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ABSTRACT

This thesis focuses on integrated structural analyses that improve the characterization and modelling of the bedrock surface morphology in areas with few direct observations of bedrock surface features. Brittle structures of the bedrock control the bedrock surface morphology at different scales. Elongate bedrock depressions form along the regional-scale network of deformation zones. The detailed morphology of the depressions is controlled by the prevailing fracture orientations observed on the outcrop-scale. The surface of elongate bedrock depressions is influenced by glacial erosion, which is governed by the brittle structures. This process causes the accumulation of glacifluvial sediment at the bottom of bedrock depressions, preventing direct observations of the underlying brittle structures. Structural analyses provide essential knowledge about the structural framework of the bedrock at different scales. This knowledge can be applied in areas that lack direct evidence of the brittle structures and bedrock surface morphology.

This thesis includes three articles (Papers I-III). They show that integrated structural analyses of the bedrock help to overcome methodological challenges when characterizing bedrock surface features in poorly-exposed areas. The structural analyses guide the bedrock surface interpolation, which results in geologically more realistic structurally-constrained bedrock surface models (bedrock-DEM). These improvements are achieved by structural analyses that recognize: i) prevailing fracture orientations (Papers I and III), ii) horizontal continuation of deformation zones (Paper II), and iii) fracture network within the damage zones of the deformation zones (Paper III). The structurally-constrained bedrock-DEMs reflect the bedrock surface irregularities controlled by brittle structures, providing more accurate background data for groundwater, geoenergy, and engineering applications.

KEYWORDS: bedrock surface, brittle structures, 3D-modelling, fractures, structural geology, geomorphology

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TIIVISTELMÄ

Tämän väitöskirjan tarkoituksena on kattavien rakennegeologisten tutkimusten sekä tarkkojen pintainterpolointimenetelmien avulla selvittää kallionpinnanmuotoja alueilta, missä suorat havainnot kallioperän ominaisuuksista ovat harvassa tai kokonaan saavuttamattomissa. Kallioperän hauraat rakenteet kontrolloivat kallionpinnanmuotoja eri mittakaavoissa. Pitkittäiset kalliopainanteet ovat muodostuneet kallioperässä olevien heikkousvyöhykkeiden seurauksena niiden suuntaisesti, kun taas kalliopainanteiden yksityiskohtaisia pinnanmuotoja kontrolloi vallitsevat rakosuunnat. Kalliopainanteiden pinnanmuotoihin on vaikuttanut merkittävästi jäätikön aikaiset eroosioprosessit, joita kontrolloi kallioperän hauraat rakenteet. Eroosion seurauksena kulunut kallioperä kasaantuu sedimenttipeitteeksi etenkin kalliopainanteisiin, joka estää suorien rakennegeologisten havaintojen tekemisen. Rakennegeologisten tutkimusten avulla voidaan selvittää kallioperän yleiset rakennepiirteet eri mittakaavoissa. Näitä voidaan hyödyntää tulkittaessa alueita, joilta suorien rakenne- ja kallionpintahavaintojen saaminen on mahdotonta.

Tämä väitöskirja koostuu kolmesta artikkelista (I-III). Nämä artikkelit osoittavat, että rakennegeologisten analyysien avulla on mahdollista parantaa kallioperän erityispiirteiden tulkintaa peitteisillä alueilla. Kun rakennegeologiset analyysit sisällytetään kallionpinnan interpolointiin, tuloksena saadaan geologisesti realistisempi kuvaus kallionpinnan korkeusvaihteluista ja siten paremmat kallionpintamallit. Nämä parannukset saavutettiin rakennegeologisilla analyyseillä, joiden avulla tunnistettiin: i) vallitsevat rakosuunnat (I), heikkousvyöhykkeiden jatkuvuus kallionpinnan myötäisesti (II) sekä rakoverkosto heikkousvyöhykkeiden tuhoalueilla (III). Rakennegeologisia epäjatkuvuuksia noudattelevat kallionpintamallit tarjoavat tarkempaa tausta-aineistoa esimerkiksi pohjavesi-. geoenergia- ja insinööritekniikan tutkimusten käyttöön.

AVAINSANAT: kallionpinta, hauraat rakenteet, 3D-mallinnus, raot, rakennegeologia, geomorfologia

Table of Contents

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
DEM	Digital elevation model
Ga	Billion years
GTK	Geological survey of Finland
LBS	Load-bearing stratum
LiDAR	Light detection and ranging
TIN	Triangular irregular network
R1	Primary fracture
R2	Secondary fracture

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Eemi Ruuska, Pietari Skyttä, Niko Putkinen, Tuire Valjus. Contribution of bedrock structures to the bedrock surface topography and groundwater flow systems within deep glaciofluvial aquifers in Kurikka, Western Finland. Earth Surface Processes and Landforms, 2023; 48(10): 2039-2056. https://doi.org/10.1002/esp.5602

II Teemu Lindqvist, Eemi Ruuska, Emilia Kosonen, Noora Hornborg, Pietari Skyttä, Niko Putkinen, Juho Mansikkamäki. Integrated geological modeling of partially exposed Precambrian bedrock surface and thickness of overlying Quaternary deposits. Engineering Geology, 2025; 346, 107902. https://doi.org/10.1016/j.enggeo.2024.107902

III Eemi Ruuska, Pietari Skyttä, Kati Ahlqvist, Kaisa Nikkilä, Nicklas Nordbäck, Pelayo Barron Francisco. The role of shear zones, faults and the associated fractures on the formation and character of bedrock surface depressions in crystalline bedrock (Turku, southwestern Finland). Solid Earth (In revision)

1 Introduction

One significant controlling factor over the morphology of the glacially eroded bedrock surface is provided by the deformation structures within the bedrock, which have either a brittle or ductile character. Brittle structures such as fractures and faults provide the primary direct control over the localized glacial erosion (DesRoches et al., 2014; Eyles, 2012; Glasser et al., 1998; Gleeson & Novakowski, 2009; Skyttä et al., 2015), while ductile structures such as foliation and folds frequently act as precursors for the brittle structures (Crider, 2015; Mancktelow & Pennacchioni, 2005; Regenauer-Lieb & Yuen, 2008; Skyttä & Torvela, 2018). The deformation zones include shear zones that involve ductile deformation and faults that are entirely brittle in character (Fossen, 2016). This thesis shows that regardless of the intensity and style of the ductile precursors, the brittle structures can generate a complex network that contributes to the roughness and heterogeneity of the bedrock surface morphology. Comprehensive analyses of the brittle and ductile structures are essential steps for generating realistic geological models over the geometry of the bedrock structures and the glacially eroded bedrock surface morphology. These models have a high utilization potential within societally important applications associated with groundwater protection and maintenance, nuclear waste disposal, geoenergy, and civil engineering.

Abrasion, plucking (or quarrying), and ripping are the main processes of glacial erosion that have shaped the present-day bedrock surface topography in areas covered by continental ice sheets (eg, Glasser & Bennett, 2004; Hall et al., 2020; Hallet, 1979; Krabbendam et al., 2022; Krabbendam & Glasser, 2011). Abrasion occurs when rock debris entrained at the base of the glacier wears the underlying bedrock surface through polishing, scratching, and removal of small rock fragments (< 1 cm). Plucking exploits pre-existing bedrock fractures and zones of weakness within the bedrock, facilitating the detachment and removal of larger fragments (> 1 cm). In contrast, ripping involves dilation and hydraulic jacking of the fractures, which allows removal of larger fragments to a greater extent. Plucking and ripping are more effective glacial erosion processes compared to abrasion, which slowly wears the bedrock surface (Glasser et al., 2020; Hall et al., 2020). The effectiveness of plucking and ripping accentuates the ruggedness of the bedrock surface in fractured crystalline bedrock often seen as elongate topographic depressions (Krabbendam & Bradwell, 2011; Krabbendam & Glasser, 2011; Olvmo & Johansson, 2002). The controlling glacial erosion mechanism is linked to ice sheet attributes such as velocity (Herman et al., 2011), thickness (Anderson, 2014) and, conditions at the base of the ice sheet, such as temperature and water-pressure (Iverson, 1991; Lai & Anders, 2021; Sugden, 1978). Fast-flowing ice sheets promote abrasion (Herman et al., 2011; Yanites & Ehlers, 2016), whereas plucking and ripping are typically attributed to glacial retreat during which warm-basal conditions of the ice sheet provide more meltwater for cavities within the underlying fractured bedrock (Hall et al., 2020).

The properties of the underlying bedrock, such as hardness, fracture spacing, and fracture orientation, influence which erosion mechanisms dominates (eg. Glasser et al., 1998; Hall et al., 2020; Krabbendam & Glasser, 2011; Phillips et al., 2010). For instance, resistance to the abrasion mechanism becomes higher when the bedrock is harder, which makes plucking the main mechanism of glacial erosion within hard crystalline bedrock. Since plucking and ripping mechanisms utilize the bedrock cavities, they become more efficient within densely fractured bedrock. Deformation zones that involve brittle deformation, particularly the faults, are characterized by densely fractured central core-domains and the surrounding damage zones, which leads to more effective disintegration of the bedrock (Dühnforth et al., 2010; Phillips et al., 2010; Skyttä et al., 2023). The core domain hosts the displacements, whereas the damage zones contain fracture networks where fracture orientations are controlled by the setting of a stress regime and the coupled kinematic evolution within the deformation zone (Choi et al., 2016; Gudmundsson et al., 2010; Kim et al., 2004). Elongate and deep bedrock depressions are typically located along the deformation zones, while the outcrop-scale fractures and exposed outcrop walls define the detailed morphology of the bedrock surface within the damage zones and the host-rocks outside of the influence of the deformation zones (Lane et al., 2015; Scott & Wohl, 2019; Skyttä et al., 2023). Ice-flow-parallel orientation of the bedrock structures promotes the formation of elongate bedrock depressions(Dühnforth et al., 2010; Glasser et al., 1998). For ice-flow-perpendicular structures, steeply dipping structures against the ice-flow generate sharper overdeepenings on the bedrock surface than gently towards the ice-flow dipping bedrock structures (Kelly et al., 2014). The result of plucking and ripping are typically visible as abrupt, vertical to steeply-dipping localized breaks along otherwise smooth and undulating erosion surfaces affected by more distributed glacial abrasion (Bukhari et al., 2021; Dühnforth et al., 2010; Glasser et al., 2020; Hall & Gillespie, 2017; Krabbendam et al., 2022).

The contribution of core and damage zone features over bedrock surface morphology is understood when the fault structure can be constrained by e.g., dense drilling or detailed geophysics, but typically only in cases where the study target is fully exposed (e.g., Skyttä et al., 2023). Within poorly exposed large-scale deformation zones, sparse input data and potential asymmetry of the core and damage zone are the main challenges in bedrock surface modelling (Chesnaux et al., 2017; Gong, 2000; Skyttä et al., 2015). Surface interpolation methods tend to over-emphasize the smoothness of the surface, which, consequently, does not honour the contribution of the controlling fractures. The above-mentioned challenges raise the following questions: i) Do the same relationships between erosional mechanisms and bedrock structures, acknowledged in the exposed parts of the bedrock, apply within unexposed large-scale deformation zones? ii) Which methods are applicable in imaging the erosional signatures of the faulted bedrock when direct observations are limited by sediment-cover?, and iii) How can the methodological limitation be improved by the integration of structural analyses in interpreting the bedrock surface morphology?

To answer the presented research questions, this thesis focuses on using integrated structural analyses, the occurrence and orientation of fractures (Papers I and III), continuity of the regional deformation zones (Paper II), and understanding the kinematic evolution of faults and the resulting fracture network within the damage zones (Paper III). Furthermore, this work evaluates the significance of the aforementioned structures for the morphology of the eroded bedrock surface and hence aids in providing valuable knowledge for the generation of more realistic bedrock surface models. The integrated structural analyses include: i) regional-scale trends of the bedrock interpreted from aeromagnetic, ground surface LiDAR, and other remote sensing data, including deformation zones, foliation trends, and ii) field mapping measurements, including foliation, fracture, and outcrop wall observations in the outcrop-scale.

This thesis includes three articles that highlights the contribution of the semi-brittle to brittle structures of the bedrock (shear zones, faults, fractures) upon the morphology of the glacially eroded bedrock surface within different geological environments. The study area in Paper I is located around a large groundwater system in Kurikka, Western Finland (Fig. 1), whereas investigations in Papers II & III are located in urban environments in Southern Finland in the cities of Helsinki/Espoo and Turku, respectively (Fig. 1). Papers I and II provide enhanced bedrock surface modelling, which takes brittle structures into consideration during the modelling process to reduce the over-emphasized smoothness of the surface. Paper I addresses how the network of steeply-dipping brittle bedrock structures recognized from field mapping and further correlated with gravimetric data control the morphology of the buried bedrock depressions. Paper II provides a new approach for the bedrock surface modelling, where 2D map level structural analysis was used to constrain the network and the lateral continuity of the bedrock deformation zones.

Consequently, it provides proxies to evaluate and model bedrock surface depressions in areas where no or only limited input data is available. Paper III tackles in detail to characterization of the relationship between the bedrock fractures and the detailed morphology of the bedrock surface within poorly-exposed bedrock depressions. This was achieved by comparing the orientation and intensity of fractures as a function of their spatial vicinity to bedrock depression, to assess i) the potential extent of damage zones, ii) the associated fracture patterns within, and iii) the linkage of fractures to the large-scale bedrock depression network.

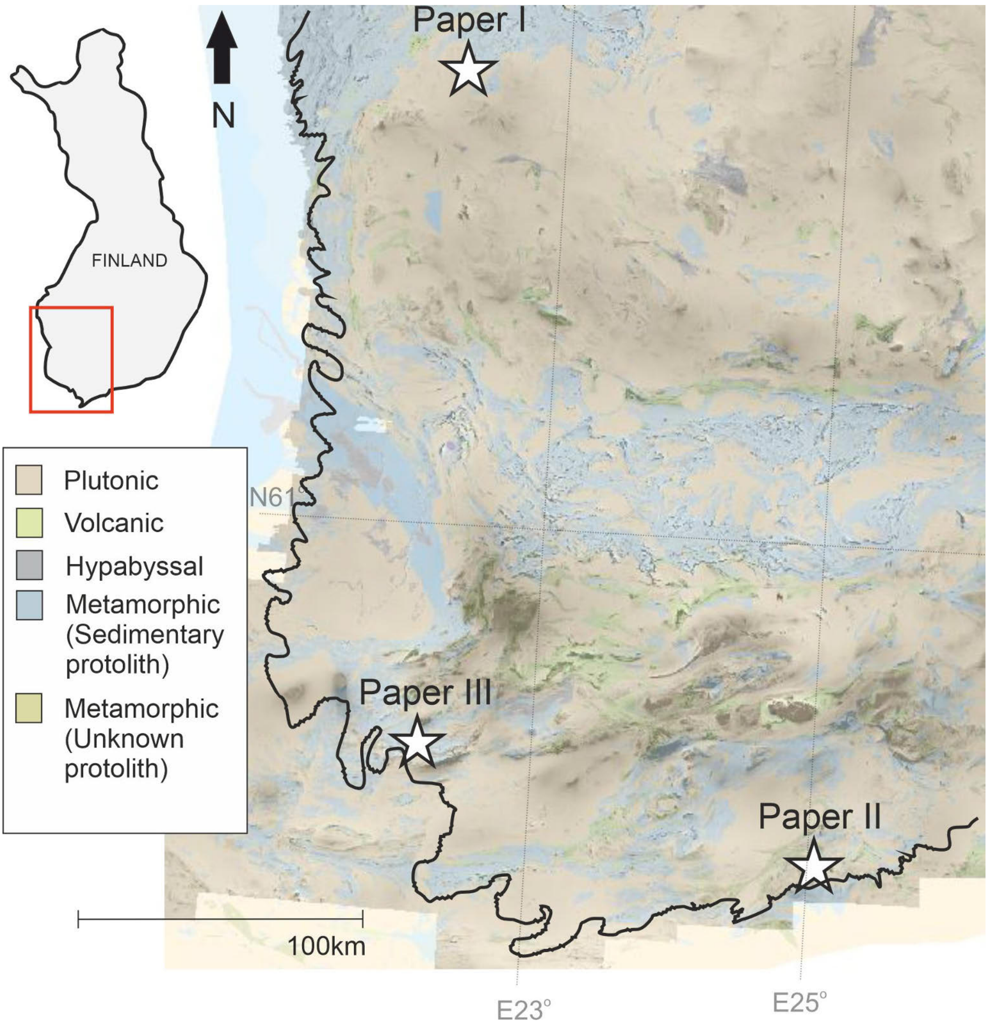


Figure 1. Location of the study areas. Low-altitude Aeromagnetic map and Bedrock of Finland scale free with lithological rock classes in the background (Geological survey of Finland).

2 Materials and Methods

2.1 2D line interpretations

2D line interpretation (trace/form lines) are made to analyse regional-scale structures in the bedrock not only for understanding the structural setting in the regional-scale, but also to fill the data gaps of detailed field mapping in sediment-covered and urban areas. The analyses were conducted using the following remote sensing data in Papers I-III:

- For providing background knowledge about the ductile setting in 2D, regional-scale ductile structures such as foliations, folds and shear zones were interpreted from low-altitude airborne aeromagnetic anomaly map of Finland (GTK; flight altitude = 30 – 40 m; flight line spacing = 200 m; distance between measuring points = 6 – 5 0m; flight direction = N-S or E-W across main geological trends).
- Regional-scale brittle structures such as faults and fracture zones were interpreted as lineaments based on linear features detected from the ground surface LiDAR DEM (National Land Survey of Finland).
- Elongate bedrock depressions recognized and modelled as 2D-lineaments based on the results of bedrock surface modelling, which utilised geotechnical ground surveys, gravimetric surveys and (limited) drill hole data.
- Lithology of the study areas from regional lithological map (Bedrock of Finland 1:200000; GTK)
- Maps of superficial deposits within the study areas to gain general knowledge about the Quaternary deposits and location of the bedrock outcrops (Superficial deposits 1:100000 & 1:20000; GTK).

2.2 Field mapping

Structural field mapping (Papers I & III) includes structural observations and measurements conducted from vertical and horizontal outcrops with varying sizes from several to hundreds of square meters. The measurements focused on characterizing fracture attributes and fracture-controlled outcrop walls, including dip, dip azimuth, intensity, density, and the mutual relationship among different fractures sets. Foliation measurements, integrated with the aeromagnetic data, were used in Paper III to constrain the regional framework of the ductile structures, and to delineate structural domains, including both low- and high-strain areas. Furthermore, two 2D-photogrammetry models were generated for creating outcrop-scale nature analogue, allowing comparison with the regional-scale structural framework of ductile and brittle (Paper I) and brittle structures (Paper III).

2.3 Integrated structural analyses

The integrated structural analyses provide combined results of regional-scale 2D line interpretations and field mapping measurements. The orientations of the ductile and brittle structures were compared to detect the significance of structural inheritance from ductile to brittle. The results were utilized to study the spatial distribution of the bedrock structures and detect structurally different domains within the study areas. Integrated analyses provide further knowledge about the correlation between the regional- and outcrop-scale structures, and how they control the bedrock surface morphology in their respective scales.

2.4 Bedrock surface modelling

Bedrock surface interpolations were conducted using bedrock surface data points from gravity and seismic survey lines, geotechnical drill cores, as well as ground surface elevation model (LiDAR-DEM). Interpolated bedrock surfaces were explicitly (manually) adjusted according to the structural analyses of the bedrock to generate geologically realistic bedrock-DEMs.

Paper I: For bedrock surface interpolation within the Kurikka aquifer system, we used the dataset described by Putkinen et al. (2012) that was further complemented with data from new gravity survey lines, refraction seismic studies, groundwater monitor data, and an initial bedrock-DEM. The final dataset comprised 71 gravity survey lines in total (c. 68.5 km), 32 groundwater observation well drilling sites, and two seismic survey lines. Detailed focus of the bedrock surface interpolation was placed in the Kuusistonloukko area, where the bedrock surface interpolation study was focused. Five intersecting gravity survey lines were selected to reinterpret the bedrock surface, which was done to account for the prevailing fracture orientations of the bedrock as mapped in this study. These reinterpreted bedrock surfaces derived from gravity survey lines, together with unmodified gravity lines, 11 groundwater wells, and two seismic survey lines, were used to interpolate an improved detailed-scale bedrock-DEM.

Improved detail-scale bedrock-DEM comprises nine separate structural blocks, which were interpolated separately in MOVE software using the Kriging method with a grid size of 7.2 m. The interpolation was conducted by utilising anisotropy in five blocks, where the prevailing structural trend of the bedrock was recognised and used as an anisotropic guideline. Four blocks, which did not comprise any notable structural trend, were interpolated without anisotropy.

Reinterpretation of the gravity survey lines included the creation of subvertical segments corresponding to fracture-controlled vertical abrupt breaks in the bedrock surface. The height of abrupt breaks was correlated with the elevation of the neighbouring gravity survey line points, and the dip of the break was assessed based on the orientation of the dominant fracture set nearby. To honour the fractured-controlled abrupt breaks in the improved detailed bedrock-DEM, we generated boundary points for each nine blocks on top of the initial interpolated bedrock surface. Subsequently, each block boundary contained a duplicate point set assigned to the opposite blocks. The point set, positioned on the lower block side, was manually lowered by 15 m to generate an abrupt break between the blocks, corresponding to the typical elevation contrast observed between the fracture-bound bedrock blocks.

Paper II: Three separate digital elevation models were generated in this work: the conventional bedrock-DEM, the top of the Load-bearing stratum (hereafter LBS) DEM, and the structurally-constrained bedrock-DEM. The conventional bedrock-DEM and the topographic depressions within were correlated with the 2D-structural analysis to interpret the final deformation zone traces. The top of LBS-DEM was used as the reference surface for the deformation zone traces, as it is based on much denser and more spatially uniform point data than the conventional bedrock-DEM, thereby providing a more reliable elevation reference.

- Bedrock surface data for the conventional bedrock-DEM was extracted from geotechnical ground investigations, LiDAR DEM (ground surface elevation model – 2 m), and acoustic-seismic profiling data to generate conventional bedrock-DEM. These verified and interpreted bedrock surface points were then used to generate the conventional bedrock-DEM. Geotechnical data included bedrock surface points, whose termination against the bedrock was reliably verified by the applied method (percussion drilling, casing, or test pits). LiDAR DEM was utilized alongside the Map of Quaternary Deposits for the City of Espoo (Espoo, 1986) and the Soil and Base maps for the City of Helsinki (Helsinki, 2017, 2019). Areas of exposed bedrock outcrops are digitized with 10 m horizontal spacing and projected on top of the LiDAR DEM.

- Interpreted surface points include acoustic-seismic bedrock surface points derived from sub-bottom profiling surveys conducted over c. 90 km of the marine areas. Unverified geotechnical data points were manually lowered and filtered by a separate triangular irregular network (TIN) surface. Only those interpreted points that underlie the TIN-surface were included.
- The top of LBS-DEM data incorporates remaining geotechnical data points, whose termination against the bedrock was not verified, and were therefore not used in the generation of the conventional bedrock DEM. These geotechnical data points were terminated against boulders, bedrock surface or a dense sedimentary layer, or were located between boulders supporting the concept of LBS, which includes roughly basal till, gravel and sand units.
- The structurally constrained bedrock-DEM includes the same data as the conventional bedrock DEM, but it is modified to highlight the deformation zone traces recognized from the 2D-structural analysis of the bedrock. The deformation zone traces were projected onto the top of the LBS-DEM and further vertically adjusted.

The conventional bedrock-DEM and the top of the LBS-DEM were interpolated with the Ordinary Kriging method with incorporating iterative semivariogram analysis. The semivariogram analysis is used to determine the spatial correlation of the data points and achieve best fit between experimental variogram (data points) and geostatistical variogram model. The interpolation of the conventional bedrock-DEM is utilized directly in the structurally constrained bedrock-DEM.

Along the deformation zone traces, the surface points of the conventional bedrock-DEM were vertically adjusted in the areas of no or limited input data using the recognized depth-to-bedrock values based on the observed LBS thickness values for the deformation zones; maximum depth of -19 m, -11 m and -5 m for the major, intermediate and minor zones, respectively (Fig. 10b-e in Paper II). These adjusted points of the deformation zone trace were utilized to pull the conventional bedrock-DEM surface down along the adjusted trace points so that the maximum depth is reached in the middle part of the trace, and progressively reduces to null at the terminations of the depressions. In case the adjusted trace points exceeded the elevation of the conventional bedrock-DEM surface, the adjusted trace points were projected on top of the conventional bedrock-DEM. The effect of deformation zone traces was laterally limited to a uniform width using 150 m, 70 m, and 50 m (major, intermediate and minor, respectively) to reflect the observed width of the ground surface depressions.

Paper III: The data of the bedrock-DEM and cross-section DEMs are compiled by integration of geotechnical point data and LiDAR elevation data from the covered and exposed areas of bedrock, respectively. The integration of the geotechnical point data follows a workflow similar that in Paper II, which is presented in detail by (Ahlqvist et al., 2025).

The wider bedrock-DEM and more detailed cross-section-DEMs are interpolated using the Ordinary Kriging method with detailed iteration of the associated semivariograms. The interpolation of the bedrock-DEM is conducted with two different grid sizes (30 m and 10 m). A grid size of 10 m is used within bedrock outcrops, where the bedrock surface data points are extracted from ground surface LiDAR and resampled to intervals of 10 m. Within the unexposed parts of the bedrock, the grid size of the interpolation is mainly 30m unless the spatial coverage of the geotechnical data points is dense enough to adapt to the 10 m grid size. A grid size of the cross-section-DEMs interpolation follows the same design as in the bedrock-DEM. However, due to smaller spatial coverage compared to the bedrock-DEM, the grid size is 2 - 5 m in exposed outcrops and 10 m within the unexposed part of the bedrock.

The lack of data points within marine areas that are often associated with bedrock depressions and underlying deformation zones helps to guide the interpolation to over-elevate the bedrock surface. Therefore, dummy points (manually added points) were generated to guide the interpolation to provide more geologically realistic bedrock-DEM. Their depth is estimated from points within other bedrock depressions in the study area.

3 Review of the original publications

3.1 Paper I:

Paper I shows the fundamental role of bedrock structures over the heterogeneity of bedrock surface morphology, which form an underlying basement for the groundwater flow in Kurikka, western Finland. The ductile framework of Svecofennian Paleoproterozoic bedrock (1.90 – 1.86 Ga) in Kurikka is characterized by upright, open folds and steeply dipping foliation with the prevailing orientations of WNW and NNW. Furthermore, the study area comprises elongated linear bedrock depressions underlain by four major shear zones striking NNE, NNW and WNW. These shear zones are associated with elevated fracture density in the bedrock, which determines the roughness of the surface morphology in the walls of the buried bedrock depressions.

To improve the morphology resulting from standard interpolations, gravity survey line data were re-interpreted, structural anisotropy caused by the bedrock fractures was determined and explicit improvements to the bedrock surface were conducted. The results provide a geologically realistic bedrock surface model, which honours the fragmentation of the bedrock along the brittle deformation zones. Detailed bedrock-DEM gives us better understanding of how the fragmented bedrock surface and the associated structures control both the deposition of the sedimentary units and the pathways of the groundwater flow within the complex aquifer system.

3.2 Paper II:

Paper II provides a novel approach showcasing how the systematic analysis of the bedrock structures may be integrated with geotechnical data to model geologically realistic bedrock surface DEMs that honour the input geotechnical datasets and, at the same time, reflect the structural character of the bedrock structures. The study site is located in southern Finland (within cities of Helsinki/Espoo) which is hosted by Paleoproterozoic bedrock basement (1.9 – 1.8 Ga) covered with coarse-grained glacifluvial sediment deposits and fine-grained basin-infill clay deposits.

The essential part of the 2D structural analysis of the bedrock was the interpretation of the deformation zones, and their later association with bedrock surface depressions as recognized from the geotechnical data. The deformation zone traces were classified into the major, intermediate, and minor classes based on their topographic signatures, cross-cutting relationships, and length attributes. The main result of this study is the structurally constrained bedrock-DEM which utilizes the thickness of the LBS along the deformation zone traces according to the given classes. Sedimentary infill is concentrated within the deformation zones of the bedrock which causes major local variations in the thickness of the LBS above the core areas of the deformation zones: 19 m in the major, 11 m in the intermediate, 5 m in the minor class and, 3m outside of the deformation zones. The improved bedrock-DEM is generated by manually adjusting the conventional bedrock-DEM according to the integrated thickness of the LBS along the final deformation zone traces, which provides significant improvement to model the structurally constrained bedrock surface morphology.

3.3 Paper III:

Paper III presents how the outcrop-scale fractures and regional-scale brittle structures define the bedrock surface morphology in different scales within the Paleoproterozoic bedrock (1.9 – 1.8 Ga) around the city of Turku, western Finland. The results of this study show how the spatial distribution of the outcrop-scale fracture sets helps to determine the damage zone areas of the deformation zones, and their contribution to the asymmetry of the bedrock surface. Fracture sets within the damage zones provide further insights about the kinematic character of the deformation zones, which supports the interpretation of deformation zone network within the areas that lack bedrock surface data.

The integrated results show that the ductile structures frequently but not always act as a precursor for brittle structures, such as faults and lineaments in the regional-scale and fractures in the outcrop-scale. The main orientation of foliation and shear zones strikes ENE throughout the study area except near the folds and in the southern part of the study area, where the strike shifts towards E-W.

Brittle structures show deviating trends since the dominant ENE and NNE to NE trends of the regional-scale deformation zones, and the resultant bedrock depressions, are contrasting to the NNE- and NNW-striking main fracture orientation observed in the outcrop-scale. NNE- and NNW-striking fractures are observed particularly near the regional-scale brittle structures, which indicates that they belong to the damage zone areas of the deformation zones. Outside of the damage zones, the number of NNE- and NNW-striking fractures decreases, and the general fracture setting corresponds to the dominant trends of to the regional-scale deformation zones.

The surface morphology of the bedrock is irregular throughout the study area as characterised by elongated bedrock depressions. The asymmetry of the bedrock surface is highlighted within the bedrock depressions, since their elongation is controlled by the underlying deformation zones but the morphology of the bedrock depression walls is also controlled by divergently striking fractures belonging to the damage zone area.

4 Discussion

4.1 Contribution of brittle structures onto bedrock surface morphology

The properties of the underlying bedrock determine which glacial erosion mechanisms are prevailed and, consequently, how the bedrock surface is finally eroded (eg. Bukhari et al., 2021; Dühnforth et al., 2010; Glasser et al., 1998; Krabbendam & Bradwell, 2011; Skyttä et al., 2023). Plucking and ripping are the dominant glacial erosion mechanisms in fractured crystalline bedrock, utilizing pre-existing fracture networks to efficiently detach and remove larger bedrock fragments, particularly along faults and shear zones.

The faults in homogeneous rocks with weak pre-existing ductile fabric are initiated by grain-scale anisotropies, such as grain boundaries and microcracks, which grow by linkage to fractures (Kirkpatrick et al., 2013). Subsequently, these fractures utilize pre-existing fractures, dikes, and other lithological weakness zones to connect with each other, and eventually generate a fault zone (Crider, 2015). Using the recognized relationship between the bedrock surface topography and the fracture network, we argue that the fracture intensity and density within the unexposed cores of the deformation zones, and partly exposed damage zones underlying the bedrock depressions, is much higher than within the surrounding bedrock. Structural characterization of the bedrock allows us to make a regional interpretation of the major bedrock deformation zones in the area, and shed further light into the origin of the studied valleys.

In all studied cases (Papers I-III), orientations of the regional-scale brittle lineaments detected from ground surface data (ground surface LiDAR) correlate well with the shear zones and faults (from aeromagnetic data), and also with the most continuous elongate bedrock depressions within the bedrock-DEMs. The framework of precursor ductile structures controls the orientation of the shear zones, while faults often cross-cut the pre-existing ductile fabrics. At more local scales, the outcrop-scale fractures show more diverse orientations than the regional-scale brittle lineaments. The difference may in part be attributed to the potential fault damage zones, where fractures strike obliquely against the shear zones and faults rather than parallel.

Correlation of the brittle lineament interpretations with the elongate depressions along the bedrock-DEM is clearly indicative that the bedrock surface depressions are associated with deformation zones within the underlying bedrock. Furthermore, fracture analyses show that deformation zones and their damage zones host certain fracture networks, which do not reflect the regional fracture network properties occurring outside of the affected area of the deformation zone. Outcrop-scale fractures control the detailed morphology of the bedrock depression. Since the individual fractures are not parallel with the elongate bedrock depressions, the morphology of the bedrock depressions often has a rough zig-zag patterns observed on the maps, and is characterized by abrupt vertical breaks controlled by the prevailing steep dip of the fractures observed in cross-sections.

4.2 Utilization of structural analyses in the bedrock surface modelling

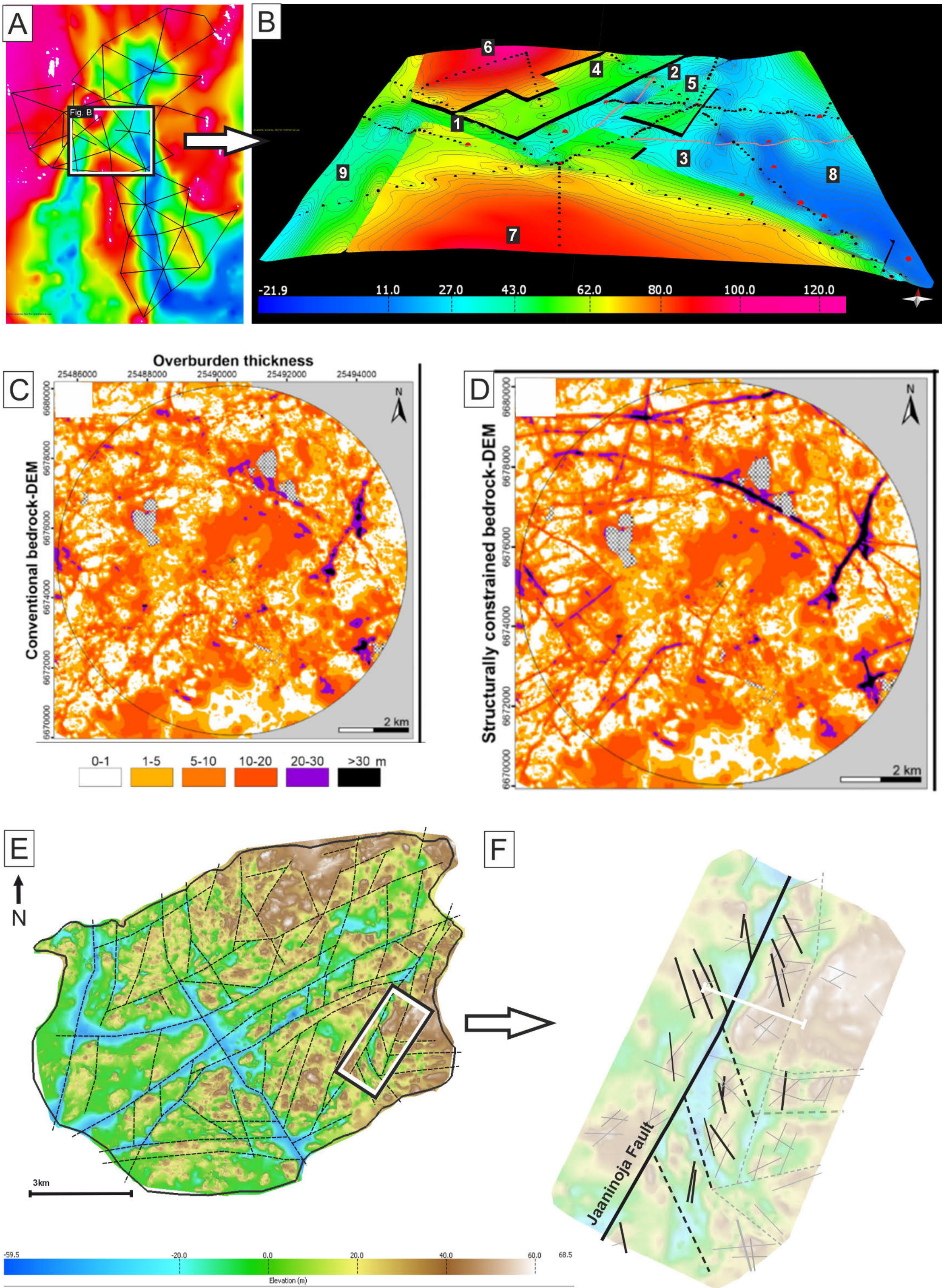
Surface-interpolation methods tend to over-emphasize the smoothness of the bedrock surface, which indicates that the contribution of the brittle structures is typically lost or underestimated. Bedrock surface data are often sparse, creating challenges to bedrock surface modelling (Chesnaux et al., 2017; Gong, 2000; Skyttä et al., 2015), but the data often becomes even less accurate within the elongate bedrock depressions associated by deformation zones due to extensive sediment-cover. Therefore, integrated structural analyses provides indirect evidence of how deformation zone related fractures within the damage zone (Choi et al., 2016; Gudmundsson et al., 2010; Kim et al., 2004) control the bedrock surface morphology within the bedrock depressions (Lane et al., 2015; Scott & Wohl, 2019; Skyttä et al., 2023).

Anisotropy of the bedrock structures is a useful tool for generating geologically more realistic bedrock-DEMs (Paper I). However, challenges arise when anisotropy is applied at large-scales in areas characterized by complex brittle structures comprising multiple structural orientations. Furthermore, the relationship between the structures with different orientations and origins (e.g., fault core vs. damage zone), and the associated relative significances, is typically not taken into consideration. Ordinary Kriging method and the semivariogram modifications within allow for reducing the smoothness, but it is highly dependent on the distribution of input data. Explicit adjustments based on structural analyses improves the accuracy of the bedrock surface model by reducing the smoothness within the deepest parts of the bedrock, and provide a method to model the true elevation of the bedrock-DEM (Papers I and II). For optimal results, the scale and resolution of structural analyses used as a guideline in the explicit adjustments must correspond to the scale of the bedrock surface model and the associated brittle structures.

In Paper I, the bedrock surface shows smooth and rounded shapes within the initial bedrock-DEM in-between the data points, which do not respect the anisotropy of the prevailing bedrock structures (Fig. 2a). The above issues were taken into consideration by constructing the improved detail-scale bedrock-DEM which comprises structurally controlled blocks (Fig. 2b). The blocks were separated by isolated bedrock breaks that were transformed into a network of bedrock discontinuities (fracture systems, faults) by correlating the breaks with fracture data and distinct linear slopes on the initial bedrock-DEM. The structurally controlled blocks honour the prevailing structural anisotropy within each block, as well as the orientation of the surrounding bedrock discontinuities. The applicability of the structurally controlled blocks was tested using specific structural anisotropies of the regional dataset to re-interpolate the area of the initial bedrock-DEM. These tests show that geologically realistic bedrock-DEMs at a larger scale cannot be generated using a single anisotropy value in surface interpolation algorithms, but a new approach involving spatial variability in anisotropy would be needed.

In Paper II, the discontinuous character of the elongate bedrock depressions along the conventional bedrock-DEM is achieved by the Ordinary Kriging interpolation. The interpolation generates zig-zag shapes or varying low and high areas due to the limited number of verified geotechnical bedrock surface points available within the bedrock deformation zones (Fig. 2c). These issues were tackled by explicitly pulling down the bedrock surface along the deformation zones traces in areas with no verified input points. The structurally constrained bedrock-DEM (Fig. 2d; Fig. 11b, d in Paper II) highlights the bedrock deformation zones as the areas of maximum thickness of the LBS and overburden compared to the thicknesses visualized using the conventional bedrock-DEM. It is likely that the resulting elongate depressions within the structurally constrained bedrock-DEM still have uncertainties related to, e.g. natural variations in the elevation of the bedrock surface even within the deformation zones along-strike.

Figure 2.► Demonstrational figure shows preliminary bedrock-DEMs (left) and structurally-constrained detailed bedrock-DEMs (right). A) The initial bedrock-DEM by GTK within Kurikka aquifer, and B) improved bedrock-DEM including nine separately interpolated blocks within Kuusistonloukko area, Kurikka (Paper I). C) The thickness of the overburden between conventional bedrock-DEM and LiDAR DEM (2m elevation model by National Land Survey), and structurally constrained bedrock-DEM and LiDAR DEM (Paper II). E) The bedrock-DEM with interpreted bedrock depressions, and F) detailed cross-section-DEM (T2-DEM) with integrated lidar lineaments and fractures (solid black lines) and small-scale bedrock depressions (black dashed lines) along Jaaninoja Fault (Paper III)



A
Fig. B
B
1
2
3
4
5
6
7
8
9
-21.9
11.0
27.0
43.0
62.0
80.0
100.0
120.0
C
Overburden thickness
25486000
25488000
25490000
25492000
25494000
Conventional bedrock-DEM
2 km
0-1
1-5
5-10
10-20
20-30
>30 m
D
Structurally constrained bedrock-DEM
2 km
E
N
3km
-59.5
-20.0
0.0
20.0
40.0
60.0
68.5
Elevation (m)
F
Jaaninoja Fault

The results of Paper III show that deformation zones related to oblique fracture orientations observed in the outcrop-scale prevail along the margins of the elongate bedrock depressions and hence provide the primary control over the detailed bedrock surface morphology (Fig. 2e, f). The oblique fractures are located within the damage zone of deformation zones, which justifies the zig-zag-patterns of the bedrock surface morphology in the detailed scale, and, consequently, enhances the knowledge of along-strike variation within the deformation zones (Paper II).

Considering potential application areas for the results of this work, the contribution of the major bedrock discontinuities and their effect on the heterogeneity of the bedrock-DEM should be defined in the studies of glaciofluvial aquifers. Structurally constrained bedrock-DEMs may result in such local variations in the morphology of the bedrock-DEM that have major significance to the groundwater flow pathways. Moreover, the structurally constrained bedrock-DEMs provides spatially continuous bedrock surface model, which helps to evaluate the thicknesses of the sediments for various engineering applications.

5 Conclusions

Structural analyses of the bedrock are an essential step needed to generate a geologically realistic bedrock surface DEM, since the bedrock surface morphology is largely controlled by brittle structures of different scales. This thesis provides the following conclusions towards more geologically realistic bedrock surface 3D-modelling, where the bedrock structures and their contribution have been acknowledged:

1) Integrated structural analyses provide knowledge about the structural setting of the bedrock in different scales, which is essential within study areas of sparsely exposed bedrock outcrops. Data gaps could be reliably interpreted when the regional- and outcrop-scale structural setting is thoroughly investigated and correlated.

2) Major deformation zones such as shear zones and faults, are the most distinct bedrock structures in the regional-scale observed from remote sensing data. Shear zones and faults are associated with ductile fabric elements (either inherited or newly generated), but they do not always follow the ductile framework systematically. Strike of the shear zones and faults controls the elongation of the bedrock depressions and generates regional-scale roughness to the bedrock surface morphology.

3) Outcrop-scale fractures show significant variation in both orientations and spatial occurrence. Consequently, it is essential to create a constant hierarchy to classify the measured fractures based on the intensity and spatial occurrence of each fracture set. This hierarchy is a useful tool to examine the prevailing fracture sets throughout the study area, determine potential subdomains, and further use this information in local-scale modelling of the surface morphology of the bedrock within these subdomains.

4) Even if the orientations of outcrop-scale fractures show some resemblance with the regional-scale brittle structures and the potential ductile precursor, these brittle structures show strong scale-dependency.

Particularly, the damage zones of the deformation zones are associated with oblique outcrop-scale fractures, which are initiated by the brittle deformation, and whose orientations are controlled by the kinematic character of the deformation zones. This scale-dependency correlates with the bedrock surface morphology; the elongation of the bedrock depressions corresponds with the strike of the underlying deformation zones while the detailed surface morphology within the bedrock depression walls is controlled by the oblique fractures of the damage zone. A segmented deformation zone network generates a more complex setting of fracture subdomains that makes the bedrock surface morphology even rougher, further on the detailed scale.

5) The bedrock surface data are often sparsely or unevenly distributed within sediment-covered areas, which emphasizes the need for well-executed interpolations. Still, these interpolations typically result in overly smoothened bedrock surface morphologies with the available data. Therefore, explicit modifications of the bedrock-DEM, based on integrated structural analyses of the bedrock, provide an essential tool to reduce the smoothness and better honour the structural anisotropy that control the bedrock surface morphology. The scale of the utilized brittle structures needs to correspond with the spatial extent of the structurally-constrained bedrock model to allow accurate execution of interpolations utilizing the structural anisotropies.

6) The role of the major bedrock discontinuities and their contribution to the heterogeneity of the bedrock-DEM should be assessed in the studies of glaciofluvial aquifers. Structurally constrained bedrock-DEMs may result in such local variations in the morphology of the bedrock-DEM that has major significance to the groundwater flow pathways. Moreover, the structurally constrained bedrock-DEMs provide a regionally continuous bedrock surface model, which can be used in evaluation over the distance to bedrock and the thicknesses of the sediments that have applicability over a wide range of engineering applications.

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