAR-derived geomorphic map of Jämtland, central Sweden

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As a first step towards producing a detailed, digital, surficial deposits map of Jämtland, the Geological Survey of Sweden has produced a geomorphic map/database of the county. Landforms were mapped at a scale of 1:10 000 from the LiDAR-derived national height model. Tens-of-thousands of previously unmapped landforms including; crags-and-tails, drumlinoids, eskers, meltwater channels, paleo-lake shorelines, and ice marginal and DeGeer moraines have now been catalogued. These new data provide a test for the existing paradigm that Jämtland hosts a long, complex history of Quaternary glaciation. While these data appear to support that view, the detail of the current mapping elucidates new information about the last deglaciation of Jämtland. For example, while landforms indicating multiple ice-flow directions have been previously noted, it appears that at least three different ice-flow directions occur in some locations. We suspect that the flow set containing the smallest landforms is the

youngest, which would indicate a dynamic late-glacial ice margin, constrained by topography, and interacting with the numerous lakes dammed between the mountains to the west and the remnant ice sheet to the east. When completed, the database will be used as an aid in both mapping the surficial deposits and planning stratigraphic investigations that are critical to understanding the Quaternary history of Jämtland. Additionally, the data will be available for download and use by researchers and the public.

Mesozoic microfossils recovered from karstified limestone in the Tromsdalen Quarry, Trøndelag – Traces of an unknown inlier basin along the Møre Trøndelag Fault Zone?

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Analyses of unconsolidated sediments infilled in karstified, Ordovician limestone of the Vuddudalen Group, Central Norwegian Caledonides, in the Tromsdalen Quarry near Verdal, Trøndelag, revealed reworked Mesozoic palynomorphs, together with younger Quaternary/recent pollen and spores. Karst features are probably of Late Quaternary age, developed in a relatively pure limestone of more than 90 % calcite. The infill sediments comprise a greyish diamicton overlying red-brownish clay and silt. Along the Møre-Trøndelag Fault Complex (MTFC), Mesozoic submerged basins are proven in Edøyfjorden by drilling and in Beitstadfjorden with seismic reflection data. Mesozoic and Upper Paleozoic sediments are also found preserved in a fault zone running parallel to the MTFC beneath Frøyfjorden. Erratics with Jurassic plant fossils and coals are found at Verran at the west coast of Beitstadfjorden. Also, reworked Jurassic and Early Cretaceous dinoflagellate cysts are recovered from Quaternary cores off Tautra and Verdal. The reworked microfloras from the karst infill sediments at the Tromsdalen Quarry comprises Jurassic-Cretaceous taxa; likely also including species of Late Cretaceous age. To our knowledge Late Cretaceous fossils have never before been recorded from mainland Norway. These discoveries point to the presence of an unknown, Mesozoic inlier basin to the E of the inner part of the Trondheimsfjorden basin. Our primary model explaining the presence of these infill sediments is that they belong to a Late Quaternary/Holocene glacio-fluvial infill episode, and is derived from a larger, upstream provenance somewhere to the east of Tromsdalen. However, there is a need for follow up investigations.

Geological investigations and archaeological excavations revealed a 2500 year old quick-clay landslide in Hovin, Gauldal, Mid Norway

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In Hovin in the Gauldal valley there is a large ice-marginal deposit that once crossed the valley. The river Gaula has during history eroded the deposits, and former river terraces are easy to recognise on the southwestern side of the deposit. Just northwest of the ice-marginal deposit Sandbrauta is located, and in 2017-2018 archaeological excavations and geological investigations were carried out here. Firm, disturbed, clayey material covered sandy river deposits. On the surface of the clay layer there were old cooking pits. In the sandy sediments below the clay, a burial site/ritual site with graves, houses, cooking pits and traces of bronze casting were detected. Radiocarbon dating was done in organic material from the settlement traces. Here the oldest age *above* the clay was 2450 ± 30 ^{14}C years BP (TRa-13637), the youngest age *below* the clay was 2675 ± 20 ^{14}C years BP (TRa -12954). The clay covering sandy sediments in Sandbrauta are interpreted as deposits from a quick-clay landslide that occurred on the southeastern side of the ice-marginal deposit. Here a 300 000 m^2 large landslide scar was mapped (Bredlia). At the most there is 100 m height difference from the top of the backscarp to the outlet of the scar. In the early 2000s, 800 m from the landslide outlet, a 3 m long log was found, buried in sediments. Radiocarbon dation of the log gave the age 2623 ± 18 ^{14}C years BP (TRa-10982). The landslide was probably triggered by erosion from Gaula. The deposits crossed the valley and dammed the river. Some of the clay was squeezed through the relative narrow opening in the ice-marginal deposit, and deposited on Sandbrauta. According to the radiocarbon datings in the area, the landslide occurred around 2500 ^{14}C years BP (end of Bronze Age).

Groundwater as a tool for understanding part of a complex rock-slope failure area, Stampa, Western Norway

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On the eastern mountainside of inner Aurlandsfjord, Western Norway, a large unstable rock massif is in danger of forming a rockslide that may cause a huge and devastating flood wave in the fjord. Due to the high instability of the northern part of the rock massif, and the possible serious consequences, lots of investigations and monitoring have been done in the area. However, access to the area is difficult and transport of drilling rigs etc. is complicated and expensive. In this project, information on structural geology is obtained through inexpensive hydrogeological investigations to get a better understanding of the northern parts of the area.

Large open fractures in the bedrock are recharge areas for groundwater. Therefore, monitoring the response in existing groundwater wells and springs in the discharge area were the main method to investigate fracture connectivity and the groundwater pressure regime. Logging of water temperature, water level and electrical conductivity in wells and springs were combined with analysis of oxygen isotopes. The oxygen isotopes helped to improve the understanding of the recharge area and transit times. Temperature and conductivity data gave information about the impact of snowmelt and groundwater flow.

Existing structural data were combined with the hydrogeological data and formed the basis for a new conceptual model. This revealed two groundwater systems: one mainly in the unconsolidated sediments, and one in the bedrock.

The groundwater flow in the bedrock suggests that two separated rock massifs are present. A large fracture with impermeable sediments is interpreted to separate the two rock massifs. Rapid variations of groundwater level up to a specific altitude in one well, revealed the presence of an open fissure in the lower bedrock massif. Little runoff in the area, as well as documented submarine springs in the fjord, suggest that much of the water follows deeper routes.

Groundwater data turned out to be beneficial for understanding the geology of the area. The combination of different methods gave information that one method alone would not be able to provide. Compared to other methods, the hydrogeological investigations are inexpensive and valuable.

Reducing risk from rain induced geohazards; Klima 2050, a Centre for Research Based Innovation

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Klima 2050 (www.klima2050.no) is a Centre for Research-based Innovation (SFI) financed by the Research Council of Norway and 20 partners from research, education, public entities and industry, with the goal of reducing the societal risks associated with increased precipitation and flood water exposure to the built environment. NGI is responsible for the work package on 'water triggered landslides', comprising innovations in numerical codes for landslide modelling, mitigation measures, early warning systems, and management of landslide risk. Achievements so far include:

- Improved reliability of landslide hazard mapping through establishment of an event-based landslide inventory, field mapping and run-out back analyses of historic landslides, and improved input parameters for landslide models for Norwegian conditions.
- A web-based toolbox for selection of appropriate landslide mitigation measures for a given case (LaRiMit - Landslide Risk Mitigation Toolbox). The toolbox contains more than 70 different measures, including Nature Based Solutions (NBS).
- Establishing a base for improving landslide warning systems using locally monitored data, and follow this up by installation of in-situ instrumentation in potentially unstable slopes.
- Improving the use of thresholds in early warning by applying ML techniques and assess the influence of rare but important extreme events.
- Identification of needs and deficiencies in landslide risk management in Norway, and establishment of a framework for municipal management of climate related risks

Pilot projects will test new methods and services in close collaboration with user partners. Pilots may be physical objects or localized sites, or they may be databases or services. Two pilots were started in 2019:

- Instrument-based warning system as a mitigation measure in potentially unstable soil slopes. This pilot will also test out various drainage solutions for their effect on stability.
- Establish a warning system for one of Norway's touristic roads, 'Trollstigen', based on improved

analyses of weather systems and the use of radar data.

Exploration of manganese crust in the Norwegian Sea

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The law on seabed minerals activities on the Norwegian continental shelf entered into force on 7 July 2019. The Ministry of Petroleum and Energy (MPE) is designated as the competent authority for the management of these resources. The NPD, which is the regulatory agency under the MPE, is delegated the tasks of mapping and assessing the resources, as well as managing all data and representative samples of seabed minerals collected from the Norwegian continental shelf.
Since 2011, the NPD together with UiB, have carried out annual marine data and sample acquisition cruises mapping the seabed in the Norwegian Sea. A large number of manganese crust samples have been collected during these cruises. Crust thicknesses up to 20 centimetres are recorded. At present, 63 samples are analysed for main and trace elements. Highlights from the geochemical analysis will be presented.

Formation of ribbed moraines and their connection to subglacial lakes

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The origin of ribbed moraines (rogen moraines) is a long-discussed topic in the field of geomorphology, and as of yet, no consensus on their formation principles has been reached. In my ongoing master thesis, we are testing whether ribbed moraines could be formed in areas of water-saturated till or even shallow subglacial lakes during the Weichselian glaciation. This hypothesis, put forward by Sollid and Sørbel (1994), evolved from observations that ribbed moraine fields are mainly found in depressions in the Scandinavian landscape. The discovery of subglacial lakes beneath the Antarctic ice sheet (Siegert et al, 2005) has further strengthened the hypothesis that water was also present at the glacial bed during the last fennoscandian glaciation, with water collecting in terrain depressions. We investigate this hypothesis in two steps. Firstly, ribbed moraine fields in the Beitostølen-Langsua area of central Norway are mapped and analysed spatially. During this work, we identified spatially confined areas of ribbed moraine fields in close relation to other subglacial landforms such as hummocky terrain, flutings, eskers, and glaciofluvial channels. Secondly, we modelled the subglacial hydrology of the last fennoscandian ice sheet to infer routing and build-up of water at the ice sheet bed. This is done by calculating the hydraulic potential (based on Shreve, 1972) from present day topography as well as ice thickness and isostasy approximations from known models. Preliminary results indicate that areas of low subglacial hydraulic potential (i.e. presence of subglacial lakes) and areas of ribbed moraine overlap. Further, geomorphological mapping also indicates rapid water flow (glacier-directed channels and dry canyons) from and between areas of ribbed moraines. We suggest that a landform assemblage consisting of ribbed moraines, glaciofluvial channels and drumlinoide landforms are indicative of areas of low subglacial potential and water accumulation at the glacier bed.

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The evidence of repeated climatic changes in a Cryogenian glacial sequence – the Port Askaig Formation, Argyll, Scotland

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The Port Askaig Formation (PAF) is a diamictite-bearing succession in the Dalradian Supergroup that provides an excellent archive of a Cryogenian glaciation in the Garvellach Islands and Islay in Argyll. The formation is approximately 1100m thick there and includes 47 diamictites interbedded with siltstones, dolostones and sandstones. Many of the diamictites were deposited from grounded ice sheets (as evidenced by glaciotectonic structures, boulder pavements, aligned boulders). A few diamictites were ice-rafted (dropstones). Many horizons show evidence of periglacial conditions (frost-contraction cracks preserved as sandstone wedges, frost-shattered clasts, frozen clasts, cryoturbati-

ons). The interbedded non-glacial sediments formed in shallow marine, lacustrine and fluvial environments.
Most of the basal contacts of the diamictites are sharp, recording the switch from non-glacial to glacial environments; one basal contact preserves evidence of the change from non-glacial to periglacial to glacial environments. Many of the top contacts of the diamictites show evidence of periglacial conditions: recording the change from glacial, to periglacial to non-glacial environments. The succession in the PAF records a total of 76 climatically-related stratigraphic episodes: 28 glacial episodes, 25 periglacial episodes and 23 non-glacial episodes.
Compared with other Cryogenian (and Phanerozoic) glacial successions, the PAF is exceptional in its combination of formation thickness, the number of climatically-related stratigraphic episodes and the considerable thickness (25km) of its host Supergroup. It does not fit the standard model of a Cryogenian 'Snowball Earth' glaciation.

Technology advances in North Sea exploration

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Equinor ASA

In despite of decades with gradually declining discovered resources, the North Sea exploration activity is still relatively high and delivers from time to time high-value discoveries. Exploration is increasingly challenging with structural closures drilled and leaving future targets in the prolific plays more subtle. Recent activity shows that the industry still has appetite for testing high-risk new sub-plays and unproven play concepts with alternative source rocks.
New technology has sparked some optimism and includes the construction of extensive well and seismic datasets, improved data access, faster computing, new data type combination and machine learning algorithms. In addition to revealing regional trends, these techniques can lead to new prospect identification.
In recent years, Equinor has put much effort into building a consistent seismic and well dataset covering Norway-UK sectors. Dense 3D seismic coverage allows us to make a seamless, high-resolution framework from which regional and detailed prospect-scale work are undertaken. Well analytics initiatives include fast extraction and spatial display of well interpretation, quality control, trend correlation, machine learning, and prediction tests. Compared to traditional approaches, the new computerized techniques provide a fast zoom-in/zoom-out method with more models to test and applied across the basin.
The Upper Jurassic petroleum system has been assessed using quantitative methods for source rock characterisation, hydrocarbon generation, migration and comparison of volumes generated vs discovered. Integrated with reservoir fairways, well shows data and hydrocarbon prediction, such models trigger discussion and new ideas. In this way, interpreters can conceptualize and develop models for subtle traps, new play models, and prioritize from portfolio.

Re-Os dating of the Mjølnir meteorite impact, Barents Sea

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The ~1.5-km-wide Mjølnir meteorite smashed into the Cretaceous marine seabed (Bjarmeland platform) with an estimated paleowater depth of ~400 meters at ~142 Ma, leaving a ~30-km-wide crater [1,2]. The impact affected several km of Jurassic-Triassic sections resting on the upper Permian at ~4 km depth. Biostratigraphic estimates for the impact age are based on the appearance of a prolific bloom of *Leiosphaeridia* that appeared post-impact and covered shelf areas adjacent to the impact site [1]. The assigned biostratigraphic age for this widespread algal bloom is 142.2 ± 2.6 Ma [1], whereas others have assigned a less precise age of 142 ± 6 Ma for the impact, based on the obsolete Volgian-Ryazanian stage boundary [2]. Here, we present the first radiometric age (Re-Os) for the Mjølnir impact, demonstrating that biostratigraphers and geochronologists are an essential pair for Geologic Time Scale work. Re-Os dating of a meteorite impact is a tricky endeavRor. An impact site destroys any semblance of earlier bedding and geologic relationships, with ensuing high-energy breccias, impact debris, and turbidite flows cast into a chaotic infilling of the crater in a matter of hours to days. *In this study, we apply a novel and untested approach:* We sampled a shale section beginning ~1 cm above the uppermost debris horizon. The remarkable isochroneity in immediately overlying shales shows that normal marine seawater was immediately re-established after the impact. In our study, we demonstrate agreement between relative ages established by biostratigraphers, and a Re-Os radiometric age that pinpoints the impact in absolute time at 141.9 ± 2.7

Ma (n = 14, MSWD = 4.6). Further, the Os initial ratio ($^{187}Os/^{188}Os$ = 0.595 ± 0.033) carries essentially no trace of the extraterrestrial body, given now well-established initial $^{187}Os/^{188}Os$ ratios for shale sections in the region [3].

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Seabed minerals of the Mohn's Ridge, Norway – the 2019 NPD survey

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In 2018, the management of Norwegian seabed mineral resources were given to The Ministry of Oil and Energy. The NPD, as the Government agency for the management of offshore geo-resources, are responsible for resource mapping and estimates, and for storage of all data and representative samples collected from seabed minerals within the Norway boundaries.

As a continuation of the 2018 survey on the Mohn's Ridge in the Norwegian Sea, the NPD, successfully completed a marine data survey and sample acquisition cruise in August-September this year. Using multiple AUVs simultaneously, a total of 3900 line-km of geophysical data was acquired. A previously unknown sulphide deposit was discovered, and an inactive black smoker field was verified, both at depths of 2800-2900 metres. Samples were recovered by use of ROV. Geophysical and geochemical analysis and conclusions from the survey are not yet available, but some preliminary results will be presented.

Elevated concentrations of manganese in some Norwegian groundwater waterworks: a possible explanation

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The waterworks at Ringerike and Lillehammer are among the largest groundwater waterworks in Norway, supplying about 25000 customers each with approximately 100 l/s. The productions wells are located in glaciofluvial aquifers close to riverbanks, securing groundwater recharge through bank filtration. Both waterworks have experienced problems with elevated concentrations of dissolved manganese after some time of operation. This has led to construction and plans to construct costly treatment plants at Ringerike and Lillehammer, respectively. Yet the cause of the problem is still uncertain. A possible explanation is related to the natural geochemical processes that occur during bank filtration. If the river water is rich in organic matter, the oxidation of this material will lead to oxygen depletion shortly after infiltration, yielding reduction and dissolution of iron and manganese. Around the production well, an oxic environment prevails due to oxygenation by gas entrapment caused by frequent groundwater table fluctuations. This leads to iron oxidation and subsequent precipitation of iron hydroxides in the sediments before the groundwater enters the production well. However, manganese oxidation kinetics are slower and craves more oxygen than iron oxidation. This facilitates the breakthrough of high manganese concentrations in the produced drinking water. The breakthrough can be damped by sorption to aquifer sediments, dependent on the sorption capacity of the aquifer sediments, primarily related to clay and organic content, and the composition of the infiltrated water (Farnsworth & Hering, 2011). In long-term this sorption capacity will be used up, as has been shown for a wastewater infiltration basin Israel, where elevated manganese concentrations appeared 500 m away from the plant after 8-12 years of operation (Oren et al, 2007). The data material available for the waterworks at Ringerike and Lillehammer is too scarce to conclude on this explanation. However, it's in the authors view that it would not take too much work to acquire data to affirm or reject this hypothesis. The data needed will be discussed during the presentation.

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Volcanic cooling followed by a warm and wet Paleocene-Eocene Thermal Maximum in Denmark

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The Paleocene-Eocene Thermal Maximum (PETM; ca. 55.8Ma) was an extreme global warming event initiated by a substantial release of $\delta^{13}C$-depleted carbon to the ocean-atmosphere system. It coincided with the opening of the North Atlantic and emplacement of the North Atlantic Igneous Province (NAIP), causing large magnitude carbon release potentially triggering the initiation of the PETM.
One of the best exposures covering the PETM interval is found on the island of Fur in northwest Denmark, where a c. 60 m thick sedimentary succession of marine clays and diatomite with c. 180 interbedded tephra layers of NAIP origin crops out. The section covers the onset-, body-, and recovery phase of the PETM, with exceptionally well-preserved sediments allowing for a high-resolution multi-proxy investigation of the environmental and climatic response to the large carbon release.
Here, we present a multi-proxy study including results from the organic palaeothermometer TEX_{86}, mineralogy, and organic and inorganic geochemical proxies. Our results indicate a temporal regional cooling of sea surface temperatures (SST) immediately below the PETM onset, most likely caused by degassing from NAIP volcanism. The PETM onset is defined by a negative ~4.5 ‰ $\delta^{13}C_{TOC}$ carbon isotope excursion. SSTs increase substantially during the PETM onset, coinciding with a shift to anoxic ocean conditions and substantially increased weathering rates. The PETM body is characterised by sustained high SSTs, high weathering rates, and steadily increasing TOC, before all decrease during the recovery phase. Our results highlight the rapid environmental response to large carbon emissions, and have implications both for our understanding of the regional climatic impacts of large igneous provinces, and for the emplacement history of the NAIP itself.

Using broadband seismic data to reveal the nature of the acoustic basement offshore SW Norway

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The onshore bedrock geology of SW Norway is well exposed and mapped in detail, and its lower to middle Paleozoic evolution is well known. Offshore, exploration for hydrocarbons has led to a thorough understanding of the Triassic-Early Cretaceous North Sea rift history, whereas the nature and evolution of the crystalline basement is very poorly known. Structurally, the coastal regions of SW Norway are dominated by extensional shear zones, notably the Bergen Arc Shear Zone and Nordfjord-Sogn Detachment Zone. Several basement shear zones have recently been interpreted in the northern North Sea rift basement, based on 2D seismic data (Fossen et al., 2016; Fazlikhani et al., 2017; Lenhart et al., 2019). New CGG regional 3D broadband seismic data are now taking mapping of the top basement and intra-basement structures to a new level. Here we will focus on two key observations from these data:

1) The transition in bedrock geology from the Bergen Arc Shear Zone to the Nordfjord-Sogn Detachment Zone at 61 °N has been a matter of debate. The transition is covered by ocean, but the offshore broadband data reveal a connection that relate to the general set of E-W folds affecting the coastal area (including Devonian basins) to the north. Hence the Bergen Arcs at least in part be associated with this fold system.
2) Impressive Devonian basins (Hornelen, Håsteinen, Kvamshesten and Solund basins) in the hanging wall of the Nordfjord Sogn Detachment Zone represent erosional products of the Devonian Caledonian mountains. These basins are bounded by a low-angle westerly dipping detachment fault and steep and straight lateral faults, and the basin fill shows a characteristic cyclic repetitions of easterly dipping sandstones and conglomerate units. We have discovered an offshore basement structure on the seismic data that is reminiscent of the structure of onshore Devonian basins. We identify seismic patterns that may be interpreted as cyclic stratigraphic units and straight lateral ENE-WSW trending faults some 6 km apart, defining a basin of ≥ 18 km length. The structure is seen south of the offshore extension of the Florø Horst. The internal reflection patterns show NW dipping layers, suggesting that the possible basin would have a polarity opposite to that of the onshore basins.

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Polyphase macro- and mesoscale interference folds and their relation to ductile shear zones and thrusting in the Palaeoprotrozoic Karasjok Greenstone Belt at Lakselv, Finnmark

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The Karasjok Greenstone Belt (KGB) is a N-S trending supracrustal belt in Northern Norway. The KGB may comprise economically important mineral resources. Thus, a better understanding of ore genesis and structural architecture is key information for future exploration. The purpose of the present study (master thesis) is to perform detailed structural analysis based on field work combined with previous geological maps and integrated with high-resolution ortho-photos and aeromagnetics data from Lakselv, as a basis for interpreting in more detail the structural architecture and compare it with less exposed areas of the KGB. According to the previous tectonic model (Braathen & Davidsen, 2000), the D1 episode is characterized by major thrust detachment zones at the base, internally, and near the upper boundary of the belt. These are associated with N-S trending regional scale recumbent isoclinal folds that invert large parts of the stratigraphy. The D2 episode is evident by SW-verging asymmetric folds and basal thrusting with a top-to-the-SSW shear component. The D3 event is marked by N-S trending upright folds that partly refolded the D1 and D2 structures. Our fieldwork and collected data do not indicate any major D1-D2 ductile thrusts, they have however been interpreted from geophysical modeling and observed farther south in the belt (Braathen, 1991). Still, the stratigraphic sequence is partly inverted, likely due to small-scale overturned folding and possible imbrication. A detailed study of F1, F2 and F3 folds in the area shows a Ramsey type 2 and 3 polyphase interference fold pattern. This pattern suggests NW - directed folding and imbricate shearing for the D1 deformation event, followed by strongly asymmetric SW-vergent shear folding (D2 event), and finally moderately plunging drag folds related to steep, dextral and sinistral, transpressive ductile shear zones (D3 event). The D1 and D3 events in the Lakselv area are not evident farther south in the KGB, where mostly linear/regular NW-SE striking magnetic anomalies are shown, which in turn might correspond to D2 structural trends seen in Lakselv. The southernmost part of the KGB shows an anomaly pattern that resembles the polyphase fold interference and shear zone pattern at Lakselv. The proposed new D1 model with imbricate folding and associated local inversion may correspond with structures in the north-eastern parts of the Kautokeino Greenstone belt and magnetic anomalies within the Jergul Gneiss Complex (Henderson, et al., 2015). Our findings call for detailed structural investigations of the kind recently performed successfully, in e.g. the Kautokeino Greenstone Belt.

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NCS Exploration: Proud history – future growth?

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Since the first licensing round in 1965, the Norwegian Continental Shelf (NCS) has had a proud and successful exploration history, and Norway is today Europe's second largest oil and gas producer after Russia.

Currently Norway produces nearly 2 million barrels of liquids and about 350 Million Sm3 gas per day from 87 fields. As new fields come on stream and lifetime extensions to many old giants continue, the production is forecasted to reach a new peak in 2023.

The total recoverable resources are estimated to almost 100 billion barrels o.e. After 50 years of production, about half is produced. With close to 25 billion barrels o.e. yet-to-find, the Norwegian Continental Shelf (NCS) still offers significant remaining potential both in mature and frontier areas.

The NCS remains attractive to a diverse range of players based on its petroleum potential and extensive infrastructure, supported by a stable, predictable regulatory framework designed to stimulate exploration. Extensive coverage of broadband 3D seismic has recently led to a renew-

al of industry prospect portfolios to support a sustained high exploration activity.
The Norwegian authorities have for almost three decades provided easy access to released subsurface data through DISKOS, the National Data Repository. This now allows for rapid implementation of big data analytics and artificial intelligence tools to support generation and maturation of the next generation of prospects on the NCS.

Global paleobathymetry for the Eocene – Oligocene boundary: Influence on ocean circulation and climate

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The Eocene-Oligocene boundary (~ 34 Ma) marks a turning point in the transition from a warm greenhouse climate to a cold icehouse climate in the Cenozoic time (66 – 0 Ma). Around this boundary, geological evidence shows the first signs of ice sheets on Antarctica, and evidence of ice rafted debris offshore East Greenland. Topographic changes, especially the opening and closing of strategic oceanic gateways, have been proposed as triggers for this climate cooling. A popular hypothesis is that the opening of the Southern Ocean through the Drake Passage and the Tasman Gateway facilitated flow of the Antarctic Circumpolar Current that caused thermal isolation of Antarctica, enabling the first Antarctic ice sheets to grow. We have developed a new paleobathymetry/topography model for the Eocene-Oligocene boundary and implemented our reconstruction in a climate model (i.e. the NorESM). Our new topography model shows that changes in Northern Hemisphere oceanic gateways also occurred around this time, especially in the NE Atlantic Ocean and the Tethys Seaway. Tectonic changes in these gateways could have been important for ocean circulation and climate. To test the influence of oceanic gateways on the cooling climate near the Eocene – Oligocene boundary, we run the NorESM with input Eocene-Oligocene topography. We change the bathymetric configuration of the most important oceanic gateways (i.e. the Drake Passage, Tasman Gateway, Greenland – Scotland Ridge and the Tethys Seaway), where all the scenarios are detailed realistic reconstructions within error of our model. Our model results quantify how the ocean circulation and climate responds to the evolution of the most important oceanic gateways, and provides new insight into the processes that triggered past climatic changes.

Diversity of mineral deposits in ultraslow-spreading systems: insights from the Arctic Mid-Ocean Ridges

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Anomalous high hydrothermal activity has been documented at the slow- and ultraslow-spreading Arctic Mid-Ocean Ridges. More than 20 unique vent fields, both active and extinct, has been documented by the University of Bergen during the last two decades. Autonomous underwater vehicles equipped with multibeam echo sounders and synthetic aperture side scan sonars enable us to explore geological processes in these inaccessible deep-sea areas. High-resolution maps and images combined with in-situ ROV sampling allow an improved spatiotemporal understanding of volcanic- and hydrothermal systems. In the Norwegian-Greenland Sea, two contrasting geological settings may promote the formation of mineral deposits. Parts of the ridge segments are characterized by high magmatic activity resulting in axial volcanic ridges (AVRs) that can be as much 30 kilometers long. In these areas, active venting are concentrated along faults and cracks with the hydrothermal flux depending on the magmatic heat. Large detachment faults, commonly developed where tectonic activity accommodate most of the spreading, expose the upper mantle and lower crust on the ocean floor. Persistent hydrothermal circulation along these faults lead to mineralization, often rich in copper and zinc due to the influence of ultramafic rocks. Here we present preliminary results from both of these geological settings highlighting the need for an integrated approach during exploration of mineral resources.

How to plan the perfect field course … – *for students, the environment and society*

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We present the evolution of the course "Field methods in hydrogeology" during the last three years, sharing insights on how to integrate student feedback in the course design.
This two-week course has run annually for more than 30 years, and the learning objectives include practical skills fundamental for hydrogeologists in academia, industry and environmental management. Field sites are selected based on scientific relevance, accessibility and societal impact. The training is research based where students are expected to learn methods, collect data in the field and interpret results. The students develop their ability to compare methods and environments, perform critical data analysis and present results adapted to different audiences. Real environmental challenges are addressed.
Overall, the course design is intact with preparation before the fieldwork, collecting data in the field and processing the data afterwards. However, we have added several small (but effective) interventions to improve the alignment of learning goals with the evaluation format. Student feedback on the teaching is used to inform the development of the course. The "traditional" field report has been replaced with digital data reporting during the field work, adding to a collective course database for current and future students. After completing practical tasks, the students select different research questions, which are investigated by integrating theory and the collective course database and finally presented in an interactive evaluation session. Findings relevant for local stakeholders are extracted and summarized in a popular science press release. Field data are published at ngu.no
Preliminary analysis of the new evaluation format indicates deeper scientific learning. However, changes in the evaluation design require thorough meta-communication to ensure student autonomy. Focus on dissemination to different audiences and publication of data improves societal relevance of the course. A new field location will be selected for summer 2020, and further adjustments will be made, potentially also implementing suggestions from the NGWM 2020 audience!

Hydrogeological characterization of Holocene deposits in the Svelvik aquifer – implications for reservoir properties

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The Svelvik ridge is a Holocene ice contact deposit located near Drammen in the Oslofjord. It is a test site for shallow CO_2 injection, where the aim is to improve monitoring techniques and extend the knowledge base for storing CO2 underground in geological reservoirs as a climate mitigation strategy. In order to predict how water and gas will behave in the reservoir, a solid geological model is fundamental. There has been extensive research focused on monitoring injection and migration of CO_2 in this shallow aquifer. There was, however, a need to improve the geological model and consider geological heterogeneities (i.e. the distribution of permeable sand versus sealing layers of silt and clay), in order to evaluate how internal layering affects reservoir properties. A detailed analysis of climatic evolution and changes in depositional environment has been performed. Analysis of new data from wells (cuttings sediment samples, wire line logs) and comparison with existing data (e.g. seismic lines, georadar profiles) indicate upwards shallowing and upwards freshening trends through the stratigraphic succession, i.e. variation in palynomorph assemblages. Data was provided by ECCSEL Svelvik CO2 Field Lab operated by SINTEF. Various thicknesses of stacked aquifers and degree of internal heterogeneity (clinoforms, unconformities, faults) are observed. This will affect CO2 distribution in the test reservoir, and is likely to lead buoyant fluids along preferential flow paths towards the North. Integrated data analysis has improved the geological understanding of the Svelvik stacked aquifer system, which may be utilized in future reservoir applications and safe storage of CO_2.

Earthquake-induced squeeze-up moraines in Sodankylä, Finnish Lapland

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Northern Fennoscandia has experienced high-magnitude earthquakes attributable to the release of lithospheric stresses within the glacial isostatic adjustment (GIA) (Arvidsson, 1996). Model predictions by Wu et al. (1999) suggest that the onset of fault instability started at 15 ky and that the maximum fault instability was reached at 13-10 ky in Fennoscandia, hence we postulate that not only

subaerial, but also subglacial types of deformations may have been associated with the past seismic events (e.g. Sutinen et al., 2019). Based on LiDAR DEM observations on landforms, such as rim-ridged/arcuate Pulju moraine and squeeze-up ridge fields may be linked to subglacial earthquakes within GIA. We applied sediment electromagnetic (EM) anisotropy data to judge if the irregular groupings of straight or curvilinear and transverse-to-ice flow ridges are comparable to annual or ice-marginal end moraines or if these display evidence of squeezing processes, eventually associated with subglacial seismic impacts. The studied bedforms are located 20-40 km down-ice from the NNW-SSE-trending Vaalajärvi-Ristomännikkö postglacial fault (PGF) complex exhibiting up to 7-km-long and 7-m-high fault scarps and hosted multiple slip events ranging in magnitude between $M_w \approx 6.7$-7.0 (Ojala et al., 2019). The EM anisotropy was not parallel-to-ice flow, but rather along the crest lines of the ridges supporting the squeezing hypothesis for the transverse-to-ice flow ridges. In addition, the EM anisotropy data on a complex of arcuate/semi-circular Pulju moraines, spatially associated with transverse-to-ice ridges, were also found to be attributed to the squeeze-up processes. We propose these transverse-to-ice flow ridges and the Pulju moraines are subglacial bedforms and the driving force for the ice crevassing was earthquake (s), which created pathways for saturated material to squeeze into the fractured ice system.

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The retreat history of the Scandinavian Ice Sheet from the coast of Northwest Norway and into Sunndalsfjella-Dovrefjell mountain massif inland

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We present the deglaciation history along a transect from Kristiansund at the outermost coast of the northwestern sector of southern Norway to the central mountain valleys in Sunndalen-Dovrefjell. The reconstruction is based on mapped moraines, sea-level data and exposure- (^{10}Be) and radiocarbon dates. We conclude that the Scandinavian Ice Sheet started to retreat from the outermost coast at around 14.5-15 ka, probably in response to the Bølling warming. Most of Sunndalsfjorden and almost all of Romsdalsfjorden were ice-free after some few hundred years with rapid ice-margin retreat in the fjords. During the Younger Dryas, probably in a late phase of this cold spell, the ice front was located at the Gikling terminal moraine across the Sunndalen valley. This prominent end moraine is correlated with distinct lateral moraines in Sunndalsfjella further inland, which in turn correspond to ^{10}Be-dated moraines 1300-1400 m a.s.l. along the valley Drivdalen. We find it likely that the corresponding ice dome, that at this time sent long ice tongues all the way down to sea level, was located over the Jotunheimen mountain massif where the ice surface must have reached up to 1500-2000 m a.s.l. However, it seems clear that during the Younger Dryas there were large ice-free areas in adjacent mountain areas to the north of Jotunheimen.

Preliminary understanding of giant tsunamigenic landslides in Greenland

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On 17th of June 2017 a rock avalanche occurred in Karrat Fjord, western Greenland, causing a tsunami that flooded a nearby village and took four lives. The disaster highlighted the need for an assessment of the risk of large, tsunamigenic rock avalanches and motivated a landslide screening led by the Geological Survey of Denmark and Greenland comprising, among many other things, a preliminary landslide inventory for Greenland.

The inventory highlights the geological Nuussuaq Basin in western Greenland as a locus of landslides and furthermore stresses the anomalous character of the Karrat 2017 rock avalanche, situated in an area of relatively few historic and pre historic landslides relative to the Nuussuaq Basin. Two historic rock avalanches in 1952 and 2000 both occurred in

the Nuussuaq Basin and may serve as a model for landslides in this area.

New analysis of the 2000 Paatuut rock avalanche shows that it caused a near-field tsunami of 35-50 m run-up that razed part of the abandoned mining settlement of Qullissat 25 km across the strait with a run-up of 10-12 m. However, the amount of material entering the sea in this event is still uncertain. The material mobilized comprised both thalus and previously displaced bedrock. Analysis of old Landsat satellite images indicates that a giant precursor landslide occurred 3-4 years before the main landslide in 2000.

Analysis of historic reports of the 1952 landslide shows that the landslide caused a tsunami of 1.5 to 2 m run-up in Qullissat, 30 km away. The tsunami took the life of a fisherman working on the coast c. 10 km from the landslide. Preliminary volume estimates based on photogrammetrical analysis of historical images and recent bathymetric studies offshore the site indicates that more than 6.5 $x10^6$ m^3 of thalus were mobilized and 2.5 x 10^6 m^3 entered the sea.

A better understanding of past events is fundamental to the assessment of the continued risk of large tsunamigenic rock avalanches in Greenland. Furthermore, the temporal evolution of previous landslides and currently instable slopes will be compared with climate models to evaluate whether the warming in Greenland is affecting slope stability.

Mercury loss from black shale during contact metamorphism and the implications for using mercury as a volcanic proxy

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Mercury is released to the atmosphere during volcanic eruptions and incorporated in living organisms. Bulk rock mercury concentrations, in particular when normalized to the content of total organic carbon (TOC), are a proxy for volcanic eruptions that links Large igneous provinces with environmental changes. Mercury records are published for many LIP-related events including the end-Permian, the PETM, the end-Triassic, and the Toarcian. Here, we challenge the idea that mercury is a unique tracer for gas release from magma during volcanic eruptions. We show that sediment-hosted mercury may get mobilized and released to the atmosphere by metamorphic and hydrothermal processes. We present data from contact aureoles in black shale from the Karoo Basin (South Africa; the Karoo LIP) and from the Oslo Rift (Norway; the Skagerrak-centered LIP). During metamorphism, the TOC content decreased in the studied shales from background values (10–15 wt.% in two of the cases), to 0–1 wt.% near the intrusion contacts. We show that the mercury concentrations in the shales correlate with the TOC, and that the shales likely lost most of the mercury during heating and organic matter transformation. The aureole gas generated in the Karoo Basin, including the mercury, escaped to the early Jurassic atmosphere through explosive pipe structures. Our findings demonstrate the importance of volcanic-induced mobilization from the vast organic-bound mercury reservoirs in sedimentary basins.

The Palaeozoic-early Mesozoic evolution of East Greenland: insights from apatite fission track ages and fieldwork: implications for exploration in Mid-Norway

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There is growing interest in the hydrocarbon potential of the Palaeozoic-early Mesozoic succession of Mid-Norway. Analogous stratigraphy is well-exposed in East Greenland and offers a natural laboratory for investigating the offshore potential. The succession in East Greenland reveals all of the elements required for a petroleum system. Protracted rifting between Greenland and Norway took place from the Palaeozoic to the Cenozoic, culminating in the Eocene separation of the Jan Mayen microcontinent from East Greenland. This has resulted in a number of seismically resolvable regional unconformities and a series of west-tilted half-grabens that are mostly filled with Mesozoic sediments. The timing of rifting and its control on sediment accumulation and dispersal is relatively well understood from the Jurassic onwards. The earlier rift history is more problematic, with loose constraints on the timing of rift inception and little established linkage between subsequent rift events and sediment deposition. Apatite fission track data and field evidence are presented, which challenges the conventional view that rifting initiated in East Greenland in the late Devonian. Instead, our evidence suggests that rifting did not commence until the Late Permian when a tectonic regime

change took place and a marine transgression resulted in the accumulation of organic-rich muds that were the first potential source rocks deposited in the Greenland-Norway rift. Continued rifting accompanied the deposition of thick and laterally extensive turbidite sands in the Early Triassic, which may form significant hydrocarbon reservoirs in Mid-Norway. As drilling campaigns begin to penetrate older parts of the Mid-Norway succession, East Greenland outcrops provide key insights into the geology and hydrocarbon potential.

Longevity of transverse folds in multi-stage rift basins; a case from the Fingerdjupet Subbasin

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In extensional fault systems with associated basin formation, transverse folds related to displacement variations along normal faults modify accommodation and facies distribution. Transverse hanging wall synclines are typically associated with maximum fault displacement, while transverse hanging wall anticlines form at the boundaries between fault segments. As rifting evolves, fault segments interact and link to form fewer but larger through-going faults. The location of maximum displacement and associated hanging wall transverse syncline migrate accordingly.
General models predict that continued displacement of the mature fault system should overprint transverse folds generated prior to linkage. In this contribution, we consider several cases where transverse folds display a conspicuous longevity, not only within single rift events, but also through successive rift events with different modes of fault reactivation. The persistence of transverse folds encompass reactivation through (i) upward propagation of pre-existing segments at depth, as well as (ii) dip linkage of vertically isolated segments.
Fault segments in the Terningen Fault Complex, which bound the Fingerdjupet Subbasin in the southwestern Barents Sea, were decoupled for >100 Myrs before achieving dip linkage. Still, a major hanging wall transverse anticline was maintained in succeeding rift events, suggesting the deep structural grain had a strong control on younger fault activity. Relay zones between young fault segments developed in the same position along fault length as older relay zones despite nucleating from significantly higher stratigraphic levels. These linkage sites remained vertically stationary through at least four rift events spanning >200 Myrs. Vertical correlation of relay zones (and associated hanging wall transverse anticlines) between non-linked shallow and deep structures suggests reactivation of the deep structure is dominant, and influences the distribution of displacement on the shallower structure. As such, the position of hanging wall transverse anticlines remains stationary after both structures become vertically linked (dip linkage). Additionally, young faults that nucleate in the overburden of older faults might preferentially propagate through weakness zones set up by differential compaction across the older faults; the shape and positions of these zones are controlled by the morphology of the deeper fault system.

Slope deformation above the Tungnakvíslarjökull outlet glacier in western part of the Mýrdalsjökull glacier

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A large slope failure was discovered in June 2019 in the mountain side north of the Tungnakvíslarjökull outlet glacier in the western part of the Mýrdalsjökull glacier in Iceland. A group of scientist from the University of Iceland have worked on collecting data from several sources and installed monitoring equipment at the site. According to observations, which were based on comparison of DEM from aerial photographs at different times, the slope has been moving since at least 1945, probably earlier. The rate of movements has been estimated for the period from 1945 to 2019. The data show that the maximum total displacement since 1945 is around 180 m. It is also found that the rate of movement has not been constant over this time period. The maximum rate is found between 1999 and 2010. During that period the total displacement was as high as 100 m. The head scarp of the slide, which is almost vertical, is around 2 km long and the sliding area is around 1 km2. The entire slope shows signs of displacement and is heavily fractured and broken up.
A GPS station installed in the uppermost part of the slope shows that the slope is moving about 3-5 mm per day, at a constant rate since installation in August.
There are several ideas about what is the main cause for the slope deformation. As for other outlet glaciers in Iceland the retreat and thinning of the glacier has been rapid, which might have caused instability in the above lying slopes. Another proposed cause for the deformation is related to its location on the western flank of the Katla volcano. Persistent seismic activity in this area for decades may be explained by a slowly

rising cryptodome, which may also explain the slope failure.

Paleocene dynamic topography along the Norwegian continental margin – evidence from seismic stratigraphy and sediment budgets

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The Mesozoic and Cenozoic onshore paleotopography along the Norwegian continental margin is a topic of continuous debate. In this discussion, the early Tertiary is a key period in geological time because it represents the transition from what has been regarded as a relatively low-relief Cretaceous landscape to a higher elevated, late Tertiary landscape. Offshore, this transition represents a shift from underfilled, chalk and mud-dominated, deep-water basins in the Cretaceous; to overfilled and significantly more sand-rich basins in the Paleocene. Thus, the Cretaceous-Tertiary boundary marks a fundamental change in basin physiography and megasequence development.
Here we investigate this transition from the Paleocene succession offshore western Norway using seismic and well data. We show that the Norwegian continental margin experienced a ~10 Myr phase of dynamic uplift, which resulted in the formation of an angular unconformity along the basin margins. This early phase of uplift was accompanied by significant mass-wasting with large slides and channelized gravity-flow deposits, suggesting tilting and instability of the slope. This was followed by a rapid increase in sediment flux and introduction of coarse-grained siliciclastic sediments, causing initial progradation of a shelf-slope wedge. Progradation halted in the earliest Eocene, when the Paleocene wedges were onlapped by Eocene sediments. Mapping of stratigraphic units also shows that the Paleocene-Eocene transition is characterized by changing of depocenters along strike.
Calculations indicate that the tectonic uplift caused an order of magnitude increase in sediment flux to the basin, peaking in the latest Paleocene. The observed sediment pulse is best explained by relatively high onshore topography of 0,6-1,1 km. It is believed that the primary driver for this pulse is linked to mantle processes that are time related to rifting and sea-floor spreading. Differences in thickness and internal stacking geometry of Paleocene wedges along strike suggest that the amount of uplift was not the same everywhere and that antecedent Late Cretaceous topography also played a role dictating the areas of high onshore erosion. This study shows that the topographic and stratigraphic evolution of the Norwegian margin not only reflects passive decay of Caledonian relief, but that also later, mantle-related processes influenced the Tertiary landscape.

Effect of volume expansion on mineral reactions during mixed-volatile infiltration in ultramafic-mafic rocks – implications for strain localization and volatile transfer from mantle to the upper crust and atmosphere

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This study demonstrates how the response of ultramafic lithologies to infiltrating H20-CO2 fluids depends on the primary mineralogy. This has major implications on fluid flow through the lower crust and upper mantle as mineral reactions control the permeability and rheology. The studied samples are from the hanging wall of a 2 kilometer -long transtensional shear zone in the Reinfjord Ultramafic Complex (RUC), part of the Seiland Igneous Province (SIP) in Northern Norway.
Fluid-rock interaction surrounding shear zones is highly variable and depends on bulk rock compositions. Thermodynamic modelling demonstrates that mineral reactions involving hydration and carbonation differ between dunitic rocks and the pyroxenitic dykes which intersect them. Alteration of dunitic rocks results in the formation of dominantly magnesite-anthophyllite-talc and talc-magnesite assemblages causing approximately 12% volume expansion. This results in a sharp reaction front contact with the host rock. When the alteration zones cross the dunite-pyroxenite boundary the associated alteration has a more gradual boundary towards the unaltered rock and the alteration zone widens by approximately 40%. In contrast to the simpler dunite alteration assemblage, the pyroxenetic dykes are altered to a complex mixture of cummingtonite-anthophyllite, magnetite and chlorite. Additionally, orthopyroxene is completely pseudomorphed by a mixture of cummingtonite and magnetite, whereas olivine xenocrysts are partly preserved and surrounded by a magnesite-anthophyllite assemblage. Other, open cavity-like areas are filled by chlorite, amphibole, and Mg-MgCa carbonates, indicating volume reduction during alteration of the pyroxene.
Accordingly, dunite alteration effectuates a significant volume expansion, is are therefore only alter-

ed locally during seismic creep events. The pyroxenites are near volume neutral throughout interaction with the same fluids, and are thus more homogeneously altered. The formation of chlorite in hybrid compositions, such as the dykes in the lower crust, may create weak permeable zones that are consequently exploited as pathways for fertile mantle fluids and will hence also be the locus of ore bearing fluids moving to the upper crust. Increased understanding of fluid mediated metamorphism increases our current knowledge on fluid flow and strain localization in the lower crust.

Impact of volatiles and variations in local bulk composition on deformation and magma emplacement processes in the deep crust and upper mantle parts of a continental rift system

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The coupling of CO_2 emissions and tectonic activity in active plate margins is becoming increasingly prominent, as remote sensing techniques make this relationship readily observable on a global scale. However, direct observations of the processes that link emissions and seismicity are lacking.
This study documents observations from the deep part of an ancient continental rift system, now exposed at the Earth's surface. We demonstrate how volatiles and preexisting magma chamber structures affect the influx of new magma and how magma induced deformation plays a key role during the shift from initial plume related magmatism to rifting, by altering the rock rheology and facilitating strain localization.
The outcrops are comprised of ultramafic cumulates, intersected by mafic dykes. The ultramafic cumulates consist of three units: the central series, upper layered series and the lower layered series, with the central series being the youngest and partly replacing the upper and lower layered series. The dykes intersecting the upper layered series are partially remolten and replaced by the influx of the central series cumulates. This is especially evident in mafic dykes in wherlitic cumulates of the upper layered series. Younger melts of the central series used the contact between the dykes and host wehrlite as a pathway. The heating caused partial melting of the mafic dyke, which acted as a lubricant during deformation. In addition to the lubrication effect of the melt, volatiles within the mafic dykes, including CO_2 react with the mafic minerals within the host ultramafic rocks, leading to fracturing and brecciation, and locally followed by diffusion creep in the finer-grained material. PT-estimates indicate that this brecciation took place under lower crustal/upper mantle conditions. Hence, conditions of deformation can shift from low strain rate plastic creep to ultrafast localized seismic creep in a short time due to local structural and compositional inhomogeneities.

Tectonic impact on Danish landscape evolution

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Tectonic impact on present Danish landscape is generally not given much attention. However, many features and observations are difficult to explain if we do not consider tectonic processes interacting with the well-known glacial processes during Quaternary time. Observations, where tectonic processes most likely have been involved, are for instance postglacial small basins known from Middle Jutland. These basins could be the result of active strike-slip faults. Other observations are areas with pre-quaternary rocks situated at quite high levels and with reported landslides in historical time – all pointing to areas dominated by tectonic uplift. Outline and structural patterns of some Danish coastlines and adjacent areas also suggests a tectonic origin. This seems for instance the case for Vejle Fjord in Eastern Jutland and the zig-zag form of Limfjord separating Middle and Northern Jutland. Reported depressions in the seafloor of Western Limfjord are by Aarhus University tentatively interpreted as pockmarks formed due to fluid escape – an interpretation that fits well with the presumed tectonic processes responsible for the zig-zag coastline. Active tectonic is generally linked with earthquakes. And earthquakes are well observed and reported from the Danish area. However, during glaciation periods with big ice sheets, the tectonic processes were suppressed for a while, because of the load from the ice. When ice load ceased, the tectonic forces were released and resulted in a pulse of earthquakes. These disturbances might be responsible for many of the dislocation structures seen in Danish coastal exposures. Traditionally the structures are referred to as formed by push from active glaciers. However, permafrozen ground and released tectonic forces could as well be responsible for the folds and thrusts exposed in the cliffs. More signs of tectonic processes active in landscape evolution are given by detailed modern satellite maps and elevation models as they reveal

structures very hard to explain without considering a tectonic origin.

Tectonic stress regimes in the Danish area from Paleogene to present time

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Based on existing published information 3 different stress regimens have been identified in the Danish area from Paleogene until present time. The first one active during Paleogene was characterized by a major inverse SSW-NNE pressure direction combined with a tilting which plunged the area towards WNW. The second one was active from the beginning of Neogene till middle of Quaternary time and was dominated by a tilting around an ESE - WNW axis plunging the area towards SSW. The last stress regime – active from middle of Pleistocene until present time – has almost the same features as the first one with dominating strong inverse SSW-NNE pressure and tilting towards WNW. All three stress fields used the same week zones to deform the area. The weak zones consist of linear parallel structures in two main directions SSW-NNE and ESE-WNW creating a sequence of individual blocks. These blocks were uplifted, subducted and tilted during the active periods in diverse ways as response to the tectonic forces. Oblique block interactions created local stress fields which resulted in trans tension and trans pression and other deformation structures hardly recognized in the unconsolidated Danish sediments.
During the last stress field period the tectonic forces interacted with the glacial processes. Ice movements and meltwater drainage followed directions set by the tectonic patterns creating for instance the big “tunnel valleys” in Denmark. Big continental ice sheets suppressed the land surface and was able to hold back the tectonic processes for a while. When the ice melted the tectonic forces were released and pulses of earthquakes occurred at the start of a deglaciation period. If the ground was still in a permafrozen state, the sediments could act as consolidated rocks, and in this way preserve some of the tectonic deformation structures.

Sedimentology and reservoir quality of the Solveig Field – the southern Utsira High, Norwegian North Sea

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The Utsira High is an intra-basinal structural high forming the eastern flank of the South Viking Graben, where granitic basement is currently buried to about two kilometers depth below the seafloor. The Solveig Field comprises a series of half-grabens on the south-western flank of Utsira High with reservoir rocks considered Palaeozoic and Triassic in age.
During this time, the Solveig half grabens contained ephemeral rivers draining into the Vea half-graben towards the south. Arid to semi-arid conditions prevailed and the graben fill comprised alluvial fan and alluvial plain deposits that also included aeolian bedforms.
Integration of sedimentological observations with processed image log results has differentiated a number of different aeolian dune types, deposited under distinct wind regimes (NW to SE in the Triassic; NE to SW in the Paleozoic). Four dune associations have been identified: simple aeolian dunes, composite transverse aeolian draa, composite linear/star draa and dunes associated with alluvial overbank, lake margin sabkha and beach deposits.
Detailed sedimentological and petrological analysis shows that the reservoir quality is controlled by the facies, in terms of texture, composition, diagenesis and there is a component of mechanical compaction of the reservoir rock. The alluvial fan deposits consist of mineralogically immature sandstones and conglomerates. Detrital grains are made up principally of quartz and feldspars and to a lesser extent mica. Granitic rock fragments, which are aggregate grains of quartz, feldspars and biotite, are common and their frequency increase with grain-size. Many samples record the presence of detrital matrix. The aeolian dune sediments of Triassic age are mineralogically mature, moderately to well sorted, fine to medium grained sandstones with associated high permeabilities. The aeolian dune sediments of Paleozoic age are mineralogically mature, moderately sorted often bimodally sorted with a very fine and medium grain size. These exhibit a high degree of mechanical compaction, so the permeability is lower compared to the aeolian dunes of Triassic age.
Patchy dolomite and calcite cements are the main authigenic phase present in the sediments. Minor

hematite cement is observed in some samples. Authigenic clays are present where chlorite, kaolinite and illite are the most common diagenetic clay minerals.

The stratigraphy of the Fossum Formation (Ordovician) in a core provided by Norcem

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The Fossum Formation (Middle to Upper Ordovician) is a more than 200 m thick unit of carbonates and shales developed in the southern part of the Oslo region. Although highly fossiliferous in parts, the precise correlations with time-equivalent formations in the Oslo-Asker district (Vollen, Arnestad and Frognerkilen formations) are still unknown. A core drilled by Norcem through the complete Fossum Formation near Brevik is the basis for a current master degree project called "Chemostratigraphy, cyclostratigraphy and biostratigraphy of the Fossum Formation, Middle-Upper Ordovician, Skien-Langesund district, Norway".
The Fossum Formation makes up most of the core with approximately 230 meters. The core has been photographed in high quality, and logged visually for lithology, sedimentary structures and fossils. Selected intervals have been imaged with micro-focus CT, confirming high densities of body and trace fossils. The magnetic susceptibility curve indicates three distinct subunits which seem to correspond with a previously suggested subdivision of the formation into the Blekebakken, Kjerrvika and Krogshavn members (Ribland Nilssen, 1985). Moreover, the susceptibility data show distinct cyclicity, especially in the lower part, as also evident in outcrop. We tentatively interpret these cycles as 400 kyr Milankovich cycles (long eccentricity). Parts of the core are measured with handheld XRF at 2.5 cm intervals. Preliminary XRF results confirm the cyclicity shown by magnetic susceptibility.
In addition, we will produce a carbonate carbon isotope curve for the complete formation. If the isotopes are not too overprinted by the relatively high-grade contact metamorphism in the area, we hope to identify the "GICE" excursion, which is a marker for the base Katian and could provide a much-needed tie-point to the successions in the Oslo-Asker district.

Land-Atmosphere Interactions in Cold Environments (LATICE): the role of atmosphere - biosphere – cryosphere – hydrosphere interactions in a changing climate

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Climate change is impacting the high latitudes more rapidly and significantly than any other region of the Earth because of feedback processes between the atmosphere and the underlying surface. A warmer climate has already led to thawing of permafrost, reduced snow cover and a longer growing season; changes, which in turn influence the atmospheric circulation and the hydrological cycle. Still, many studies rely on one-way coupling between the atmosphere and the land surface, thereby neglecting important interactions and feedbacks. The observation, understanding and prediction of such processes from local to regional and continental scales, represent a major scientific challenge that requires multidisciplinary scientific effort. LATICE, which is recognized as a strategic research initiative by the Faculty of Mathematics and Natural Sciences at the University of Oslo, aims to advance the knowledge base concerning land atmosphere interactions and their role in controlling climate variability and climate change at high northern latitudes. The consortium consists of an interdisciplinary team of experts from the atmospheric and terrestrial research fields, with the long term aim to improve model parameterizations of key processes in high northern latitudes. Observations are vital for improving Earth System Models and the group has established a high resolution measurement infrastructure site in a mountain region, Finse, including a stationary eddy -covariance (EC) tower. In addition, a mobile EC tower is currently installed at Iskoras – a palsa mire in Finnmark. The network of instruments provides high resolution data for estimating the water and surface energy balance, as well as CO_2 and CH_4 fluxes. Here, we present the LATICE concept; its main research areas and activities, along with selected results based on observations and integrated modelling efforts in Norway.

Reprocessing of ERT and Refraction Seismic data from the Unstable Slope in Åknes

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NGU performed geophysical investigations in Åknes from 2004 until 2007 in response to the slope stability issues in the area. These investigations consisted of 10 km of ERT profiling distributed in 10 profiles. Processing of resistivity data took place with Res2DInv software version available at the time and interpreted using inversion techniques aimed at highlighting horizontal structures and thus mapping the water-saturated part of fractured gneiss more effectively. During the last 15 years, new inversion algorithms have been developed which in connection with the demand for 3D presentation of the results and the suggestion to stabilize the slope by means of drainage, led to the reprocessing of the existing ERT profiles along with a new profile measured in 2017. Data were reprocessed using a larger variety of approaches like aiming towards accentuating possible sub-vertical fracture zones, processing with separate and combined measuring arrays etc. Additionally, NVE commissioned a private contractor to perform seismic investigations distributed in 3 profiles with total length of 2.7 km. These investigations were aimed at the thickness of the overburden material and fractured bedrock as well as tectonic faulting within bedrock. NGU has done extensive research on the use of Rayfract® program and has obtained relevant knowledge on the software via modeling of synthetic and real data processing. In this sense, NVE has provided NGU with the refraction seismic data to undergo reprocessing in Rayfract® and deliver results in 3D format. In both ERT and refraction seismic result presentation we employed point-cloud classification in order to make interpretations in relation with the water-saturated and drained part of fractured bedrock as well as possible weak zones in Åknes. We attempted to prompt clear limits within the resistivity and velocity distribution in order to help determine the glide-plain in Åknes in connection with structural mapping, hydrogeological studies and information extracted from boreholes. It has been shown that potential rockslide materials in Åknes are characterized by velocities below 500 m/sec while the fractured / water-saturated bedrock could be pinpointed between 2,000 and 3,500 m/sec. The respective ERT resistivity classes for these two formations were over 50,000 Ωm for the former and less than 12,000 Ωm for the latter. Results using the mentioned classification showed a high correlation between the two methods for neighboring profiles.

Linking single secondary mineral growth zones to craton-scale deformation events – the advent of in situ Rb-Sr dating of faults and shear zones

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Direct dating of secondary minerals formed along rock discontinuities such as faults, fractures and shear zones is essential to constrain the timing of brittle and ductile deformation in the Earth's crust. Absolute ages of deformation can be difficult to obtain, especially in structures featuring multiple generations of discrete fine-grained mineral growth zones formed by repeated reactivation events. Here we apply *in situ* Rb-Sr dating by reaction cell LA-ICP-MS/MS (Hogmalm et al., 2017; Zack & Hogmalm, 2016) to acquire absolute geochronological data with a spot size of 50 µm, high analytical precision and textural control of reactivated faults and shear zones in Palaeoproterozoic basement granitoids of Sweden. This novel technique enables dating on a more detailed scale than previously attainable by conventional bulk methods as single grain overgrowths and isotopically homogenous fault gouge can be targeted specifically without requiring grain-size separation or sample pre-treatment. The high spatial and depth resolution of single laser ablation spots and the capability of detecting fluid alteration and mineral phase mixing increases the potential for recognizing crystal nucleation, dissolution-precipitation and radiogenic isotope systematics. The complex interplay between these chemical processes and the physical mechanisms that include fault slip, shearing and neocrystallization requires integration of structural analysis of the dated samples. Our procedure utilizes kinematic indicators on fault planes and shear zones for texturally linking the isochron ages of coeval Rb- and Sr-abundant phases such as illite, adularia and calcite to specific reactivation events. These temporal constraints consequently provide the means to determine the timing of crustal response to far-field tectonic activity in the Fennoscandian craton. The results demonstrate that this new methodology aids detection and interpretation of episodic reactivation in the evolution of fault and shear zones.

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Crystal zone-scale in situ dating of multistage mineral growth formed by microbial activity in deep crustal fractures

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Minerals precipitated on fault and fracture walls in crystalline bedrock disclose information about tectonothermal events, palaeohydrological conditions, ancient microbial activity and other bio- and geochemical processes occurring meters to kilometers down into the crust. Understanding of these systems and their development through space and time is dependent on quantitative access to subsurface samples and environments, as well as subsequent temporal constraints of mineral precipitation. We utilize well-preserved fracture surface samples from drillcores in granitoid bedrock across Sweden at Laxemar, Forsmark and Lockne sites. High-precision age determination of fine-grained vein formation and discrete crystal growth zones in micas, feldspars and calcite crystallized on fracture walls was performed using *in situ* Rb-Sr dating by reaction cell LA-ICP-MS/MS at University of Gothenburg. Our textural and geochronological analyses recognize several low-temperature Palaeozoic precipitation events in complex intergrowths of secondary minerals whereas extensive fluid inclusion and stable isotope composition data constrain the prevailing geochemical and geothermal conditions at each time and site of precipitation (Drake et al., 2015; Drake et al., 2017; Drake et al., 2018; Tillberg et al., 2019). $\delta^{13}C$ signatures in authigenic calcite reveal the spatially and temporally dynamic nature of a carbon cycle mainly related to methane circulation in deep fracture systems. Large variations and extreme values of $\delta^{13}C_{calcite}$ namely evidence ancient episodes of methanogenesis and anaerobic oxidation of methane (AOM) in the upper 800m of the crystalline basement. Coupled $\delta^{13}C_{calcite}$ and $\delta^{34}S_{pyrite}$ fractionation during AOM proceeds in closed systems by a microbial consortium consisting of anaerobic methanothroph *archaea* and sulphate-reducing bacteria. The connected AOM and bacterial sulphate reduction is enabled by descending surficial sulphate-rich fluids mixing with saline basinal brines rich in organic matter. Biofilm remnants fossilized to mixed-layer clay are further evidence of ancient microbial activity identified by biomarker analysis. *In situ* Rb-Sr dating of the fossil biofilm determine the timing of clay alteration which represents the minimum age of the microbial life as well as the timing of fracture reactivation that allows methane to transfer between shallow and deep terrestrial crust. This multi-disciplinary study thus causally identifies the connection between the deep biosphere, the geochemical mechanisms of fluid-rock interactions and the geochronology of tectonic events by using a dating technique that via microscale control of isotopic equilibrium, inclusions, zonations and alterations directly can date fracture and vein precipitates prone to open system conditions during million or even billions of years.

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Timing and sulphide crystallization sequence of the Håkansboda Cu-Co deposit in Bergslagen, Sweden

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The Håkansboda Cu-Co sulphide deposit in the Bergslagen ore district, south-central Sweden, is located in a metacarbonate unit within a folded sequence of metavolcanic and metasedimentary rocks in the Guldsmedshytte syncline. The chalcopyrite and pyrrhotite-dominated mineralization is hosted by quartz-rich volcano-sedimentary, calc-silicate and carbonate host-rocks. Solid-solution element exchange between cobalt-bearing sulpharsenides in the NiAsS-CoAsS-FeAsS system suggests that glaucodote formed at temperatures of at least 650°C. Cobaltite crystallized at temperatures below 450°C in equilibrium with the bulk of low-temperature chalcopyrite-pyrrhotite mineralization. In-situ U-Pb dating of hydrothermal monazites with LA-ICP-MS yield a concordia age of 1786 ± 23 Ma, overlapping late Svecofennian granite intrusions and regional meta-morphism in Bergslagen. $d^{34}S_{V\text{-}CDT}$ values of ten mineralized samples in varying host-rocks range between -3.0 and -4.7, indicating a predominant magmatic sulphur source. Hot fluid infiltration, probably driven by granitic intrusions or related regional metamorphism, formed the present outline of Cu-Co ore bodies. The main mineralization is structurally controlled and preferentially replaces folded quartz-rich layers associated with dissolution of feldspar and micas. Sulphide crystallization at a late magmatic-metamorphic retrograde stage thus implies that certain stratigraphic layers acted as mechanically and chemically preferred pathways for migration

of sulphide-mineralizing fluids through the uptight sub-vertical synclinal structure. These insights into the late-orogenic ore-forming development of the Håkansboda deposit bear impact on exploration strategies for finding and understanding similar deposits in Bergslagen and elsewhere.

What to do with a Lineament Map?

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Lineament maps are frequently featured in structural studies, but how useful are they really? Except for the basic analysis of orientation and lineament density, few if any quantitative tools have been developed with which to rigorously identify and describe lineaments such that they can be categorized, separated, or otherwise analyzed. Similarly, the ability to quantitatively cross-analyze lineaments or lineament families with independent datasets has not been fully realized.
Technical biases that afflict manual ('traditionally" produced) lineament maps stem from factors such as illumination direction and resolution of the DEM/orthophoto, the scale at which lines are picked, and especially the expertise, experience, and fatigue level of the persons involved (Scheiber et al., 2015). Conceptually, many of these biases can be partly overcome by computer algorithms that employ IF/THEN/ELSE rules to identify elements from the input data set as linear features worth recording. Whilst algorithmic rules also constitute bias, their results will be repeatable, and homogeneous across the dataset.
Within the framework of NGU's FINE project ("Forkastninger i Norge", which aims to produce a freely available map database of brittle faults on- and offshore), we have developed an in-house algorithm for automatic detection of linear features from raster datasets. Using a cost-function analysis, our codes generate vectors that track dataset minima or maxima. Our method eliminates directional biases such as illumination, human biases such as experience or fatigue, and operates at the scale of the input data set. It produces internally uniform vector datasets where each feature is populated with attributes that describe parameters such as length, depth, width, cross-sectional shape, and orientation.
Additional in-house codes are then applied to map our vector lineament datasets with respect to quantities such as lineament density, geomorphological parameters and statistically definable azimuthal trends. By applying GIS-based methods of classification we anticipate the possibility of helping to fill some of the knowledge gaps that bare-bones lineament maps, by themselves, cannot address. We aim towards a series of rasterized maps that link field observations of discontinuous and minor (e.g., 'unmappable') brittle faults with specific lineament families or regions. The societal impact of these maps may encompass improved assessments of uncertainty and risk associated with rockslides, construction projects, earthquakes, and perhaps even offshore petroleum prospecting.

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Ordovician biodiversity, climate and mass extinction

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The Phanerozoic was dominated by a greenhouse climate with high atmospheric CO_2 levels, interrupted by three main periods of cold (icehouse) conditions. The latest Cambrian and earlier Ordovician warmth is reflected in the massive carbonates widespread in many continents. That was echoed by the great variety and increased speciation of not only benthic phyla, particularly trilobites, brachiopods, and echinoderms, but also swimmers including cephalopods and conodonts. A progressive steady reduction in sea-surface temperature (SST) from about 42°C at around 489 Ma to about 30°C at around 465 Ma, after which the average temperatures hovered with some fluctuation until they started to fall near the end of the Katian, before plunging to 23°C during the Hirnantian glaciations. The Great Ordovician Biodiversification Event (GOBE) has been linked to an emerging mid-Ordovician icehouse, there are no known mid-Ordovician glacial deposits at that time, but GOBE was probably triggered when SST approached modern values at around 470 Ma. The Hirnantian glaciation was followed by widespread extinctions near the Ordovician-Silurian boundary (~445 Ma), the first of the "Big Five" extinctions, and

three of these have been linked to Large Igneous Province (LIP) activity. The end-Ordovician extinction cannot be linked to any known LIPs but recently (and surprisingly) related to LIP activity in South Korea; this link, however, is erroneous as magmatic activity there occurred in the Neoproterozoic. Also recently, it was suggested that the breakup of an L-chondrite parent body in the asteroid belt at 466 Ma caused enormous amounts of dust in the atmosphere and triggered "the mid-Ordovician ice age", which was in turn linked to the GOBE. In fact, there are no proven glaciogenic deposits and no ice age at 466 Ma, although global temperatures were lower than earlier in the Ordovician. Not only that, but soon afterwards at about 453 Ma there occurred a warming event (BODA), and it was only after then that there was the well-known and substantial global cooling which peaked in the Hirnantian glaciation event. Although an asteroid breakup may have significantly affected the Earth's climate at the time, it can be ruled out as a cause of the glaciations and the consequent mass extinctions more than 20 Myrs later. The end-Ordovician icehouse and mass extinction is still shredded in mystery and other explanations include increased weathering rates, reduction in plate tectonic degassing, or a combination of these mechanism's that can lead to global cooling.

On the importance of hydrodynamic conditions in geothermal potential reconnaissance

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Sedimentary basins depending on their temperature conditions are targets for installation of geothermal power plants and for direct-use of thermal water. The necessary elements of a fluid–based geothermal systems are the reservoir with sufficient hydraulic parameters, the favourable quantity of heat and the production fluids which can transport heat during abstraction (Dickson and Fanelli 2004). These elements should be investigated for the study area during reconnaissance phase of geothermal exploration whether they are available or not. However, the availability of fluids not only depends on the permeability of the reservoir but also on the regional flow systems and hydrodynamic conditions. The hydrogeological aspects of geothermal energy utilization are in the focus of interest nowadays, nevertheless, our knowledge regarding geothermal resources in the context of basin-scale flow systems, especially in deep confined carbonates is very restricted.

This study intended to highlight the importance of basin hydrodynamic character in planning of geothermal interventions. The geology, basin depth and geometry can modify the groundwater flow and heat pattern, as well, these constraints have important role in evolution of heat accumulation for geothermal utilization.

Several cases in various geologic settings across Hungary could demonstrate the hydrodynamic conditions acting as a main agent determining the geothermal potential and utilisation possibilities. Especially for deep carbonate aquifers, the results showed that the siliciclastic cover is responsible for heat accumulation in carbonates. Therefore position of unconfined and confined parts is decisive in geothermal heat utilization in carbonates. The unconfined carbonates have potential only for shallow geothermal utilization, e.g. heat pump, however at confined regions economic geothermal production is feasible. These outcomes have benefits for geothermal exploration and utilization. Evaluation of hydrodynamic situation is not a conventional element of a geothermal reconnaissance, but it is also important for economic production. Basin-scale hydrogeological studies can reveal the hydrodynamic conditions which affect the feasibility and efficiency fluid-based geothermal systems.

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Cretaceous and Cenozoic tectono-stratigraphic evolution of the southern Lofoten margin: valuable new insights for the Norwegian Sea exploration

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While the Vøring margin is extensively studied, the Lofoten margin is one of the least explored areas on the Norwegian continental shelf. The tectono-stratigraphic evolution of the southern Lofoten margin and its immediate transition towards the northern Vøring margin has been studied in detail

utilizing 2D multi-channel seismic reflection profiles, available wells, in addition to gravity and magnetic data. New and better refined structural elements have been mapped, including (informally named) the West Røst High Fault Complex, Røst Syncline, and Sandflesa High. The study has highlighted details on the Cretaceous evolution that can be particularly important and applicable to the rest of the Norwegian Sea. In this context, beyond refinements to the regionally dominant Late Jurassic-earliest Cretaceous rifting, there is clear evidence for intra Early Cretaceous (Aptian-Albian) and mid-Cretaceous (Albian-Cenomanian) rifting that affected the study area. More importantly, the study provides details on the onset and evolution of the composite Late Cretaceous rift phase that gave rise to prominent westward-dipping low-angle detachment faults. Paleocene rifting generated new faults and reactivated several earlier faults, prior to continental breakup and seafloor spreading initiation at the Paleocene-Eocene transition. The Bivrost Lineament, separating the southern Lofoten and northern Vøring margins, exhibited a distinct morphological expression during Cretaceous-Cenozoic and is recognised as a structural "corridor" which segments highs and basins/ sub-basins. Furthermore, two dome-shaped features have been observed on the southern Lofoten margin and have probably experienced several phases of growth from Late Cretaceous to Miocene times. The domes are located in close proximity to the outer Vøring margin and Bivrost Lineament that are believed to have facilitated the transfer of imposed compressional deformation on the NE Atlantic margins. Finally, a comparison of the study area to the conjugate Northeast Greenland margin provides valuable insights on the margin evolution in a regional and conjugate setting.

What the $^{234}U/^{238}U$ AR in groundwaters can tell about U mobility

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Variable and in some sections high, dissolved U (up to 170 µg/L) have been found in deep, Fe(II) containing (i.e reducing) groundwater in Forsmark, eastern Sweden. The study site is situated in mostly till covered, crystalline bedrock, on the Baltic Sea coast where the Swedish Nuclear Fuel and Waste Management Co (SKB) has conducted a site investigation to construct geological, hydrogeological and hydrochemical models of the area. The groundwater is described as mixtures of Meteoric, Brackish marine (Littorina Sea), Glacial and Old saline water. The highest U contents are found in some of the Brackish marine water samples suggesting that U has been susceptible to leaching of this water. Groundwater monitoring at the site yielded a unique set of principle chemical parameters and U isotopes from several borehole sections at 25 m to 650 m depths. The $^{234}U/^{238}U$ activity ratio (AR) varied from 1.5 up to 3.5 and showed invariable section-specific values suggesting different U sources in the sections. ^{234}U against ^{238}U were plotted to study their relative release and get an idea of U source. Correlation factors were good (R^2 >0.92) allowing isotope release ratio to be determined. Equal ^{234}U and ^{238}U release mechanism was obtained in some sections (Y-intercept in origin) supporting a U(VI) source. In some of the sections positive y-intercept suggested addition of extra ^{234}U into the water which was thought to relate to á-recoil during prolonged water exchange or due to U rich source. In the groundwater section where the highest dissolved U was measured (at 500 m depth) the presence of a U(VI) source is evident. The $^{234}U/^{238}U$ AR = 2 for this source further indicates that the dissolved U phase must have precipitated during the late Quaternary (i.e. < 250 ka), because the original ^{234}U excess has not fully decayed. This supports a model with U mobilisation during the last glaciation when basal melting prevailed, and glacial melt water intruded to significant depths in the bedrock and U was deposited along the flow paths. Subsequent dissolution of deposited U resulted from interaction with intruded anoxic brackish marine water with suitable complexing agents of carbonate and Ca providing favourable conditions for U dissolution.

Nd, Sr, Pb, and Os isotopic composition of Luenha picrites suggest a primitive mantle source for the plume component of the Karoo large igneous province

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The mantle sources of the Karoo large igneous province (LIP), which lies on the boundary of the African LLSVP (large low shear velocity province) are a subject of continued scientific interest. Research on the Karoo LIP is limited by the rarity of primitive lava or dike compositions not influenced

by differentiation processes and interaction with the lithosphere.

The Luenha picrite lava series from Central Mozambique includes samples that have not been significantly modified by differentiation processes. In addition, they contain high-Mg olivine, which together with the whole-rock geochemistry suggests derivation from picritic to komatiitic primary melts. Chondrite-like ratios of refractory lithophile incompatible elements in the most primitive samples of the Luenha picrites indicate a mantle source similar to primitive mantle. In terms of radiogenic isotope compositions, the most primitive sample shows only slightly superchondritic initial ε_{Nd} (+1.4) and bulk-silicate-Earth-like (BSE) initial $^{87}Sr/^{86}Sr$ (0.7041). The initial $^{187}Os/^{188}Os$ ratio (0.12585) falls between primitive upper mantle and depleted MORB mantle ranges. The initial Pb isotope ratios, $^{206}Pb/^{204}Pb$ of 17.75, $^{207}Pb/^{204}Pb$ of 15.73, and $^{208}Pb/^{204}Pb$ of 38.0 can be closely replicated by a single-stage 4.55 Ga evolution model of a primordial reservoir, which bears $^{238}U/^{204}Pb$ = 8.77 and $^{232}Th/^{204}Pb$ = 36.81. Each of the studied isotope systems is therefore consistent with a primitive mantle source for the Luenha picrites.

The other picrite types previously identified in the Karoo LIP are not petrogenetically related to the main volume of the Karoo flood basalts and have likely sampled depleted mantle, subcontinental lithospheric mantle, and anomalous recycled sources. The Luenha picrites may provide the first direct evidence of magmatism related to a mantle plume that sampled ancient mantle sources with primitive, undifferentiated mantle compositions. If these sources reside in the LLSVP, the Luenha picrites may also provide compositional constraints for LLSVPs. Geochemical similarities suggest this source was important in the generation of the main volume of flood basalts in the Karoo LIP.

Permo-Carboniferous paleokarst structures at Wordiekammen, central Spitsbergen, Svalbard

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The inner Billefjorden area in central Spitsbergen exhibits a range of paleokarstic features developed in the Moscovian-Sakmarian Minkinfjellet and Wordiekammen Formations, which may provide outcrop analogues for structures potentially encountered in paleokarst plays in the Barents Sea. We here present results based on a combination of virtual outcrop images, shallow geophysics and traditional field techniques. The study focusses on the spatial distribution of paleokarst structures in outcrops along the Wordiekammen plateau, located on the eastern margin of the Billefjorden basin.

Vertical breccia pipes intersect the entire Wordiekammen Fm, and are linked to a system of infilled and collapsed caves straddling the transition between the Wordiekammen Formation and the underlying Minkinfjellet Formation. Elements of this cave system can be mapped along the base and in the lowermost beds of the Wordiekammen Formation. Due to poor exposure, the extent of this system could not been investigated in detail in the Minkinfjellet Fm, but isolated outcrop observations suggest that cavities extended tens of meters down from the top of the formation and may be connected to stratal dissolution features observed by previous studies.

The paleokarst features inside the Wordiekammen Fm exhibit a wide range of sedimentary structures and textures formed by flowing water, mass flows and gravitational collapse. In several places the shapes of the original cavities are preserved and filled with bedded sediments. Mapped bed thickness variations and faults in the Wordiekammen Fm. indicate both syn- and post-depositional faulting. Faults can be seen off-setting both cave fill and breccia pipes, and collapse structures are sometimes bounded by sub-vertical faults. The observed faults can be linked both to regional fault movements and local gravitational collapse of underlying cavities. Our structural mapping suggests that the Wordiekammen plateau is part of a km-scale relay ramp between two main N-S trending faults. Analysis of breccia pipe shape and distribution – used as a proxy for shape and position of the cavities to which they connect – shows preferential orientation patterns matching the structural grain. In sum our observations suggest that the presence, formation, infill and breakdown of a large scale cave system at Wordiekammen was controlled by tectonic features that remained active throughout its development and afterwards.

Hi-tech and critical commodities in Cu-Mo-Au porphyry systems

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The latest list of critical metals issued by the European Union[1] contains 27 materials. Many of the metals listed are by-products of other commodities such as base metals (Cu, Zn, Pb).

Porphyry Cu-Mo-Au deposits are not the prime source of critical elements. However, given the demand for critical metals in our society it makes

sense to investigate the potential of deposits as a source for some of those metals that occur as by-products of copper and molybdenite production. The high tonnage of porphyry systems could potentially contain a significant amount of critical metals.

Among critical commodities it is Te (and Se, however Se is not on the EU list of critical metals) that are directly related to copper mining from porphyries. On average 65g Te could be extracted form one ton of copper, leading to over 1000tons of Te when using the global Cu production. Similarly, several 100s of grams of Se could be extracted form one ton of Cu[2].

Furthermore, several porphyry Cu-Au deposits have been found to contain elevated Pd and Pt concentrations. These metals typically occur in minerals consisting of Pt-Pd-Bi-Te. They are found as inclusions in sulphide or silicates (quartz, biotite) or along their grain boundaries. Calculations using the total amount of Cu mined at the Skouries Cu-Au deposit, Greece show that around 15tons of Pd and 3-4tons of Pd could be extracted[3].

Compared to porphyry Cu-Au deposit the Mo deposits are not found to be enriched in any of the critical metals, although Re is the main by-product from molybdenite production.

There are other metals on the list of critical metals such as Co, Bi and In, that potentially could be found in sulphides associated with porphyry systems. Bi is known to be contained in bornite, In can occur in chalcopyrite and Co is a by-product of copper oxide mining and hence could possibly be found in supergene enrichment zones of Cu porphyries.

The presentation will review the existing literature and discuss the common characteristic of critical commodities in porphyry systems. Moreover, the ore forming processes of magmatic-hydrothermal systems will be reviewed in light of critical metal transport. Finally, some ideas will be presented about future research and the viability of porphyries to become a source of critical metals.

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Dynamics of lithospheric overturns and implications for Venus' surface

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Venus remains enigmatic in terms of its interior evolution and surface tectonic history. On Earth, major resurfacing processes are linked to plate tectonics for which no evidence exists on present-day Venus. The primary understanding of resurfacing processes on Venus comes from geologic mapping and analysis of the impact crater distribution. The possible occurrence of episodic global resurfacing events has been proposed to explain the sparse and essentially uniform distribution of impact craters. The characteristic, rather uniform, surface age is thought to be 0.75±0.25 Ga, which constraints the timing of the latest overturn event. However, timing and occurrence of such overturn events and how they may shape Venus' surface remains debated.

Here, we investigate Venus' mantle evolution using numerical models of mantle convection to provide better insight into Venus' current dynamic state. We investigate the role of governing parameters namely the mantle reference viscosity and the yield stress of the lithosphere. These models feature melt production and crustal growth as a result of eruptive volcanism, which allows us to generate distributions of crustal thickness and surface age.

Our models predict very thick basaltic crust and a very young surface in the stagnant-lid scenario, thus without overturn events. Lower reference viscosity leads to thinner crust and reduced melt eruption efficiency leads to an older, but not uniformly aged surface. In contrast, models with overturn episodes result in non-uniform resurfacing. Crustal thickness is generally lower and surface age tends to be older, more in line with other estimates for Venus. The overturns rapidly resurface most of the planet but small portions (<10-20%) of the pre-overturn crust possibly resist the resurfacing event. Such a fraction is comparable to the amount of Venus', supposedly old, tesserae units, which could according to our models thus be relicts from Venus' state prior to its latest resurfacing episode.

Rock functional properties steered by the metamorphic evolution – a case study of the transition from greenschist- to high-pressure granulite-facies in the Eastern Segment, Sveconorwegian orogen

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In the petrological community, it is well-known that the P-T-t-d evolution of a metamorphic unit (e.g. a high-pressure unit) holds key information about its tectonic history. More rarely is it emphasized that the same factors also determine the physical properties of the rock and thereby its technical properties. Basic research in metamorphic petrology thus contributes with a fundament to applied and technical science, e.g. by providing data that lead to quarrying of proper materials.
We have studied the correlation between petrological characteristics and technical properties of an eclogite-bearing terrane and its high-pressure granulite-bearing footwall in SW Sweden. Our data show that felsic orthogneiss from the granulite gneiss domain have the best technical properties (most suitable for road and railway), as opposed to felsic orthogneiss in the eclogite-bearing domain. Characteristic micro-textures in granulite-facies orthogneisses include complex grain boundaries and microperthitic textures; furthermore, these rocks have low biotite content and absence of pronounced banding (segregation of light and dark minerals) and veining. Such textures are in contrast to the coarser, even-grained and granoblastic texture in migmatites of the eclogite-bearing domain. Thus, petrographic parameters that are a result of the metamorphic evolution govern the technical differences.
Measurements included the Los Angeles, Micro-Deval and Nordic Abrasion value tests. The Los Angeles test value is a measure of the resistance to fragmentation (EN 1097-2, 2010). The Nordic Abrasion value and MicroDeval tests measure resistance to wear. High values for these tests represent poor technical properties. Our tests of felsic gneisses in the granulite and eclogite domain, respectively, demonstrate that rocks which underwent partial melting yield high values. The latter rocks have poor properties for production of road aggregates and are suitable only for unbound layers. In contrast, gneisses that recrystallized under high temperature and dry conditions, with no or low degree of partial melting, have low test values. This group includes rocks of high quality for production of road aggregates, suitable for asphalt paving. Our ongoing studies focus on the properties of felsic orthogneiss and metagabbro, respectively, along a 120-km metamorphic field gradient grading from greenschist- to high-pressure granulite-facies.

Reference:
European Committee for Standardization 2010: EN 1097-2 Tests for mechanical and physical properties of aggregates – Part 2: Methods for the determination of resistance to fragmentation.

Crater statistics and Geological history of Jezero Crater and Oxia Planum regions

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Has there ever been life on Mars? Two rovers are heading to Mars in 2020 to help answer this question. They are going to land in deltaic regions where there are higher chances of finding biosignatures. Additionally, one of the missions (Mars 2020) can collect core samples of the most promising rocks and soils. Knowing in which unit of the landing site the chance of finding biosignatures are higher depends on the formation age of the unit, but also on its exposure age because of radiation affecting the first meters of the surface. Determination of the ages of planetary surface is based on crater statistics and it is calibrated traditionally on the Moon. Although it is the only efficient tool. Ages from craters statistics on Mars can be very uncertain compared to the Moon because the impactor flux and its evolution through time may have differed significantly from the one estimated for the Moon. It's also uncertain because we have only very limited radiometric absolute age with crater statistics. Determining the age of planetary bodies, and therefore times and rates of geological processes, are crucial to the study of geological history of the martian surface by remote sensing.
This project aims to combine several dataset of remote sensing data (topography and images) to map both landing sites and to measure crater statistics. This will be valuable data for the next in situ missions to reconstruct the emplacement history of the different units and to locate which unit has a higher probability of finding preserved biosignatures. Additionally, the samples that will return from Mars will provide absolute ages and they will need a proper geological context to be paired correctly to crater statistics.

Modelling and optimization study on a high-temperature borehole thermal energy storage concept driven by power plant waste heat

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High-temperature borehole thermal energy storage has potential to increase energy efficiency by storing surplus heat produced by industry. Borehole thermal energy storage is one of the most price-competitive and mature technology among seasonal thermal energy storage technologies. Waste heat by power plant can be stored during summer for later use during high demand winter season with efficiency of 40–65 % (Malmberg, 2018). The effect of borehole spacing and length on the performance of borehole thermal energy storage has not been properly explored. This study investigates how borehole spacing and depth affect large-scale storage performance and investment cost.

To study the effect, a numerical model, based on the method proposed by Al-Khoury and Bonnier (2006), is created using COMSOL Multiphysics software. In the method, fluid flow is modelled in a single U-tube pipe in a one-dimensional (1D) heat pipe element and heat transfer in bedrock is in the three-dimensional (3D) domain.

This study included 21 modelling cases. The created model was simulated with seven borehole spacing and three different ratios of storage width to height. Based on information found in the literature borehole spacing was varied at 0.5 meters interval from 2.0 m to 5.0 m. The storage width to depth – ratios used were 1.0, 0.67 and 0.5.

The results indicate that the most economically optimal storage with the capacity of 4.46 GWh is to drill 550 boreholes to the depth of 172 m using 3.5 m spacing. The BTES solution modelled in this thesis has the potential to yield 2-5 MW thermal energy continuously and 10 MW thermal energy for one-hour peaks.

Economically optimal borehole spacing should be based on the determination of the optimal storage minimum and maximum temperatures during operation and extraction of energy during discharging period within time t. Therefore, optimal spacing should be chosen based on the thermal properties of the storage medium, charging and discharging inlet temperatures of the fluid, required injected and extracted energy, and the length of the time period within which the power needs to be charged or discharged. Deeper boreholes do not seem to have a significant effect on storage performance or investment cost; however, this study did not consider increased heat losses due to suboptimal storage shape. Based on simulation results, the same capacity may cost 1.5 million € more in suboptimal case (1122 boreholes, spacing 2.0 m and depth 114 m) than in the optimal one.

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The temperature and oxidation state of magmatic systems across Iceland

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Iceland serves as a natural laboratory to study the generation of melts at a spreading axis interacting with a mantle plume. The oxygen fugacity of Icelandic magmatic systems, however, remains poorly documented. We present a comprehensive data set of ~1600 olivine-spinel pairs that is used to calculate representative temperature and oxygen fugacity for Iceland's different rift segments and off-rift volcanism. Equilibrated olivine-spinel pairs indicate temperatures between 1170 and 1350 °C and oxygen fugacities (fO_2) between -0.8 and +0.2 log units relative to the Fayalite-Magnetite-Quartz (FMQ) buffer for rift volcanism and 1225-1310 °C and fO_2 of ΔFMQ -0.5 to +1 for flank volcanism. The slightly alkaline flank volcanism derives from more oxidised sources than rift volcanism, but we find no evidence for the previously suggested highly oxidised plume sources. Our data set provides a robust framework for future studies of melt generation and magma plumbing systems in Iceland.

The potential use of heat waste energy in urban areas

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The Urban Heat Island (UHI) effect describes the consequences of human activities on an urban area in terms of surplus heat. UHI has mainly been described as mechanism behind increased surface temperature, but also enhances the subsurface temperature by a couple of degrees (Subsurface Urban Heat Island *or* SUHI). This makes urban areas more attractive for geothermal purposes as there is a possibility to make use of this thermal waste energy.

Various studies done around the world in urban areas recognized this effect, with an increasing

subsurface temperature of 2-5°C. In Istanbul groundwater temperatures are elevated with 3.5 degrees compared to rural areas. A similar effect is recognized in cities like Munich and Cologne in Germany, but also Winnipeg, Shanghai and Tokyo.
A recent project in the centre of Oslo revealed the same effect occurs here. To supply a new building with green energy, 12 shallow wells ranging between 50m – 150m depth, have been drilled at a site in central Oslo. These wells have been thoroughly logged and tested to define the best solution for a low-enthalpy geothermal system.
The groundwater temperature in Oslo is expected to be 7.5°C degrees at 100m depth, followed by increasing values of 3 degrees per 100m. However, at this site in central Oslo the temperatures are higher than normal. The fluid temperature measurements in the uppermost interval of the wells (0 -100m) indicate temperatures ranging from 17.5°C degrees at the top of the well to 9.5°C at 100m depth. From 100m depth, the geothermal gradient increases at a rate of 3 degrees per 100m and sometimes even more. This means that the centre of the city has a higher groundwater temperature of at least 2°C degrees compared to rural areas.
This increased groundwater temperature improves the potential for geothermal energy in urban areas like Oslo and enables the potential of recycling heat waste energy.

Effect of water content on CO_2 flow phenomena through tight, clay-rich rocks

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Achieving secure subsurface storage of CO_2, requires the long-term integrity of the caprocks overlying reservoirs and aquifers targeted for injection. As shale is an important caprock for many such reservoirs, it is thus important to fully understand the permeability and fluid flow behavior of such rocks when exposed to a flow of (dry), possibly supercritical CO_2. Here, this is investigated through permeability measurements on natural shale samples, as well as on analogue samples composed of quartz, smectite and kaolinite, under in-situ conditions, to explore the effects of effective confining pressure, clay content and type, and water content on CO_2 permeability, and to identify potential leakage mechanisms.
The experiments show that water content has a major impact on CO_2-permeability and fluid flow behaviour of both natural and analogue samples. Injecting water into natural or clay-bearing analogue samples resulted in a decrease in CO_2-permeability by several orders of magnitude. In the analogue samples, such decreases in permeability were observed regardless of clay-type or content. The observed effects of water content were completely reversible, as demonstrated by the return of permeability after subsequent drying of the samples. In addition, during constant flow measurements on both natural and analogue samples that contained water, rapid increases in CO_2-permeability, i.e. breakthroughs, were observed. After such constant flow tests, enhanced sample permeabilities were still observed over several days.
These results show that, in addition to effective confining pressure and mineral composition (or grain size distribution), water content is an important factor controlling the CO_2-permeability of clay-rich caprocks. Furthermore, as the injection pressure increases, so does the potential for CO_2 to break through narrow flow pathways blocked by pore water. This can cause a rapid increase in permeability that may persist after the CO_2-pressure has decreased. The most likely mechanism by which water controls tight rock permeability to other (non-wetting) fluids is by inhibiting flow through narrow pathways, such as fractures and pore throats. When exposed to dry supercritical CO_2, this water may be displaced into open pores or it may evaporate over time, leading to an increase in effective permeability.

From river to delta; Amalgamated sheet sandstones and the dispersive nature of subaerial unconformities (Dakota Group, USA)

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The adequate documentation and interpretation of key stratigraphic surfaces in river-to-delta systems are important to understand the interaction between sediment supply and changes in base level, and the resulting sediment distribution. Full-transect depositional profiles are essential to establish robust stratigraphic frameworks; however, exhumed examples showing a complete river-to-delta transition, and particularly those formed under low -accommodation conditions, are rarely preserved.

This study focuses on the Cenomanian Mesa Rica Sandstone (Dakota Group), of which the lower unit represents coeval fluvial-to-deltaic deposition in the Western Interior Basin. The ~400 km transect is exhumed along a NNW-SSE depositional dip-parallel profile, from southeast Colorado to central -east New Mexico. The combination of previous publications with newly collected sedimentary logs, drone survey data and grain-size samples, provides an extensive dataset with numerous photopanels and 125 logged sections throughout a ~40,000 km^2 study area. This allows mapping of down-dip changes in facies distribution, fluvial architecture, and the spatial extent of key stratigraphic surfaces.

Data analysis led to the recognition of multiple depositional environments, regionally-extensive stratigraphic surfaces, and sub-regional flooding surfaces. The upstream fluvial strata record deposition of vertically-stacked channel belts forming multi-valley sheets, changing downdip into a >80 km-wide, single-storey channel sheet. Downstream, the coeval fluvial-marine transition zone represents deposition in a shallow mixed-energy setting. The most distal expression of the system that can be studied is characterized by coalesced mouth bars, consistently overlain by sand-filled amalgamated distributary channels. Whilst a basal erosional composite scour underlies the fluvial strata in the upstream zone, the down-dip equivalent of this sequence boundary consists of several dispersed conformable surfaces in the marine part of the system, rather than one single surface. This sheds a new light on the impossible quest for a single correlatable sequence boundary surface in the marine realm, given that regional composite scours may be generated in the fluvial realm throughout a transgression-regression (T-R) cycle.

This case study provides an example of sand-prone shallow-marine deposition despite significant fluvial sediment storage. The work is important to understand other low-accommodation systems elsewhere, such as Mesozoic strata in the Barents Sea. Seismically-imaged fluvial and deltaic strata form potential reservoir-grade intervals with considerable uncertainties as regard connectivity. Studying exhumed systems like the Mesa Rica Sandstone improves our understanding of facies changes, sediment partitioning and distribution along different source to sink segments of low-gradient depositional systems. The results are applicable for modelling sandstone distribution and reservoir quality in these settings.

Water quality affected by interactions with filter media in raingarden(s)

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It has been expressed a need for stormwater management practices that mitigate the negative effects of urbanization on water quality and the hydrological cycle. Solutions which are sustainable, decentralized, perform well in winter conditions, and which add a restorative natural green space to the urban landscape have been encouraged by the Norwegian Water Association. Raingardens, also referred to as bioretention or biofilters are useful tools that can provide many of these services. Untreated surface runoff may contain several contaminants and can have serious implications for freshwater ecosystems. The objective of this thesis is to investigate how the filter media in raingardens can affect the water quality. This will be done by comparing water quality of the water entering the raingarden with the quality of the water exiting the raingarden. Water sampling and flow measurements will be done in the research raingarden at NMBU Campus Ås and the Bolstadhagen raingarden in Drammen. The water will be tested for nutrients, metals and in the case of Bolstadhagen also salts. Due to the composition of the raingardens with both an organic rich mixed soil layer and a sand layer it should be able to both adsorb dissolved components and remove particulate bound contaminants. To study these effects, soil samples will be tested for cation exchange capacity and organic matter and compared with samples from before the raingarden was planted. To study the water flow and retention time, I will utilize the Hydrus 3D model, calibrated with data from the NMBU raingarden, this will hopefully be a useful tool to predict how other raingardens perform, both with respect to water quality and water retention. The NMBU raingarden is equipped with groundwater wells and sensors measuring incoming water, soil moisture and temperature and overflow water, this paired with weather data from local metrological measuring stations will likely provide a good base for calibrating the Hydrus model.

Permafrost degradation in the Western Sector of Russian Arctic

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Permafrost plays an important role in the functioning of ecosystems and strongly affects human activities in the Arctic. Numerous studies have documented permafrost warming, increasing in the active layer thickness, and the northward retreat of southern permafrost boundaries caused by global climate change. The Russian European Arctic and Western Siberia are regions that have experienced some of the highest rates of permafrost degradation.

While climatic factors play major role in permafrost and active layer dynamics across large regions, local vegetation and soil variability can also significantly affect these trends. The variable response of the permafrost system to changing climatic conditions requires further investigations to better inform large scale models of socio-ecological and economic systems of Russian permafrost regions.

Long-term data from eight permafrost monitoring sites were collected to evaluate permafrost change in ecosystems typical of the Russian European North and West Siberia. All bioclimatic zones from typical tundra to northern taiga are covered by permafrost monitoring.

Our study evaluates climate changes across the region and how these changes affect permafrost temperature and active layer thickness. Sites located in typical tundra on continuous permafrost show increases in active layer thickness from 1.0 to 1.2 m during the period from 1997 to 2018. Sites located in southern tundra show evidence of permafrost table lowering from 1.2 m below the ground surface in 2000 to 1.8 m in 2016.

The greatest changes in the position of permafrost table were found in well-drained landscapes of forest-tundra zone. The lowering of permafrost table in Southern Urnegoy region was noticeable in the mid-1980s, but accelerated in the 2000s until it reached 10 m by 2014. Northern taiga ecosystems on permafrost are generally represented by bogs interspersed with elevated polygonal peatlands. While permafrost table in bogs lowered to 4 m below the ground surface, the permafrost table in peatlands is relatively stable.

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Comparison of pyrite trace element and sulphur and boron isotope characteristics from the Hirvilavanmaa Au-only and the Naakenavaara Au-Cu-Co-Ni orogenic gold mineralization in the Central Lapland Greenstone Belt, northern Finland

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The Paleoproterozoic Central Lapland Greenstone Belt (CLGB) is one of the most important metallogenic belts in the Fennoscandian shield. Most of the known orogenic gold deposits and occurrences in the CLGB are spatially associated with the east-west trending Sirkka Shear Zone (SSZ) (Eilu et al. 2007). Several occurrences along the SSZ are enriched in base metals (Cu, Co, Ni) in addition to gold. Another important structure in the CLGB is the NNE-trending Kiistala Shear Zone (KiSZ). The KiSZ hosts several gold-only deposits, including the Suurikuusikko gold deposit, which is currently the largest gold producer in Europe. In this study, we investigate two occurrences that are spatially associated with these two major structures. The Hirvilavanmaa Au deposit is situated near the intersection of the SSZ and the KiSZ. This gold-only deposit is hosted by altered ultramafic and mafic metavolcanic rocks. The Naakenavaara Au-Cu-Co-Ni ore occurrence is situated just 5 km south of the Hirvilavanmaa deposit. There the mineralization is hosted by altered phyllite and it is characterized by zones with distinctive metal enrichments. Trace element contents of pyrite were determined by LA-ICPMS analyses. Results shows significant differences in the concentration of Co, Ni, Cu, As, Se, Au, Te, Ag and Pb in pyrite between these two occurrences. Furthermore, within the Naakenavaara occurrence, pyrite trace element contents discriminate Co-rich and Cu-Au -rich zones. Sulphides from Hirvilavanmaa have $\delta^{34}S$ values with a median of +1.2 ‰. Sulphides from Naakenavaara show considerably heavier $\delta^{34}S$ values with a median of +9.9 ‰. Tourmaline associated with sulphides in mineralized zones has higher $\delta^{11}B$ ‰ (median -5.8) compared to tourmaline from barren zones (median -8.5) at Hirvilavanmaa. Tourmaline from Naakenavaara shows even lower $\delta^{11}B$ ‰ values with a median of -9.4. The trace element and stable isotope data together indicate that fluids with different characteristics were responsible for the gold and gold-base metal mineralization in the deposits studied.

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The Urban Water Cycle – linking surface water to subsurface processes and

groundwater; example from Bryggen in Bergen, Western Norway

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Bergen city centre, Western Norway, is prone to both subsidence and flooding. With a predicted increase in precipitation due to climate change a higher proportion of rainfall becomes surface runoff, which results in increased peak flood discharges. In addition, sea level rise and increasing storm surges are predicted which causes coastal flooding (Hanssen-Bauer, et al., 2017). We claim that there is a link between areas that suffer from surpluses or shortages of water and subsidence in urban areas, based in analysis of InSAR data and data collection from the Bryggen site. Results can be used to prioritize areas to implement measures such as Sustainable urban Drainage Systems (SuDS).

Infiltration systems were built to protect and preserve the UNESCO World Heritage Site Bryggen Wharf and its cultural layers below. This location is an example where SuDS have been implemented to collect, infiltrate and store surface water with the purpose to restore the groundwater level and increase soil moisture. A total of 46 boreholes are located within the study area that are continuously monitored with several parameters, there amongst groundwater level (Rytter & Schonhowd, 2015).

The hydraulic infiltration capacity of the rain garden has been tested with a full-scale infiltration test with the response on the groundwater levels monitored in wells. Result show that infiltration capacity meets the international guidelines requirement of 100 -300 mm/h, with 1600 mm/h for the large and 510 mm/h for the smaller under saturated conditions. An immediate response of the full-scale infiltration test is shown in the wells located closest to the infiltration point, with a delayed response in the wells further away. Results show that he infiltration capacity of the rain garden exceeds the amount of available surface water and the groundwater level would, in dry periods, benefit from more water, to preserve cultural layers. Therefore, the connected runoff area can be extended to the total catchment area. This can be used for improving existing and future urban drainage and water quality models used to assess the performance of SuDS, where Bryggen is a Best Management Practice (Venvik & Boogaard, *in review*). In addition, a study to develop risk assessment maps for areas most prone to the combination of both flooding and subsidence was carried out. These risk assessment maps can be used to identify areas where mitigation of subsidence and adaptation for surface water management will be most efficient (Venvik et al., *in review*).

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www.inxces.eu https://insar.ngu.no/ www.climatescan.nl www.sub-urban.eu

Large drumlins as a potential groundwater resource – an example from Småland, Southern Sweden

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Sweden’s drinking water supply is to about half obtained from geological formations. During 2016, 2017 and 2018 southern Sweden was affected by historically low groundwater levels due to periods of drought. Where low precipitation during the winter period led to a decrease in groundwater recharge. This put the society’s system of water supply and the water resources to a serious test. In the region of Småland in southern Sweden there are few large aquifers (i.e. large eskers and deltas). Therefore, to make sure that the society’s water supply can adapt to a changing climate, it is of great interest to investigate other geological formations that may be potential groundwater resources. It has long been acknowledged that areas of sorted sediments covered by till exist in this region, often found within large drumlins.

Drumlins are elongated hills formed by the action of glacier ice in the direction of ice flow and are a common feature in the glacial landsystem. We have studied a large drumlin in Berg using existing data from groundwater drillings as well as new corings and sondings to get a better understanding of the drumlin's internal stratigraphy. Furthermore, to connect these cores and to investigate the sediments properties we used geophysical resistivity measurements. Preliminary results from drillings show that this drumlin has a sorted sediment core and the resistivity measurements yield either water saturated sediments or clay. Based on above we discuss the potential to use large sediment cored drumlins as a groundwater resource.

XRF(Scanning) data of the Lomonosov Ridge Core PS2185-1 SL, Arctic Ocean - Glacial Changes

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Elemental analysis of Arctic Ocean cores are is used for cyclostratigraphy (Mn content), stratigraphic correlation (e.g. Schreck et al., 2018, Arktos), and the interpretation of sedimentary and diagenetic processes. For fast and high-resolution elemental analyses, XRF core scanning is increasingly applied. For the first time we applied both, the AVAATECH and the ITRAX core scanners on the same sediment core, gravity core PS2185-1 from the Lomonosov Ridge, Central Arctic Ocean to assess the quality and comparability of elemental composition data between the two core scanners. Both XRF-scanners measured PS2185-1 with a different resolution and different measurement times. These data were groundtruthed using calibrated elemental XRF analyses of discrete samples from the adjacent Kastenlot core PS2185-6. The core has been extensively investigated and is nearly depleted.
Additionally, the new core scanner data are compared with sedimentological and inorganic geochemical analysis, foraminiferal and isotope data on discrete samples from Kastenlot core PS2185-6. Only the scanners allow for high resolution investigation of the sedimentary environment with reasonable effort. The sedimentary sequences reveal periods of massive melting events of ice shelves surrounding the glaciated margins of the Arctic Ocean which alternate with phases of nearly zero sedimentation under permanent ice cover. Our presentation will illustrate how these drastic changes of the sedimentary environment are expressed in the elemental composition of the sediments.

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Schreck, M. et al., 2018. Improved Pleistocene sediment stratigraphy and paleoenvironmental implications for the western Arctic Ocean off the East Siberian and Chukchi margins. arktos, 4(1): Paper 21(20 pages), https://doi.org/10.1007/s41063-018-0057-8.

Vanadium and nickel leaching from Mustavaara and Titania tailings

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Tailings from the closed Mustavaara vanadium and the active Titania ilmenite mines have been actively leached for vanadium and nickel extraction in laboratory column experiments. Mustavaara Fe-V-Ti deposit is part of the Koillisima mafic layers intrusion. The Tellnes deposit at the Titania mine is an ilmenite rich norite in the Egersund anorthosite complex. Five columns of tailings from each of the deposits where leached with sulfuric acid, sulfuric acid enriched with ferric iron, deionized water (as a control), ammonium oxhalate in sulfuric acid and hydrochloric acid. The Titania tailings were also leached in acid wastewater from the mining operation. Each column contained approximately 2.5 kg tailings; and leach solution was added at a rate of 0.5 L per 24 hours. The Mustavaara tailings contain approximately 700-800 ppm V and around 150 ppm Ni. The Titania tailings contain approximately 250 ppm Ni and 300 ppm V. Vanadium is extracted in step 3 and 4 in sequential chemical extraction (ammonium oxhalate at pH 3) indicating that vanadium is associated with iron oxide phases. Magnetite /ilmenomagnetite constitute most of the iron oxide phases. The tailings are highly acid consuming making it difficult maintain a low pH. When pH goes below approximately 3.5, Ni concentration increases drastically in the pregnant leach solution. Vanadium is leaching distinctly better in ammonium oxhalate, however, with low concentration so far. Vanadium cannot be extracted for a profit at the current release rate.

Effects of shear enhanced decompaction weakening on channelized fluid flow and seismicity

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Fluid flow instability in viscously deforming porous rocks commonly known as solitary porosity waves has been used to explain formation of seismic chimneys, which are one of the most important expressions for the localized fluid flow in the subsurface. Experimental data show that volumetric deformation of rocks is strongly coupled with shear deformation, which leads to shear-induced decompaction at low confining pressure and shear-enhanced compaction at higher confining pressure. Decompaction weakening during the volumetric deformation is an important factor in chimney formation. A simple weakening factor of R is usually introduced for the decompaction weakening when the effective pressure is negative. While this approach has successfully reproduced the channelized fluid flow in the numerical models, it doesn't consider the effect of the shear deformation on the bulk viscosity. In this study, we use a new viscoplastic rheology that takes account on different compressive and tensile strengths (different critical pressures for the onset of pore collapse and pore generation) and the shear-enhanced weakening that fits with the experimental data. Our model produces fluid channels similar to previous studies that use a simple weakening factor of R for decompaction. Without the shear-enhanced effect, a tensile strength that is 10~100 times lower than the compressive strength is required for chimney formation in our model. Our models with the shear-enhanced effects show that the shear failure can be triggered during the formation of the fluid channels, both at the front of the fluid channels and the surrounding area. This is another type of fluid flow instability trigged by shear stress but not fluid pressure, which might be related to the micro-seismicity. Therefore, the shear enhancement of volumetric deformation might be of key importance for the initialization and propagation of fluid channel and accompanying micro-seismicity, especially at a tectonic active area.

A 3D analytical model for reservoir uplift

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Injection of CO2 in aquifers or depleted oil- and gas reservoirs leads to pressure build-up, reservoir expansion and surface uplift. We have developed a 3D poroelastic model with three layers for the geomechanical implications of reservoir pressure build-up. The model has an overpressured reservoir in between an overburden and an underburden. An analytical solution is presented for the displacement, strain and stress for the three-dimensional poro-elastic model. The fluid pressure in the reservoir is assumed symmetrical around the z-axis and represented by a Fourier cosine series. The poro-elastic solution is expressed as a superposition of the solutions for each term in the Fourier series. It is shown that the surface uplift can be written in a similar form to the 1D vertical expansion of the reservoir layer, but where the fluid pressure is based on the Fourier series. Amplitudes of the fluid pressure with average wavelengths much longer than 2 times pi times the thickness of the overburden produce surface uplift, but wavelengths much shorter do not. The stress in the overburden, which is generated by the reservoir fluid pressure, is also analysed in terms of the wavelengths. A case is given where the analytical uplift is compared with the results of a numerical simulation and the agreement is excellent.

A Holocene tephrochronology for the Faroe Islands; new results and correlations

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The Faroe Islands hold a key position for linking the proximal tephrochronology in Iceland with distal tephra networks on the European continent and the British Isles. Several tephras have been described in peat and lake sediment sequences, including the type sites for the Saksunarvatn and Mjáuvøtn tephras (10.2 ka yr BP and 6.6 ka yr BP, respectively). Several other important Holocene tephras are well represented on the Faroe Islands and may provide more precise ages than elsewhere. Examples of this are the early Holocene Hässeldalen and Askja-S tephras. Another is the basaltic Mjáuvøtn Tephra which has a potential to become an important marker for the middle Holocene although its relation with other middle Holocene tephras from Katla needs to be better resolved. The early Holocene Saksunarvatn Ash is now considered a result of several eruptions in the Grímsvötn volcanic system rather than one major eruption. It can be separated into two phases on the Faroe Islands: the early phase with two precursor eruptions has lower MgO concentrations (4.5-5.0 wt%) and the

later phase has higher MgO concentrations (5.5-6.0 wt%), and includes the visible Saksunarvatn macrotephra. The Tjørnuvík Tephra (c. AD 800s), previously considered to be a primary tephra, is now interpreted as a reworked deposit with material from at least two middle Holocene eruptions of Hekla, Hekla-S and Hekla-4. Several of the tephras identified on the Faroe Islands provide useful isochrons for climate events during the Holocene, e.g. the 8.2 ka and 4.2 ka BP events.

Reference:
Wastegård, S et al. 2018. Towards a Holocene tephrochronology for the Faroe Islands, North Atlantic. Quaternary Science Reviews 195, 195-214.

Near surface geophysical analysis of proglacial sediments at Midtdalsbreen, southern Norway

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The utility and capability of near surface geophysical techniques has rapidly advanced over the past three decades. They offer a valuable means to undertake non-destructive subsurface exploration meaning methods such as ground penetrating radar (GPR) are now standard practice in many sedimentological and environmental studies. Proglacial sediments and landforms provide valuable insight into past glacier dynamics. However, the remote location, harsh terrain and complex subsurface of proglacial environments has impeded the development of geophysical techniques for internal, subsurface studies of these sediments. Traditionally, features such as moraines have been studied using glacial geological techniques such as sedimentary logging. While this provides valuable, in situ information, there are numerous limitations, namely poor availability and spatial extent of exposures. In this study, geophysical methods, such as ground penetrating radar (GPR), seismic refraction and multichannel analysis of surface waves (MASW) have been combined with sedimentological investigations to image the proglacial sediments across the foreland of Midtdalsbreen, an outlet glacier of the Hardangerjøkulen icefield, southern Norway. Multiple methods have been deployed to overcome the inherent limitations of each technique and to enable evaluation of their performances in the proglacial setting. Three sites with contrasting sediment properties have been surveyed; (a) an area of sand-rich hummocky moraines, (b) a silt-rich lateral moraine with abundant surface boulders and (c) a prominent terminal moraine consisting of coarse, blocky sediments. Through comparing the results from sites a to c, the capability and suitability of each of the aforementioned geophysical techniques has been analysed. Going forward, integration of these datasets looks to provide more extensive knowledge of the proglacial sediments and sedimentary structures present within the foreland of Midtdalsbreen. This will improve our understanding of the controls on moraine deposition, morphology and preservation, in turn, leading to an advanced understanding of past ice dynamics and the associated palaeoenvironments at Midtdalsbreen and the future rate and style of retreat of the Hardangerjøkulen icefield.

Gas composition of the Svelvik Ridge Aquifers used to design noble gas tracers for a CO_2 injection experiment

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The ECCSEL Svelvik CO_2 Field Lab is used for water and CO_2 injection experiments. Investigations on monitoring techniques for Carbon Capture and Storage (CCS) shall support the development of CCS in Norway.

Noble gases are one approach to identify the source of CO_2 anomalies, possible leakages. Explicitly, the challenge is to differentiate natural CO_2, from injected CO_2. Inherent noble gas signatures can be used, meanwhile added tracers might be more reliable. Experiments will be conducted with helium and krypton, as our field equipment is able to analyse water and gas on Helium and Krypton semi-continuously.

The siliciclastic sediments of the Svelvik ridge contain a fresh water aquifer at the top and salt water in deeper strata. We sampled two wells (6.5 and 64 -65 m depth) on dissolved gases in order to design a noble gas tracer experiment for CO_2 injection. We measure depleted oxygen and CO_2 and enriched helium concentrations in the saline aquifer indicating radiogenic accumulation; meanwhile krypton concentrations are not naturally increased. The upper fresh water aquifer is not as depleted in oxygen and has atmospheric noble gas composition.

We adjust the amounts of tracer to the background and install a designated setup that allows the quantification of tracer injection simultaneous to CO_2 injection. Monitoring during CO_2 injection in fall 2019 will allow us to analyse the behaviour of noble gases in comparison to CO2 and possibly

identify leakages. Further, we might be able to confirm observations from small-scale experiments that the noble gases can act as early warning tracers.

Magnetotelluric Analysis for Greenland and Postglacial Isostatic Evolution (The MAGPIE Project)

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Mass loss from the Greenland Ice Sheet has accelerated during the past decade due to climate warming. This deglaciation is now considered a major contributor to global sea level rise, and a serious threat to future coastlines. It is therefore vital to measure patterns and volumes of ice sheet mass loss. However, measurements of the ice sheet's mass and elevation, both of which decrease as the ice melts, are also sensitive to ground deformation associated with glacial isostatic adjustment (GIA), which is the solid Earth's response to ice loss since the last ice age. For Greenland, GIA is poorly constrained in part because Greenland's complex geologic history, with a recent passage over the Iceland Plume, probably created large lateral viscosity variations beneath Greenland that complicate the GIA response.
The Norwegian MAGPIE project (Magnetotelluric Analysis for Greenland and Postglacial Isostatic Evolution) seeks to develop new constraints on mantle viscosity beneath Greenland by collecting magnetotelluric (MT) data on the ice sheet. MT images the Earth's electrical conductivity, which is sensitive to two of the major controls on mantle viscosity: temperature and water content of mantle rocks. We therefore plan to use MT data, together with existing seismic data, to map viscosity variations beneath Greenland. Using these inferred lateral viscosity variations we will test for a hot, low-viscosity channel beneath the Iceland Plume track. Additionally, we will build a new set of GIA models for Greenland by repurposing a mantle flow code with adaptive mesh refinement to solve the GIA problem with 3D viscosity variations. This open-source code will be available to the geophysical community for solving similar problems, which are also vitally important in Antarctica. Using this code, we will generate the first GIA models for Greenland that include constrained 3D viscosity variations. These predictions of GIA uplift will enable us to greatly improve estimates for modern-day ice loss in Greenland.

New constrains on the hydrological and thermal conditions of Surtsey

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In summer 2017, the Surtsey Underwater volcanic System for Thermophiles, Alteration processes and Innovative Concretes (SUSTAIN) drilling project (Jackson et al., 2019; Weisenberger et al. 2019), drilled three cored boreholes through Surtsey Volcano, a very young oceanic island, nature preserve and UNESCO World Heritage site. The new boreholes (SE-2a, 2b and 3) in addition to the borehole drilled in 1979 (SE-1) provide a unique opportunity to study the subsurface geothermal system on a young volcanic island. Time serious measurement of well SE-01 show that the maximum temperature at a vertical depth of about 100 m has dropped since 1980 from about 140°C to 124°C, although the general shape of the temperature profile remains similar over the time period. The temperature profile of SE-2a shows a similar trend. However, the maximum temperature in SE-2a is about 1.5°C higher. Temperature logs of the vertical wells indicate an inflow of cold water at about 145 m below the surface. The temperature in the diatreme beneath the island is about 60°C, well above the expected ambient temperatures for ocean floor. The maximum temperatures in the angled well SE-3 measured during the annual Surtsey research expeditions 2018 yield a temperature of 138°C, which is 14°C hotter than in the vertical wells with the temperature maximum being about 20 m deeper than in the vertical wells. Time series measurements started shortly after drilling was completed. They indicate that the well SE-3 had reached thermal equilibrium after drilling in 2017. The rise in temperature towards west suggests that the hottest part of the geothermal reservoir within the edifice lies under the main craters of the 1963-1967 eruption. The thermal conditions of Surtsey were analyzed after the drilling in 1979 by Axelsson et al. (1982) and Stefánsson et al. (1985). These analyses suggest that the geothermal area in Surtsey could be explained by heat release from sizeable intrusive bodies within the edifice. The new data from Surtsey holds the potential for test-

ing this and other hypotheses on the heat sources of this ocean-island geothermal system.

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Geomorphologic and geochronological reconstruction of Holocene jökulhlaups along the Hvítá River and Gullfoss waterfall, Iceland

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Glacial lake outburst floods (jökulhlaups) have occurred across the planet throughout the Quaternary. Iceland experiences more frequent jökulhlaups than nearly anywhere on Earth, yet most research focuses on volcanogenic floods beneath its southern ice caps. However, floods from proglacial lakes may be a better analogue to most global jökulhlaups. As the Icelandic Ice Sheet retreated across Iceland in the Late Pleistocene-Early Holocene, meltwater pooled at ice margins and periodically drained in jökulhlaups. Some of the most catastrophic floods are hypothesized to have drained from ice-dammed Glacial Lake Kjölur, surging across southwestern Iceland from the interior highlands to the Atlantic Ocean. These floods left extensive erosional and depositional evidence along the modern-day course of the Hvítá River, including boulder fields, cataracts, canyons, and Gullfoss waterfall. The largest events reached an estimated maximum peak discharge of 300,000 $m^3 s^{-1}$, ranking them among the largest known floods in Iceland and on Earth.

Yet, all our evidence for the Kjölur jökulhlaups comes from only one publication to date (Tómasson, 1993). My research employs new methods to better constrain flood timing, magnitude, routing, and recurrence interval at this underexplored site. This talk presents new and synthesized geomorphologic evidence, preliminary hydraulic modeling results, and ongoing geochronological analyses using cosmogenic nuclide exposure dating and tephrochronology. Reconstructing jökulhlaup timing and dynamics will advance understanding of Icelandic Pleistocene-Holocene deglaciation chronology, proglacial hydrology, and the role of extreme events in landscape evolution. Moreover, the Kjölur floods may serve as an analogue to contemporary glacial outburst floods, which pose a significant geohazard in Arctic and alpine regions worldwide due to climate-driven meltwater lake expansion.

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Lunar Cratering Chronology – review and revision.

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The Apollo and Luna mission samples obtained on the lunar surface still provide most valuable temporal information to decipher lunar planetary surface evolution. Sequences of geological events can also be dated by crater statistics. Cratering chronology models have been derived using sample ages and crater statistics at the landing sites for calibrated absolute model ages. Since the initial models developed several decades ago, and despite increasing numbers of sample ages and improvements in crater statistics, the cratering flux is still debated to be mono-spike (terminal cataclysm or late heavy bombardment, sawtooth), multi-spike (spiky, sawteeth, picked fence) or monotonically decaying (tail end of planet formation).

Here, we present an in-depth evaluation of 1) newly mapped reference geologic units based on spect-

ral and morphologic data along with 2) the cratering statistics of these units and 3) recalculated sample ages using recent monitor sample ages and updated K- and Rb-decay constants. Both sample ages and crater frequencies are new calibration input for the chronology models.
The recalculated sample ages tend to show increased age for already previously old ones, but less systematic changes for younger samples, which effectively slows the cratering flux decay. Compared to other landing site characterisations, the spectral data suggest a reduction of area size that considered being homogeneous. It caused for the following crater counting evaluation a reduced crater size range for the interpretation of crater frequency. In the smaller crater-size range in old units, saturation and resurfacing events modify the crater record and result in apparently smaller crater frequencies.
The interpretation of collected samples linked to extended surfaces is hampered by the lateral transport of material (e.g., basin ejecta) across Moon. Despite additional mineralogical data, linking sample ages to surface units has been the main challenge. We therefore provide a sequence of basin ejecta for each landing site, which characterises the landing sites for potential contamination by ejecta from other (large) basins, and we use the superposed crater record to define the amount of impact gardening, local reworking of shallow stratified ejecta "sediments". This way we get a better understanding of which sample ages are likely local and which may be ejecta from elsewhere. Jointly, these three puzzle pieces provide the base for discussion on the evaluation of current lunar cratering chronology models. We provide also our favourite new lunar cratering chronology model.

The role of source facies on bitumen-derived thermal maturity parameters, Botneheia Formation (Middle Triassic), Eastern Svalbard

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Organic-rich, oil-prone shales of the Middle Triassic Botneheia Formation onshore Svalbard and its offshore and slightly older equivalent, the Steinkobbe Formation, represent regionally important source rock units. The present day maturity trends of these shales vary laterally, primarily reflecting the different structural domains across the Barents Shelf and Svalbard. In addition, the widespread emplacement of igneous intrusions during the Early Cretaceous has reportedly influenced the observed maturity variations. In this study, we investigate thermal maturity variations of the c. 80 m Botneheia Formation within and between the early–peak mature Blanknuten and Skrukkefjellet locations on Edgeøya, eastern Svalbard. Former work indicate less thermal influence in the Skrukkefjellet locality compared to the Blanknuten locality, and no gradational thermal inference from igneous intrusions at either location. We are therefore able to test how source input variations influence commonly applied bitumen-derived maturity parameters between and within these localities. The investigated maturity parameters are derived from biomarkers (GC-MS), n-alkanes (GC-FID), bulk hydrocarbon fractions (Iatroscan TLC-FID), and total organic carbon (LECO).
Our study demonstrate that several parameters, including Ts/(Ts + Tm), 29Ts/(29Ts + norhopane) terpane ratios and the methyl phenantrene ratio show inconsistent variations with depth. Instead, they co-vary with changes in kerogen type. Thus, source input variations have probably greater influence on these maturity parameter variations at each locality than heat contribution. In contrast, the αα/(αα + ββ) and 22S/(22S + 22R) ratios from C_{29} steranes seem less influenced by source input, as both of these parameters generally show decreasing values with less burial, although exceptions do occur. The Carbon Preference Index and saturate/aromatic ratio (SAR) also show co-variance with kerogen type, indicating that the source input largely influences the total extract composition. Comparing the correlative stratigraphic units across the two localities, the Skrukkefjellet outcrop generally shows lower maturity.
To conclude, we show that Middle Triassic shales at both locations exhibit vertical trends in certain routine thermal maturity parameters that correlate with kerogen type. In addition, the Skrukkefjellet locality is generally less mature than the Blanknuten locality within correlative stratigraphic units, complying with previous regional maturity studies.

Seabed morphology and sedimentary processes on the Kveithola TMF, Bear Island, Norway

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As the smallest of the paleo-ice stream systems along the northeastern Atlantic Margin, The Kveithola Paleo-Ice Stream and its related remnants give a unique opportunity for mapping the entirety of the system. Both due to its size and history, as a small ice stream nestled between its two major counterparts, the Bear Island and Storfjorden Ice Stream, has put the Kveithola System in the focus for several studies during the last decade. Following three recent cruises, the Mareano-programme have collected a new dataset, where this study is focusing on the data retrieved from the end member of the Kveithola Paleo-Ice Stream, the Kveithola Trough-Mouth Fan (TMF). The dataset contains new bathymetry data from the Kveithola TMF, which have a higher resolution than previous studies (10m cell size) that is covering an area of more than 2000 km^2 from the shelf edge and towards the deep ocean. Within this grid, the surface has been further sampled in a series of stations that contain video lines and van Veen grab samples that have been used to further illuminate the nature of the sediment surface. The surface revealed by the new data display a morphology that is highly influenced by mass movement processes, where the majority are interpreted as either sliding events or glacigenic debris flows. Additionally, two new slumping events on the upper-mid slope have also been discovered. Based on the bathymetry, the slides appear to differentiate in age, where both older and younger events are present (possibly pre- and post- Last Glacial Maximum), and to have occurred both as single or sequenced events. Among the sequenced events are the Kveithola Slide, which appear to have several levels within the slide scar, where one level has a very distinguished character consisting of a series of small ridges. The Kveithola Slide appears to have had a retrogressive development, and within the new data there have been observed two minor retrogressive cracks that foreshadows the potential for the occurrence of new events in the future.

A geological hike through the Dala sandstone on the eastern slope of Fulufjället; experiences from the INTERREG project GEARS - Geologiskt arv i inre Skandinavien

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Fulufjället is a low relief mountain of sandstone in the northern part of Dalarna, Sweden. The highest peak is approximately 1000 m and its flat appearance is caused by morphological features of the bedrock. Fulufjället is a national park in both Sweden and Norway, with Naturum Fulufjället acting as a visitors centre for both national parks.

On the Swedish side, the national park has a network of certified local guides. Both Naturum and the guide network offer guided tours within the national park. Often these tours include short walks along existing pathways to sites such as Njupeskär or Old Chikko. Within GEARS, an opportunity of further geology training was offered to the guide network and staff at Naturum, so that they also can tell the geological history of Fulufjället.

In the project, Naturum wanted to develop a new experience for the more advanced hikers visiting the national park. The new experience is a 4-5 hours guided hike through rough terrain on the eastern slope of Fulufjället. In August 1997, 400 mm of rain fell during two dramatic days. The soils on Fulufjället and the bedrock could not keep the large amount of water, hence enormous amounts of water was released along scars and rivulets, such as Kloran and Göljån, cleaning the river sections from vegetation and loose debris, redepositing them down-stream. The natural cleaning has provided a unique opportunity to understand the depositional environment of the Dala sandstone.

Since hiking in most part of the Kloran gorge is very difficult and even dangerous at places, the guided hike mainly follows the rivulet from above the gorge. The Kloran hike provides a short course of the bedrock characteristics found on Fulufjället and you can see the traces of the catastrophic days in 1997. Along the trail you also pass typical deglaciation features from the last ice age, such as glaciofluvial drainage channels and ridges. Cultural aspects of geology can also be found along the hike, with old trapping pits and remains of whetstone quarries.

Technology developed by pathologists provides free online access to 240 000 palynological slides

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The palynology slide archive at the Norwegian Petroleum Directorate (NPD) contains more than 120 000 slides from exploration and development wells in addition to outcrop sections. Additional procurement during 2020 will double the number of slides and well sections. As part of its uninter-

preted data release practice, the NPD has loaned slides to companies, consultancies and academia since the early 1980s. Loaning out slides reduces demand for core and cuttings, thereby reducing the degradation of valuable geological material. However, loaning paly-slides for six-months or longer is not an efficient use of data, as it allows only one company or institution access to a well during a loan period. In addition, considerable slide breakage has occurred during transport, and hundreds of slides have been lost in transit or destroyed during the last three decades. The solution to this problem is to use digital technology that the medical sciences have developed during the last fifteen years: high resolution whole slide scanners and machine learning software. The development of this technology has been driven forward by its main users: pathologists and histologists. The current phase of palynology digitalisation will provide public online access to 240 000 digital palyslides for visual and machine learning analysis. Each slide's digital resolution is 4000 pixels per millimetre, yielding up to 17 billion pixels for each focal layer. The scanning optics are 0.95 numerical aperture, providing an optical resolution of 0.29 µm. The imaging optics are therefore optimally matched to the detector's physical pixel size which produces the 0.25 µm/pixel digital resolution of the final image. To enable communication between palynologists, the user may add annotations and comments to any number of fossil specimens on the scans. The second phase of digitalisation is palynological analysis through machine learning. The production of large, accurate image recognition training sets for fossil microplankton, pollen and spores may enable robotic analyses to quickly generate interpretations of taxonomy, palynofacies and depositional environments, - all with a high degree of objectivity and consistency. What does this entail to be fully operative? - a cooperative effort involving the entire palynological community.

Ice sheet-gas hydrate interactions in the Barents Sea

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Large amounts of the powerful greenhouse gas methane are stored in the Arctic as gas hydrate. These exist under specific pressure and temperature conditions, small changes in which can destabilise the gas hydrates and trigger large-scale methane release. In past ice ages, vast ice sheets covered much of the Arctic and high pressure, low temperature conditions beneath these would have provided ideal conditions for the formation of thick, stable gas hydrate reservoirs. Combining marine geophysics with numerical modelling we study how the advance and retreat of successive Barents Sea ice sheets has influenced methane storage and release, and how subglacial gas hydrate formation has influenced ice sheet dynamics. We show examples from the Barents Sea to demonstrate that the presence of gas hydrate in subglacial sediments and bedrock has a fundamental influence on subglacial thermal regime; determining rates of ice stream flow and efficiency of erosion. Furthermore, on deglaciation these reservoirs are vulnerable to destabilisation, potentially triggering abrupt methane gas release. The storage and export of carbon from glaciated areas is poorly understood. Our new understanding is crucial to improve the prediction of greenhouse gas release from the Greenland and Antarctic ice sheets, and to understand controls on ice sheet dynamics and erosion.

Geochemical variation in modern stromatolites from different environments: a potential palaeoenvironmental proxy

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Stromatolites, generally speaking, grow as a result of the precipitation of carbonates or silica as a result of cyanobacterial activity. In the Archaean rock record, stromatolites are interpreted by many as the oldest direct record of life on Earth. These are typically compared with locales such as Shark Bay, Australia, which often leads to interpretations of these structures as indicative of both warm climate and shallow, quiescent water environments. However, modern cyanobacterial activity is not restricted to such a narrow range of environmental conditions. These modern cyanobacteria also produce similar depositional structures as observed in ancient stromatolites, albeit typically on a smaller scale.
In this study, stromatolites have been collected from a variety of modern settings, including hypersaline lakes, hot and warm springs, salt pans, and

peritidal marine environments. Furthermore, the definition of "modern" was extended for this study to include samples from Pleistocene ice lakes. Tropical, subtropical, arid, temperate, and periglacial climates have all been sampled for this study. While the idea of examining modern stromatolites to understand the ancient rock record is not new (see e.g. Golubic, 1991, and references therein), the literature continues to be largely devoid of comprehensive trace element data, including the REE+Y.

In this study, the geochemistry of these modern stromatolites is examined to seek out potential trace element indicators of environmental conditions. Major elements have been analysed by XRF and trace elements by LA-ICP-MS at the University of Stellenbosch, South Africa. Preliminary results show that REE+Y data from various environments shows discernable differences. Data concerning other potential trace element markers are still being evaluated and results will be presented at the meeting. It is hoped that these markers can be applied to samples in the ancient rock record to better understand paleoclimatic conditions.

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Basin fill dynamics of the Triassic alluvial succession in the Øygarden area, Norwegian North Sea

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The Triassic continental succession west of the Øygarden Fault Complex in the northern North Sea is studied using 2D and 3D seismic lines integrated with well pattern analysis to discern the basin fill history and structural development of the area. The Øygarden Fault Complex is located within the N-S trending Horda Platform east of the deeply faulted Viking Graben. A series of large west-dipping faults bounding east-dipping half grabens characterize the Horda Platform area. The focus area is within a rotated fault block between the basement-bounding Øygarden Fault in the east and the Vette Fault in the west.

The Triassic fill forms a 1300 m eastward thickening unit, commonly regarded as part of the Late Triassic post-rift stage. A wedging of some intervals is however indicative of active faulting during deposition. Previous studies have subdivided the strata in the Tampen Spur area into a late Permian-early Scythian syn-rift basin fill and three post-rift phases; 1: Late Scythian to Ladinian, 2: Carnian to Norian, 3: Norian to Rhaetian, defined by bounding unconformities and depositional patterns. This study subdivides the Øygarden area succession into seismic facies where reflection patterns indicate depositional characteristics. Reflection pattern analyses reveal depositional features such as channels, hangingwall fans, and footwall fans. A shift in facies trend between mud and sand rich intervals indicates variance in subsidence rate and sedimentation supply related to tectonic displacement rate and climate. The climate changed from arid to semi-humid in the Latest Triassic according to studies from Tampen Spur: (1) a shift in palaeosol types, (2) increase in carbonate material, (3) seasonality indicated by isotope analysis, (4) absence of anhydrite, (5) an increase in abundance and thickness of the mud-dominated intervals related to an increase in pluvial lacustrine conditions, (6) a change in palaeolatitude, and (7) increased fluvial channel stability indicating increasing sinuosity. Humid climate results in denser vegetation, which strengthens levees and their channels. During increased runoff, the sediment yield increased, with correspondingly coarser grained material delivered to the basin. Models for sedimentation fill and stratal package geometries in rift systems can be applied to the Øygarden area. The analysis suggests a depositional system with N-S trending highs bounding narrow elongated basins. Alluvial fans prograded from the ranges into the basins. Changing subsidence rate and climatic variations controlled the magnitude and style of axial draining channels along with the dispersal and preservation of surrounding finer grained alluvial plain style deposits.

Integrated seismic and geomechanical/ flow modelling study of focused fluid flow

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The main aim of this work is to de-risking prospects for charge - and seal issues. The improved resolution of recent seismic surveys has made seismic chimney structures a common observation in sedimentary basins worldwide and on the Norwegian Continental Shelf. Focused fluid flow in vertical chimneys is an important and poorly understood feature in the petroleum system. Oil and gas migrate through preferential pathways from source rocks to structural traps where they form reservoirs. Further migration or leakage from reservoirs leads to formation of shallow hydrocarbon accumulations and gas pockets. In some cases, leakage through preferential pathways can be traced up to the surface or to the sea floor, where it leads to formation of mud volcanoes, mounds and pock-

marks. Here, we present results of an integrated case study, which is performed on a 3D seismic data set that covers an area of approximately 3000 km^2. The seismic sequence stratigraphic interpretation is complemented with a study of seismic fluid migration paths. Detection of seismic chimneys is a challenging task. State-of-the-art chimney cube technology based on self-educating neural networks was used to automatically identify possible structures. The results of seismic inversion in combination with available well data provided a set of surfaces distinguishing various stratigraphic layers and their properties. Obtained geological model was used as a basis for coupled geo-mechanical / fluid flow modelling that reconstructed the fluid flow processes in the geological past that lead to formation of chimney structures. Our numerical model of chimney formation is based on the two-phase theory of fluid flow through (de)compacting porous rocks. Viscous bulk rheology and strong nonlinear coupling of deforming porous rocks to fluid flow are key ingredients of the model. Chimney formation is linked to pressure build-up in the underlying reservoir. We reconstruct the fluid flow processes in the geological past that lead to formation of chimney structures and provide expectations for their present-day morphology, porosity and fluid pressure. Conditions of chimney formation, their sizes, spatial distribution and times of formation are investigated and linked to the volume of the source reservoir, porosity and material parameters of the reservoir rock and saturating fluid. The fate of the chimney after it has been created and its role as a fluid pathway in the present-day state is studied.

Timing – an underestimated key factor for source rock evaluation, case study from NE Java, Indonesia

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When performing petroleum system analysis, temperature is usually treated as a key parameter, affecting the alteration of the organic matter and hydrocarbon generation. Temperature assessment is crucial for sedimentary basin analysis and modelling since it is closely tied to the maturation level of the source rock, its remaining generational potential, critical moment, and expulsion. The applied methods to evaluate the temperature (e.g. Rock Eval pyrolysis, vitrinite reflectance, thermal alteration index (TAI), steranes and terpanes isomer ratios of the extracted bitumen, carbon isotopes of the organic matter and hydrocarbons) are typically coherent with each other. However, not all these methods may be applicable when doing assessments in sedimentary basins affected by volcanic activity.

A multidisciplinary study was performed on a set of erupted rock clasts collected from the Lusi site (Indonesia): the Earth's largest mud vent active since May 2006. The long lasting activity of this system is fuelled by the Holocene magmatic intrusion that penetrated Paleogene organic-rich shales at ~4.5 km depth. Lusi constantly erupts mud breccia, boiling water, gas and oil. Among the erupted clasts we identified the samples of the Paleogene organic-rich formation and performed a set of geochemical (Rock-Eval pyrolysis, vitrinite reflectance measurement, bitumen extraction, GC and GC-MS-MS) and palynological analysis. The results show that the analysed samples have very high organic matter content as well as amount of extractable organic matter. However, temperature estimations using different methods revealed discrepancies of at least 100 °C. While Rock-Eval pyrolysis and sterane isomers suggest the beginning – middle of the oil window, vitrinite reflectance, microthermometry, and palynology methods indicate the end of the dry gas window–overmature zone. These discrepancies are interpreted to be the result of heterogeneity of the organic matter and the uneven maturation rate of its particles under a geologically short heat impact. Our study highlights the relevance of targeted geochemical and microscopy methods (i.e. palynology, organic petrology, and chlorite microthermometry) that are capable to estimate the temperatures in sedimentary basins affected by volcanic activity. We suggest that timing (of the rock clasts exposure to high temperatures, favouring hydrocarbon generation), along with the temperature, is a crucial parameter for evaluating the hydrocarbon source rocks.

Towards better understanding of volcanic rifted margins: insights from contemporary study of the Møre and Vøring basins, offshore mid-Norway

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An understanding of the rifted structure and basin evolution of the mid-Norwegian margin (MNM) up to the onset of NE Atlantic magmatic breakup in the earliest Eocene remains incomplete and debated. A main point of a debate is whether the MNM developed through in either several and episodic extension events, or instead a single phase of continuous extensional deformation leading to breakup similar to magma-poor margins. The aim of this contribution is to critically evaluate the development of the MNM leading to breakup based on a new generation of long-offset 2D seismic data, large 3D surveys, and potential field data. This comprehensive dataset provides much better imaging of the geometries of the deep Cretaceous sub-basins and sub-basalt structures. Recent wells in the outer Møre and Vøring basins constrain better the regional tectonostratigraphic framework. During this integrated study, we confidently mapped eight Cretaceous-Paleocene horizons and constructed a series of regional transects and thickness maps. Our interpretation was also tested and validated by 2D potential field and geodynamic modelling. Our seismic interpretation shows that the basins were subjected to episodic Cretaceous-Paleocene rifting events with intermediate cooling/subsidence phases. These successive periods of extension and relaxation preconditioned the MNM lithosphere prior to breakup. Active deposition in the Early Cretaceous was mainly focused in the Møre Basin. In the Cenomanian to Paleocene largest depocentres developed in the Vøring Basin and migrated sequentially west towards the present ocean. We explain this migration of the rift and basin depocentres by a strain hardening due to lithospheric cooling with possible enhancement from lateral lower crustal flow. Seismic interpretation, refraction data and potential field modelling suggest that the volcanic margin developed preferentially either on thick continental ribbons or moderately thinned continental crust. The MNM is fundamentally different to magma-poor passive rifted margins in its basin architecture, long and polyphased development (>200 myr) and the magmatic budget.

Effects of rotational submarine slump dynamics on tsunami-genesis – new insights from idealized models and the 1929 Grand Banks event

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Tsunamis are natural hazards that can be caused by submarine landslides. Landslides with short run-out and duration are called slumps, and their tsunami generation have commonly been modelled simplistically by using blocks. The block approach was used for modelling tsunamis of important historical events such as the 1998 Papua New Guinea (PNG) and the 1929 Grand Banks. While such a method has the advantage of being simple to use, it offers no or little insight into physical processes like ductile deformation of the sediments during the slump motion. Here, we use a viscoplastic landslide model with Herschel-Bulkley rheology to model the deformable sediments on a simplified geometry. The sediment's yield strength is an important factor for the tsunami-genesis, and the resulting translational kinematics relate to the tsunami height as studies for long run-out landslides have already shown. In this study, we also show the importance of the rotational slump motion related to the tsunami-genesis, for the first time, by using a deformable slump. In addition to the idealized study, we use the same viscoplastic model to simulate the 1929 Grand Banks event under consideration of the updated slump source representation. The size of the tsunami simulated for the Grand Banks event modelling confirms that our viscoplastic model can be used for complex slump induced tsunamis. On the other hand, more work is needed to understand the exact generation mechanism.

Model-data discrepancies in mid-Pliocene Arctic warming and implications

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The mid-Pliocene Warm Period (mPWP, 3.2 Ma) has been extensively studied to improve the understanding of past warm climates and for its potential to serve as an out-of-sample evaluation of climate models in light of projections of future warming. Thus far, simulations of mPWP climate have consistently underestimated the strong Arctic warming inferred from paleoenvironmental reconstructions. Here, we analyse simulated Arctic (55–

90°N) temperature anomalies in the Pliocene Modelling Intercomparison Project Phase 2 (PlioMIP2) ensemble. The PlioMIP2 ensemble simulates a climate that is 1.4–4.9°C warmer globally than pre-industrial with temperature anomalies in the Arctic ranging from 3.2–9.6°C. Data-model comparisons show that significant underestimations of Arctic warming are still present in PlioMIP2 simulations with median biases ranging from -9.1 to -3.9°C for mean annual surface air temperature, and from -3.3 to 0.5°C for mean annual sea surface temperature. Changes in boundary conditions compared to previous PlioMIP1 improved the agreement between data and models only regionally, with additional warming occurring in the North Atlantic. The reduction of uncertainties in paleoenvironmental reconstructions did not improve the model-data discrepancies. The simulated temperatures are substantially influenced by the simulated sea-ice extent and associated to climate sensitivity of the model. We further compare the Arctic amplification in the PlioMIP2 ensemble to ensembles simulating other climates and find that Arctic temperature changes may be structurally underestimated by climate models, implying an underestimation may occur in future projections as well.

Geological and palaeoclimatic signals following the end-Permian mass extinction on central Spitsbergen, Svalbard

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The high-arctic regions of Canada, Greenland, and Svalbard beautifully expose the Permian-Triassic, northern margins of Pangaea, defined by the First Appearance Datum (FAD) of *H. parvus* (~252 Ma). The near complete recovery of two 90 m cores, drilled across the Permian/Triassic Boundary (PTB) in Deltadalen, Central Spitsbergen, complemented by material collected in a river section ca. 1 km north-east of the drill site, allowed high-resolution analyses of this sequence. The cores have been logged and analyzed in detail, including organic and inorganic geochemistry, isotope geochemistry, petrography, and biostratigraphy. Combining U-Pb TIMS dates of zircons with palynological and micropalaeontological data, the PTB in central Spitsbergen now lies within the *Reduviasporonites chalastus* Assemblage Zone, 2.50 m above the lithological change from bioturbated to dark grey, laminated mudstones. This corresponds to the local position of the Late-Permian Mass Extinction event (LPME) and its associated sharp negative $\delta^{13}C_{org}$ excursion. High-resolution environmental proxies indicate a dramatic change in provenance from an acidic to a more basic sediment source across the PTB, and a transition towards a more arid climate in the earliest Triassic. This transition was contemporaneous with prolonged bottom-water dysoxic or anoxic conditions, following a Late Permian increase in volcanic activity, probably linked to the emplacement of the Siberian Traps Large Igneous Province. Statistical analysis conducted on each elemental ratio suggests that the system recorded about two full, long eccentricity (400 kyr) cycles during the Induan. A smaller $\delta^{13}C_{org}$ negative excursion occurs 22 m above the major, LPME, negative $\delta^{13}C_{org}$ shift. This excursion has been recognized in other Panthalassic and Tethyan sections as the "Dienerian Crisis", suggesting a global extent of this crisis. The exact cause(s) of the bottom-water dysoxia or anoxia which accompanied that Dienerian Crisis remains to be fully understood.

A high resolution LiDAR DEM and field investigations of Weichselian ice flow patterns in the Ice Divide zone of Central Finnish Lapland

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The Weichselian depositional history in Lapland is a result of unusual preservation of strata from consecutive glacial and non-glacial climate events offering a promising but still inadequately known window to climate history of the core area occupied by the Scandinavian Ice Sheet. In eastern and western Lapland, three distinct till units, interpreted as corresponding Early, Middle and Late Weichselian glacial events, have been observed. However, the central Finnish Lapland ice divide

zone lacks sedimentary record from the Middle Weichselian glacial advance. In this study, known features indicating ice flow directions such as till fabrics, eskers and lateral moraines were compiled in a GIS environment to study ice flow patterns within the Central Finnish Lapland ice divide zone. Additionally, 2-meter-resolution hillshaded LiDAR DEM and DEM 25 m were used to identify streamlined features indicating glacial movements. These observations were combined with OSL age determinations and field observations on Weichselian sedimentary sequences in Sodankylä area, located in the central part of the ice divide zone. New evidence from the till fabrics and OSL age determinations indicate three glacial advances in the Sodankylä area. One of the ice advances was dated to Middle Weichselian, with the till fabric indicating a glacier flow from NNE. The DEMs of the same area, in turn, lack any lineations and overridden sediment mounds. These features indicate a local cold based and sluggish ice-flow setting for the investigated area in Sodankylä. Streamlined directed patterns are visible ca. 20 kilometers eastwards and ca. 30 kilometers westward. Unlike in the ice divide zone in the Sodankylä area, the DEMs in western Finnish Lapland show well-developed streamlined features including crag and tail like pattern, as well as overridden and streamlined mounds and eskers. In eastern Finnish Lapland, the bedrock dominates the topography, and therefore the streamlined features are less pronounced. However, ice flow directions can be detected from the orientation of the esker chains and ribbed moraine fields in river valleys.

Use of 3D hydrostratigraphy models to estimate groundwater flow and recharge/discharge patterns – testing increasing model complexity

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The main aim of hydrogeological studies is often the flow modelling, and the 3D structure of geology is simplified. However, the variation of hydraulic conductivity and the geological structure has a great impact on groundwater flow and groundwater discharge patterns. The construction of the 3D hydrostratigraphical model prior to flow modeling is beneficial (Artimo 2004, Barthel & Banzhaf 2016, etc.) especially when hydraulic conductivity of geological units vary a lot.

The Sakatti mining project in northern Finland (Browncombe et al. 2015) is located in an area of complex hyrodrostratigraphy consisting of weathered/fractured bedrock and variating till and sorted sediment units (Åberg et al. 2017, Åberg et al. 2019). In this mining development project, water balance has an important role in the environmental assessment, and it has been studied with 3D flow modelling. Understanding the connections of the surficial Quaternary aquifer-aquitard system, fractured/weathered bedrock, river nearby as well as Viiankiaapa mire that lies above the Sakatti deposit is needed.

Our target was to analyze how the modelling results of groundwater flow and discharge–recharge patterns change when using simple or more elaborate hydrostratigraphical models of the study site. A workflow of 3D hydrostratigraphical modelling with Leapfrog Geo and flow modeling with MODFLOW-NWT was developed and used to detect how the model complexity and accuracy affects the results. Four different versions of hydrostratigraphical model were used.

Increasing the hydrostratigraphical details seem to improve the residual between observed and simulated groundwater table and the overall fit of the flow modeling results and calibration. More complexity in layer structures of the Quaternary sediment gives more realistic groundwater discharge patterns especially in the mire and river areas. In the simplest model, the groundwater table was smooth and groundwater flow predominantly horizontal. More detailed models resulted more variable groundwater recharge/discharge patterns. It seems to be important to define the interlaying till units that can limit groundwater infiltration and also affect groundwater discharge patterns. The groundwater recharge estimation based only on surficial deposit can be too high if interlayered tills are omitted. The calibration of simple model is straightforward, but the connections of the aquifers to each other can be misleading. More complex model is more realistic, but its uncertainty is harder to evaluate. Most detailed models seem to indicate areas with calibration uncertainties, and thus they can be used to identify sites where hydrostratigraphical data and recharge estimation need to be defined in more detail.

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The geophysical and mineralogical expression of ultramafic rocks in the Møre-Trøndelag Fault Zone near Sparbu, Trøndelag

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Based on detailed investigation of geological maps and geophysical data in the data bases of the Geological Survey of Norway (NGU), several peridotite bodies have been located along the Møre-Trøndelag Fault Zone (MTFZ). Peridotites are known to be the dominant rocks in the earth's upper mantle. Their rather rare exposure at the surface offers therefore a unique opportunity to investigate processes that have led to their formation, metamorphism, location and exhumation. This study focuses on ultramafic bodies found in the MTFZ near Sparbu. Previous work on this area by Mortenson (1973) located three separate ultramafic bodies. The largest body is located at Slipsteinsberget, which is a quarry with exposed serpentinites, and is the main field area in this study. Fieldwork includes geological mapping, sampling of oriented blocks, magnetic susceptibility measurements as well as a ground magnetic survey. One of the aims is to understand the depth extent and geometry of the ultramafic body within the enclosing rocks, along with its magnetic response. A preliminary 3D magnetic model will be presented. The model is constrained by information from well cores of 7 boreholes, provided by the NGU core repository in Løkken, and structural measurements done on site. Results from field work indicate that the central area of the quarry exposes highly magnetic rocks with susceptibility values ranging from 0.04 up to 0.8 [SI]. The helicopter-borne magnetic survey (NGU, "kartblad Stiklestad"), acquired in 1991, is utilized for a magnetic interpretation on a larger scale with focus on the geometry and the interaction of the ultramafic bodies with the faults of the MTFZ. Field samples are further processed and investigated by X-ray diffraction, measurements of density, magnetic susceptibility & Natural Remanent Magnetization as well as thin section microscopy. Preliminary results of this ongoing work will be presented. This work from the micro- to the km scale is expanding the previous knowledge of mineralogy, metamorphism, petrophysical parameters and tectonic processes of the ultramafic rock suite in the study area. Furthermore, the results are also of general interest for an understanding of the role of serpentinites in major fault zones.

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Addendum

New fault gauge dating (K/Ar) shows Late Jurassic folding and thrusting on Bjørnøya, Svalbard

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Structural geological field work on Bjørnøya was conducted in the autumn of 2018. In addition, ground-borne gravity and magnetic data were acquired in 2016 and 2017.
Bjørnøya is located in the central part of the Stappen High. The main objective of the study is to understand the tectonic timing and evolution of the island. Using field measurements, fault gouge sampling, hand camera and drone photos, the tectonic evolution was documented. Locations visited are from Bjørnøya Radio on the north coast to Ærfuglvika on the southwest coast, including Raudnuten/Oswaldfjellet, central on the island . Miseryfjellet could only be studied from a distance. Measurements of fabric, fracturing, striations, fold axes and fault planes (including thrust planes and back sliding) are interpreted as compressional deformation from a W-NNW direction. These observations are from three stratigraphic levels: 1) interbedded red shales and sandstones in the Landnøringsvika Fm, 2) interbedded shales and sandstones the Bogevika Mb and 3) sandstones of Kapp Hanna Fm. Associated thick competent carbonates in Kapp Kåre and Kapp Duner fms are only gently folded.
In the literature, deformation on Bjørnøya is generally described as Carboniferous rifting where the above mentioned cover rocks, down to the Caledonian basement, are related to a large scale monocline dipping to the west towards the inferred master fault, the Knølegga Fault Complex. All the observed deformation is seen on this dipping monoclinal surface, similar to an orogenic wedge, which can explain the difference in degree of deformation between tilted Carboniferous/ Lower Permian strata and the more flat lying competent silicified carbonates of the Miseryfjellet Fm of Upper Permian age. This observed deformational direction also coincides with the southern part of the West Spitsbergen fold and thrust belt).
Three fault-gouge samples from reverse and normal faults in the Bashkirian Landnøringsvika Fm in Kobbebukta, northern coast of Bjørnøya, have been radiometric dated by kali/argon. The age of deformation is Late Jurassic, strikingly surprising but very interesting. This implicates that Bjørnøya show hard data that can explain late Jurassic structuration in the Western Barents Sea.
Analogue structuring to this observation on Bjørnøya can be found in Wandel Sea Basin Strike-slip Mobile Belt. Two different structural models from the Wandels Sea Basin have been discussed in the literature. Model 1 has Late Jurassic transpressions overprinted by Paleogene wrenching. Based on new field observation the model is disregarded and re-interpreted to be post -Coniacian NW-SE – trending normal faults and passively folded by a later possible Paleocene-Eocene N-S compressional event (Model 2).
The new Upper Jurassic fault gouge datings on Bjørnøya is in best accordance with Model 1 from the Wandel Sea Basin and might have structural interpretations implications for the Greater Barents Sea.

Geology and fish! MarFisk - detailed bathymetric and sediment maps used in active fisheries

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The Norwegian Mapping Authority, the Institute of Marine Research and the Geological Survey of Norway (NGU) produce a series of seabed maps through the programs MAREANO (shelf, continental slope) and Marine Base Maps (coastal areas). Detailed sediment and bathymetry maps have been made available on chart plotters used by the fishing fleet and the aqua culture industry like Olex, SailorsMate and Furuno. Knowledge of the bottom type and seabed morphology has always been the basis for deciding where to fish and the MAREANO/Marine Base maps show exactly that. For many years we have been convinced that the geological and geomorphological information must be important for fishermen and have worked actively to get it onto their chart plotters. Through the MarFisk project (2017 -2019) an intensified effort has been made to spread the knowledge of these maps to the fishing fleet and to urge them to use the maps in active fishing. Detailed maps of bathymetry and seabed sediments, from parts of the Norwegian offshore and coastal areas were the datasets provided through the project. In total 19 fishing vessels from offshore trawlers and longliners to coastal danish seiners, gill netters and line boats were involved in the project. After a year we got reports from 11 of these vessels who had been working in areas covered by the maps. The overall response was very positive. They concluded that the active use of the maps will lead to finds of new fishing areas, increase catches, give less damage of equipment and seafloor habitats and reduce fuel consumption.

Watch out for groundwater drainage - Ground settlements measured 400m away from excavation

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The aim of this work is to evaluate the information obtained from hydrogeological modelling for infrastructure projects, and when it should be part of the planning process. Between 2001 and 2005 a new railway track from Sandvika to Asker was established. Parts of the track were built in tunnels, some sections in bedrock other sections in unconsolidated sediments, mainly clay. During the construction work in a clayey tunnel section, sinking pore pressures were observed in the layer just above the bedrock at Jong. This pore pressure reduction was observed in a radius up to 400m away from the construction ditch. This has possibly caused subsidence damages to some buildings in the area. The large extent of the pore pressure reduction is most likely caused by a piercing of the confining clay layer during installation of pillars to bedrock to support the railway construction. To avoid this happening in the future, we propose that better information about the hydrogeological conditions before the project is started is necessary. Better understanding of the local hydrogeology will help to implement counter measures in advance of the construction work.
The main task of this master thesis work, is to establish a hydrogeological model based on the investigations performed during the project at Jong. The main investigation at the site is cone penetrating and piezometers located in areas with most buildings. Some information about the properties of the sediments, such as hydraulic conductivity, porosity and vertical compressibility is however missing, and parameters from the literature are used in the model. To investigate the importance of the model parameters, a sensitivity analysis was performed for a system similar to the Jong situation. A simplified MODFLOW model of Jong shows that a confined system is highly affected by drainage. Stratigraphy and its associated hydraulic conductivity and specific storage seem to be the most important to characterise to understand how the system might respond to draining during construction works. The simplified/schematic MODFLOW model is compared with a combination of LeapfrogWork and SEEP/W to test whether a more realistic geological model has a big effect on the outcome.

Slope deformation above the Tungnakvíslarjökull outlet glacier in western part of the Mýrdalsjökull glacier

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A large slope failure was discovered in June 2019 in the mountain side north of the Tungnakvíslarjökull outlet glacier in the western part of the Mýrdalsjökull glacier in Iceland. A group of scientist from the University of Iceland have worked on collecting data from several sources and installed monitoring equipment at the site. According to observations, which were based on comparison of DEM from aerial photographs at different times, the slope has been moving since at least 1945, probably earlier. The rate of movements has been estimated for the period from 1945 to 2019. The data show that the maximum total displacement since 1945 is around 180 m. It is also found that the rate of movement has not been constant over this time period. The maximum rate is found between 1999 and 2010. During that period the total displacement was as high as 100 m. The head scarp of the slide, which is almost vertical, is around 2 km long and the sliding area is around 1 km2. The entire slope shows signs of displacement and is heavily fractured and broken up.
A GPS station installed in the uppermost part of the slope shows that the slope is moving about 3-5 mm per day, at a constant rate since installation in August.
There are several ideas about what is the main cause for the slope deformation. As for other outlet glaciers in Iceland the retreat and thinning of the glacier has been rapid, which might have caused instability in the above lying slopes. Another proposed cause for the deformation is related to its location on the western flank of the Katla volcano. Persistent seismic activity in this area for decades may be explained by a slowly rising cryptodome, which may also explain the slope failure.

Xinjie layered intrusion and lavas within the Miyi rift segment, Emeishan (SW China)

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The ~260 Ma Emeishan igneous province is linked to a mantle plume source; yet, also formed behind a coeval collision zone between the SE Asian and South China cratons. Its more voluminous and often picritic low-Ti 'center' coincides with the edge of a complexly deformed Tibetan foreland, surrounded by better preserved but thinner piles of high-Ti Emeishan flood basalts in the west. These two areas are separated by a N-S trending Panxi Rift, within which an isolated 30 x 14 km-large volcanic Miyi segment appears surrounded by lava-barren horsts. This Miyi area hosts the Xinjie mafic-ultramafic layered intrusion as well as an estimated 4 km-thick lava pile with basal ankaramites. The ultramafic lower zone of Xinjie becomes both more diffusively and heterogenously layered towards the south-east as well as its steep NE-contact. Towards the north-west, a 'basal' reversal is more distinctly 'overlain' by a peridotitic, clinopyroxenitic and gabbroic zone, the latter of which has oxide-rich margins and is bound on both sides by clinopyroxenites. This apparent axial symmetry, combined with an elongated and almost vertical geometry of the Xinjie intrusion, is tentatively interpreted as reflecting an overall symmetrically disposed dyke-like layered intrusion. Average Mg# of clinopyroxenes within Xinjie's ultramafic cumulates range between 76-83, markedly similar to phenocrysts in the basal ankaramites, and all in equilibrium with near-primary basaltic melts. It is tempting to interpret these ankamarites as potential parents to the Xinjie intrusion, were it not for the intrusion cutting across overlying younger lavas. Nevertheless, we use this theoretical link between a layered intrusion and its surrounding lava pile to investigate magmatic processes within a volcanic Miyi segment that appears to have formed in isolation, between Emeishan's central low-Ti and peripheral high-Ti zones. This in turn may possibly provide additional petrogenetic clues as to how this enigmatic igneous province formed.

CONTRIBUTORS

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