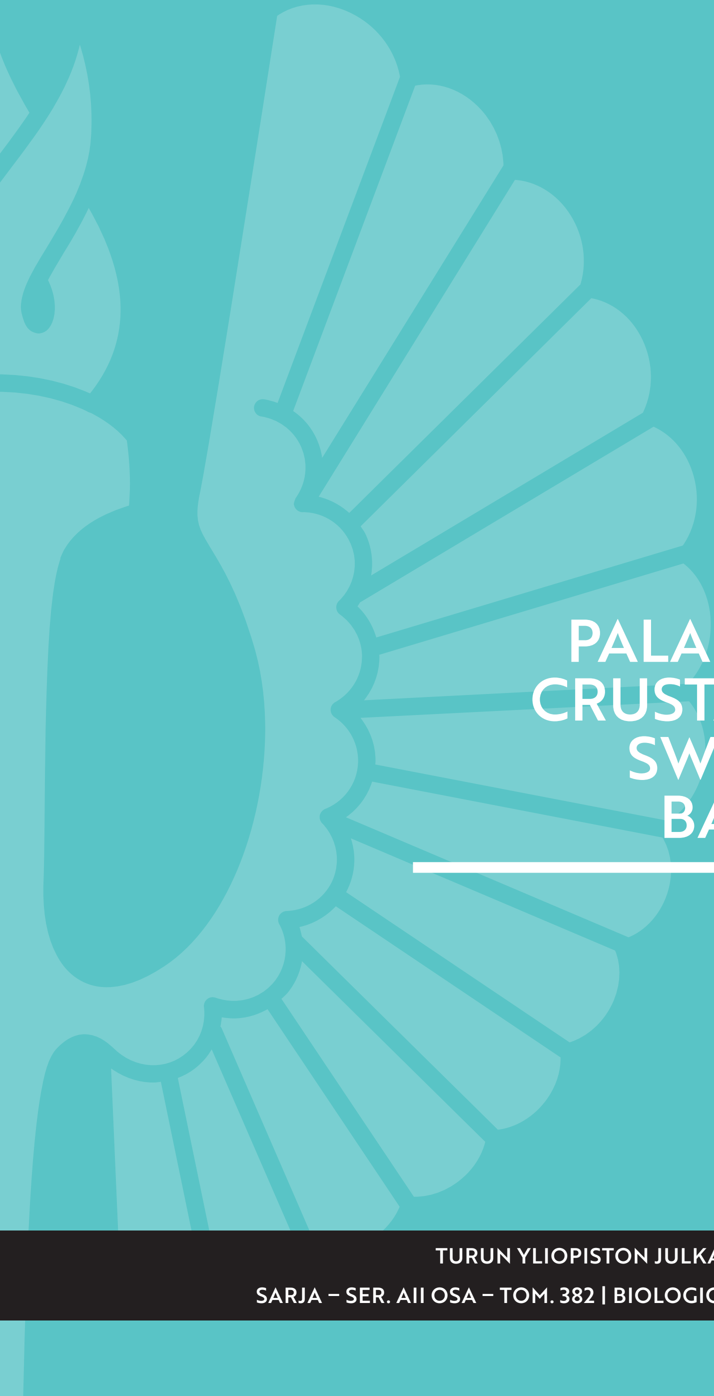
TURUN
YLIOPISTO
UNIVERSITY
OF TURKU



PALAEOPROTEROZOIC CRUSTAL EVOLUTION IN SW FENNOSCANDIA, BALTIC SEA REGION

Evgenia Salin

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
SARJA – SER. AII OSA – TOM. 382 | BIOLOGICA – GEOGRAPHICA – GEOLOGICA | TURKU 2021

TURUN
YLIOPISTO
UNIVERSITY
OF TURKU

PALAEOPROTEROZOIC CRUSTAL EVOLUTION IN SW FENNOSCANDIA, BALTIC SEA REGION

Evgenia Salin

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
SARJA – SER. AII OSA – TOM. 382 | BIOLOGICA – GEOGRAPHICA – GEOLOGICA | TURKU 2021

University of Turku

Faculty of Science
Department of Geography and Geology
Geology and Mineralogy
Doctoral programme in Biology, Geography and Geology (BGG)

Supervised by

Professor Krister Sundblad Institute of Earth Sciences Saint Petersburg State University Russian Federation	Dr. Jeremy Woodard Department of Geological Sciences School of Agricultural, Earth and Environmental Sciences University of Kwa-Zulu Natal, Westville South Africa

Reviewed by

Docent Karin Högdahl Department of Earth Sceince Uppsala University Sweden	Associate Professor Gražina Skridlaitė Institute of Geosciences Vilnius University Lithuania

Opponent

Professor Ulf Söderlund
Department of Geology
Lund University
Sweden

ISBN 978-951-29-8509-8 (PRINT)
ISBN 978-951-29-8510-4 (PDF)
ISSN 0082-6979 (Print)
ISSN 2343-3183 (Online)
Painosalama Oy, Turku, Finland 2021

“Science knows no country,
because knowledge belongs to humanity,
and is the torch which illuminates the world.”

– Louis Pasteur

UNIVERSITY OF TURKU
Faculty of Science
Department of Geography and Geology
Geology and Mineralogy
EVGENIA SALIN: Palaeoproterozoic crustal evolution in SW Fennoscandia, Baltic Sea region
Doctoral Dissertation, 180 pp.
Doctoral Programme in Biology, Geography and Geology (BGG)
August 2021

ABSTRACT

The Palaeoproterozoic crustal evolution of the Fennoscandian Shield involves significant crustal growth with a marked zonation from older rocks in the northeast to younger rocks in the southwest. Following the same pattern, the southwestern margin of the 1.96-1.86 Ga Svecofennian Domain is truncated by the 1.85-1.65 Ga Transscandinavian Igneous Belt (TIB). Both Svecofennian and TIB units are well exposed in southeastern Sweden, but the knowledge about their distribution in the Baltic Sea area has been limited due to a thick (up to 2.5 km) Phanerozoic sedimentary cover and sea water. Petrological, geochemical and geochronological data reported in this dissertation have shown that the evolution of the Palaeoproterozoic crust can be presented as a sequence of younging belts from the central part of the Baltic Sea (northern Gotland) towards northern Poland:

1. Svecofennian metasedimentary rocks form the northern part of Gotland. Detrital zircons from these rocks record three age populations: 2.11-1.96, 2.95-2.63 and 3.29 Ga, which indicate pre-Svecofennian sources. A Svecofennian amphibolite-granitoid complex on central Gotland consists of 1.90-1.88 Ga orthogneisses and amphibolites with a volcanic island arc affinity. The central Gotland complex can be correlated with southern Bergslagen in the Fennoscandian Shield and has been identified in an offshore drill hole NW of Liepaja, but appears to be absent in the coastlands of SW Latvia and Lithuania.
2. A km-thick sequence of ca. 1.87 Ga fluvial, tidal and turbiditic quartz-dominated metasedimentary rocks in the Västervik area along the Svecofennian margin is intercalated with mafic metavolcanic rocks with within-plate basalt affinity.
3. A 1.85 Ga rifted marine volcanic arc was identified within the Vetlanda-Oskarshamn belt and was shown to be contemporaneous with the continental margin TIB 0 granitoids and granitoids of the Mid-Lithuanian domain.
4. After the accretion of the volcanic arc to the Svecofennian margin, three generations of continental margin granitoids (TIB 1 a-c) were emplaced. The 1.81-1.79 Ga TIB 1a granitoids intruded into the Svecofennian crust and TIB 0 granitoids, while the 1.79-1.77 Ga TIB 1b granitoids intruded into the Vetlanda-

Oskarshamn belt and the TIB 1a granitoids. Finally, the 1.77-1.75 Ga TIB 1c granitoids intruded into the TIB 1b granitoids. Thus, the continental margin moved stepwise southwards from the central to southern parts of the Baltic Sea region.

5. Later evolution of the Proterozoic crust in the Baltic Sea region includes the intrusion of ca. 1.5 Ga plutons observed on southern Gotland and Öland related to the Danopolonian orogenic event.

KEYWORDS: Precambrian, Svecofennian Domain, Transscandinavian Igneous Belt, TIB, Baltic Sea, Fröderyd Group, Vetlanda-Oskarshamn belt, geochemistry, U-Pb, zircon

TURUN YLIOPISTO
Luonnontieteiden tiedekunta
Maantieteen ja geologian laitos
Geologia ja mineralogia
EVGENIA SALIN: Paleoproterotsooinen kuoren kehitys lounaisessa Fennoskandiassa Itämeren alueella
Väitöskirja, 180 s.
Biologian, maantieteen ja geologian tohtoriohjelma
Elokuu 2021

TIIVISTELMÄ

Fennoskandian kilven paleoproterotsooiseen evoluutioon liittyy merkittävä kuoren kasvu vanhemmasta koillisosasta nuorempaan lounaisosaan. Svekofennistä 1,96–1,86 miljardia vuotta vanhaa aluetta luoteisosassa leikkaavassa Transskandinaavisessa 1,85–1,65 miljardia vuotta vanhassa magmaattiseessa vyöhykkeessä (TIB) on samankaltainen kehitys. Kummatkin, Svekofenninen ja TIB ovat hyvin paljastuneita Kaakkois-Ruotsissa, mutta niiden laajuuden arviointi on rajallista Itämeren alueella, pohjalla olevien fanerotsooisten paksujen sedimentti kerrosten (jopa 2,5 km) ja meriveden takia. Tämän tutkimuksen petrologinen, geokemiallinen ja geokronologinen aineisto osoittaa, että paleoproterotsooinen kuoren kehitys voidaan esittää sarjana nuorenevia vyöhykkeitä, Itämeren keskiosasta (Pohjois-Gotlanti), kohti Pohjois-Puolaa.

1. Svekofenniset metasedimentit muodostavat Gotlannin pohjoisosan kallioperän. Metasedimenttikivien detritaaliset zirkonit edustavat kolmea ikäpopulaatiota: 2,11–1,96 miljardia vuotta vanha, 2,95–2,63 miljardia vuotta vanha ja 3,29 miljardia vuotta vanha, jotka viittaavat Svekofennistä vanhempiin lähteisiin. Svekofenninen amfiboliitti-granitoidi kompleksi Keski-Gotlannissa koostuu 1,90-1,88 miljardia vuotta vanhoista ortogneisseistä ja amfiboliiteista, jotka ovat koostumukseltaan saarikaari-tyyppisiä. Keski-Gotlannin kompleksi voidaan korreloida Eteläiseen-Bergslagenin alueeseen, Fennoskandian kilvellä ja on tunnistettu avomerellä sijaitsevasta, Liepajasta luoteeseen sijaitsevasta kairareiästä. Lounais-Latvian ja -Liettuan rannikolta Keski-Gotlannin kompleksi kuitenkin puuttuu.

2. Västerviikissä Svekofennisen reunalla sijaitseva kilometrin paksuinen sarja (n. 1,87 miljardia vuotta vanha) metamorfisia kvartsi-rikkaita joki- tulva- ja turbidiittii-sedimenttikiviä, jotka sijaitsevat koostumukseltaan laatansisäisten mafisten metavulkaniittien välissä.

3. 1,85 miljardia vuotta sitten revennyt merellinen vulkaaninen kaari on havaittu Vetlanda-Oskarshamn vyöhykkeellä ja on yhtenevä iältään mannerreunan TIB granitoiden ja Keski-Liettuan vyöhykkeen granitoidien kanssa.

4. Vulkaanisten kaarien kasautumisen jälkeen Svekofenniseen mannerreunaan asettui kolme eri ikäryhmää granitoideja (TIB 1 a-c). 1,81–1,79 miljardia vuotta sitten TIB 1a granitoidit asettuivat Svekofenniseen kuoreen ja TIB 0 granitoideihin, samaan aikaan 1,79–1,77 miljardia vuotta sitten TIB 1b granitoidit asettuivat leikaavaan Vetlanda-Oskarshamn vyöhykkeeseen. Viimeisenä, 1,77–1,75 miljardia vuotta sitten TIB 1c granitoidit asettuivat TIB 1b granitoideihin. Esitetyn kehityksen takia, mannerreuna on vaiheittain liikkunut etelämmäksi Itämeren keskiosasta.
5. Itämeren alueella proterotsooisen kuoren myöhempään evoluutioon luetaan Etelä-Gotlannissa ja Öölannissa sijaitsevat 1,5 miljardia vuotta vanhat intruusiot, jotka ovat osa Danopolonian vuorenmuodotusta.

ASIASANAT: Prekambri, Svekofennia, Transskandinaavinen magmaattinen vyöhyke, TIB, Itämeri, Fröderyd ryhmä, Vetlanda-Oskarshamn vyöhyke, geokemia, U-Pb, zirkoni

УНИВЕРСИТЕТ ТУРКУ
Факультет Науки
Отделение Географии и Геологии
Геология и минералогия
ЕВГЕНИЯ САЛИН: История развития палеопротерозойской земной коры юго-западной Фенноскандии в центральной части Балтийского моря
Докторская диссертация, 180 стр.
Докторская программа по Биологии, Географии и Геологии
Август 2021

АННОТАЦИЯ

История развития Фенноскандинавского щита в палеопротерозое включает значительный период роста континентальной коры, характерной особенностью которого является ее «омоложение» с северо-востока на юго-запад. Подобная тенденция прослеживается в ходе образования Трансскандинавского магматического пояса (далее ТМП; 1.85-1.65 млрд лет), внедрившегося в юго-восточную окраину Свекофеннского домена (1.96-1.86 млрд лет). Обе структуры хорошо обнаженны в юго-восточной Швеции, при этом в центральной части Балтийского моря перекрыты фанерозойскими отложениями Русской плиты, что затрудняет оценку области их распространения. Петрологические, геохимические и геохронологические данные, представленные в работе демонстрируют, что формирование палеопротерозойской континентальной коры региона связано с развитием последовательно сменяющихся поясов (более древних в центральной части Балтийского моря (о. Готланд) к более молодым в районе северной Польши):

1. Свекофеннские метаосадочные породы слагают северную часть о. Готланд. В спектре распределения возрастов детритовых цирконов из этих пород выделяются три популяции: 2.11-1.96, 2.95-2.63 и 3.29 млрд лет, что указывает на досвекофенские источники сноса. Свекофеннский амфиболит-гранитоидный комплекс в центральной части о. Готланд представлен ортогнейсами с возрастом 1.90-1.88 млрд лет и амфиболитами близкими по составу к базальтам вулканических дуг. Данный комплекс коррелируется с провинцией Бергслаген Фенноскандинавского щита. Схожие породы были вскрыты морской скважиной к северо-западу от Лиепаи, однако они не были обнаружены в юго-западной Латвии и Литве.

2. Терригенные метаосадочные породы преимущественно кварцевого состава в районе Вестервик образовались около 1.87 млрд лет назад вдоль Свекофенской окраины. переслаиваются с внутриплитными мафическими метавулканитами.

3. Океаническая вулканическая дуга с возрастом 1.85 млрд лет была идентифицирована в районе пояса Ветланда-Оскарсхамн. Образование которой происходило одновременно с внедрением гранитоидов ТМП 0 и гранитоидов Средне-Литовского домена в пределах континентальной окраины.

4. Аккреция вулканической дуги к Свекофеннской окраине сменилась последовательным внедрением трех типов гранитоидов в области активной континентальной окраины (1a, 1b и 1c). Тип 1a (1.81-1.79 млрд лет) внедрялся в Свекофеннскую континентальную кору и гранитоиды ТМП 0. Тип 1b (1.79-1.77 млрд лет) внедрялся в породы пояса Ветланда-Оскарсхамн и 1a гранитоиды. Тип 1c (1.77-1.75 млрд лет) внедрялся в 1b гранитоиды. Таким образом, континентальная окраина постепенно переместилась от центральной к южной части современного Балтийского моря.

5. Дальнейшее развитие протерозойской континентальной коры в районе Балтийского моря заключается во внедрении плутонов с возрастом около 1.5 млрд лет, обнаруженных на юге о. Готланд и о. Эланд. Интрузивный магматизм данного этапа связан с Данополонской орогенией.

КЛЮЧЕВЫЕ СЛОВА: Докембрий, Свекофеннский домен, Трансскандинавский магматический пояс, Балтийское море, группа Фрёдерюд, пояс Ветланда-Оскарсхамн, геохимия, уран-свинцовый метод, циркон

Table of Contents

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 Salin, E., Sundblad, K., Woodard, J., O'Brien, H. **The extension of the Transscandinavian Igneous Belt into the Baltic Sea region.** *Precambrian Research*, 2019; 328: 287-308.

II Salin, E., Woodard, J., Sundblad, K. **Tracing the SW border of the Svecofennian Domain in the Baltic Sea region: evidence from petrology and geochronology from a granodioritic migmatite**. *International Journal of Earth Sciences*, 2021; doi.org/10.1007/s00531-021-02005-z

III Salin, E., Sundblad, K., Lahaye, Y. **A 1.85 Ga volcanic arc offshore the proto-continent Fennoscandia in southern Sweden.** *Precambrian Research*, 2021; 356: 106134.

IV Sundblad, K., Salin, E., Claesson, S., Gyllencreutz, R., Billström, K. **The Precambrian of Gotland, a key for understanding the Proterozoic evolution in southern Fennoscandia.** *Manuscript (submitted)*

The original publications have been reproduced with the permission of the copyright holders.

Contributions

I Salin was responsible for all laboratory work related to geochronology and sample preparation for geochemical analysis as well as petrography, SEM analyses and interpretations. Figures and tables were done by Salin. Manuscript text was written in collaboration with Sundblad. Woodard contributed with the zircon separation and ICP-MS analysis for the E7-1 sample. SIMS analysis was conducted in collaboration with Woodard. ICP-MS analysis for other samples was conducted in collaboration with O’Brien.

II Salin was responsible for zircon separation, petrography and SEM analysis, as well as for figures 1-12 and tables 1-2. Salin and Woodard were responsible for sample preparation for geochemical analysis. Woodard was responsible for figures 13-14. Discussion and table 3 were done in collaboration with Woodard. Early drafts of the manuscript were written in collaboration with Sundblad.

III Salin was responsible for zircon separation, petrography as well as SEM analyses and interpretations. Figures and tables were done by Salin. Discussion and interpretations were done by Salin in collaboration with Sundblad. ICP-MS analysis was conducted in collaboration with Lahaye.

IV Salin and Sundblad were responsible for the text and final version of the manuscript. Salin was responsible for petrographical and geochemical descriptions and interpretations as well as interpretation of geochronological data of magmatic rocks. Gyllencreutz was responsible for geophysical data and their interpretations, as well as figures 1-4 and 14. Claesson was mostly responsible for description of geochronological data from sedimentary rocks. Interpretation of these data was done in collaboration with Salin. Salin was responsible for figures 5-11 and 13; tables 1 and 4. Billström was responsible for Rb-Sr and Sm-Nd data, their interpretation and tables 2-3.

1 Introduction

1.1 Significance of the subject

The Fennoscandian Shield is an exposed part of the East European Craton in northern Europe (Figure 1), which the southern and eastern margins are covered by km-thick platform Phanerozoic sedimentary sequences. The Precambrian basement beneath the Baltic Sea constitutes a continuation of the Fennoscandian Shield covered by the platform sedimentary rocks. It remains less studied relative to the exposed parts of the shield north and west of the Baltic Sea as well as the extensively drilled platform areas east and south of the Baltic Sea.

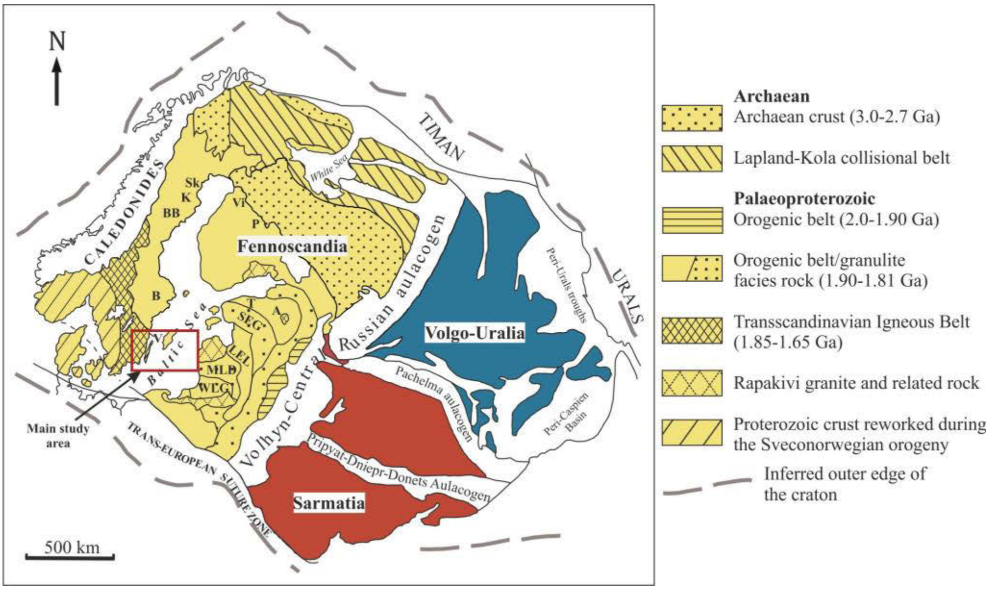


Figure 1. Main provinces and structures of the Fennoscandian crustal segment as a part of the East European Craton (modified after Gorbatschev and Bogdanova (1993) and Bogdanova et al. (2015)). A – Alutaguse domain; B – Bergslagen area; BB – Bothnian basin; K – Knaften arc; LEL – Latvian-East Lithuanian domain; MLD – Mid-Lithuanian domain; P – Pyhäsalmi; SEG – South Estonian granulite domain; Sk – Skellefte district; T – Tallinn domain; V – Västervik; Vi – Vihanti; WLG – West Lithuanian granulite domain

Our current knowledge about the structure of the Precambrian crust in the Baltic Sea region is mostly restricted to data from geophysical studies (BABEL Working group, 1993; Meissner et al., 1992; Lund et al., 2001; Wilde-Piórko and Grad, 2002; Bogdanova et al., 2006). Seismic and magnetic profiles recorded a significant decrease in crustal thickness from 50 km in the northeast to 38 km in the southwest (Guggisberg et al., 1991; Lund et al., 2001). Geophysical studies are complemented by other significant sources of knowledge, based on drill cores and percussion-drilling cuttings. For a long time, the best summary of the Precambrian in the Baltic Sea region existed only in an extended abstract by Sundblad et al. (2003), who proposed that a shift from a thicker to thinner crust in the Baltic Sea area was caused by a change from the metamorphosed Svecofennian crust to the granites of the Transscandinavian Igneous Belt.

1.2 Objectives of the thesis

This study aims to understand the Palaeoproterozoic crustal evolution along the southwestern margin of the Svecofennian Domain based on petrological, geochemical and isotopic data. The thesis presents and discusses the gradual change in geological environments recorded in the Precambrian crustal units in the Baltic Sea region, which can be traced from the Fennoscandian Shield towards the Baltic republics (Papers I, II and IV). Interpretation of the tectonic evolution between 1.87 and 1.77 Ga, which triggered formation of the Vetlanda-Oskarshamn belt (VOB) along the southwestern margin of the Svecofennian Domain, is discussed in the Paper III.

2 Geological setting

2.1 Geological setting of the area west of the Baltic Sea

This thesis focuses on the formation of new Proterozoic crust, not on reworked and metamorphosed rocks, that is why the term “Svecofennian” will be applied to the Svecofennian Domain and rock complexes involved in a crustal concept of Gaál and Gorbatschev (1987).

The Svecofennian Domain is a collage of continental volcanic arcs, primitive island arcs and microcontinents amalgamated and accreted to the craton in the northeast between 1.96 and 1.86 Ga (Lahtinen et al., 2009). Accretion of the terranes took place in a convergent setting within a subduction zone with a roughly northwest trend. The Svecofennian Domain is mostly composed of metamorphosed granitoids, volcanic and sedimentary rocks formed at 1.90-1.87 Ga. The northern part of the Svecofennian Domain is occupied by the Skellefte volcanic arc complex with either primitive island arc or continental arc origin (Allen et al., 1996a; Weihed et al., 2002). The oldest rocks are ca. 1.96 Ga volcanic rocks in the Stensele basin (Eliasson and Sträng, 1998), contemporary granitoids and supracrustal rocks of the Knaften arc (Wasström, 2005) and the 1.93-1.92 Ga primitive island arc rocks in the Vihanti-Pyhäsalmi area (Lahtinen et al., 2009). The central part of the domain, the Bothnian basin, is dominated by a 10-km thick sequence of metagreywackes deposited from more than 2.03 to 1.87 Ga (Claesson et al., 1993; Claesson and Lundqvist, 1995; Weihed et al., 2002) in a submarine basin simultaneously with the emplacement of the granitoid plutons (Lundqvist et al., 1998). The southern part of the domain includes the Bergslagen area mostly composed of felsic metavolcanic and associated metasedimentary rocks formed in an active continental margin (Vivallo and Rickard, 1984; Allen et al., 1996b).

Another sedimentary basin south of the Bergslagen area is composed of the 1.87-1.86 Ga Västervik quartzites intercalated with mafic metavolcanic rocks. The Västervik basin is a km-thick succession of metamorphosed quartz-dominated sedimentary rocks deposited in tide-dominated estuaries, deltas and wave-dominated shallow-water environments along a continental margin (Russell, 1967; Sultan and Plink-Björklund, 2006).

Continuous subduction along the Bergslagen active continental margin caused emplacement of several generations of granitoids, comagmatic volcanic rocks and minor mafic intrusions within the Transscandinavian Igneous Belt (TIB; Nyström, 1982; Högdahl et al., 2004). Intrusion spans a time interval from 1.86 to 1.67 Ga and includes several pulses: TIB 0 (1.86-1.85 Ga), TIB 1 (1.81-1.75 Ga) and TIB 2 (1.71-1.67 Ga); Larson and Berglund, 1992; Ahl et al., 2001; Gorbatschev, 2004. The TIB 0 granitoids are mainly I-type quartz monzonites and quartz syenites with alkali-calcic metaluminous to peraluminous geochemical signatures (Ahl et al., 2001). The TIB 0 generation forms large homogeneous bodies (Persson and Wikström, 1993) or strongly deformed slivers of granitoids and augen gneisses (Wikström, 1991; Wikström and Persson, 2002), which intruded into the Svecofennian crust of the southwestern Bergslagen area and the Västervik basin (Kleinhanns et al., 2015). The TIB 1 generation is the most voluminous part of the belt extending for 600 km from the Trysil area in Norway, where it is covered by the Caledonian nappes, towards the Baltic Sea. This generation is dominated by I-type quartz monzonites to granites characterized by alkali calcic to calc-alkaline, metaluminous to peraluminous compositions. The TIB 1 granitoids are associated with felsic volcanic and subordinate mafic rocks (Andersson, 1997; Ahl et al., 1999, 2001). The TIB 2 granitoids are recognized both east and west of the TIB 1 generation and have both I- and A-type signatures (Andersson, 1997; Ahl et al., 1999; 2001).

The Vetlanda-Oskarshamn belt (VOB) separates the TIB 1 granitoids in Småland into a northern and a southern part~~s~~ (Vimmerby and Växjö batholiths, respectively). The ages of the Vimmerby Batholith granitoids (TIB 1a) vary from 1808 to 1794 Ma (Jarl and Johansson, 1988; Mansfeld, 1991; Kornfält et al., 1997; Kleinhanns et al., 2015), while the granitoid ages within the Växjö Batholith (TIB 1b) vary from 1793 to 1769 Ma (Patchett et al., 1987; Jarl and Johansson, 1988; Wikman, 1993; Johansson, 2016).

The Tving granitoids in the Blekinge Province is located immediately south of the Växjö Batholith (TIB 1b), but are separated from it by the Småland-Blekinge Deformation Zone (SBDZ; Wiklander, 1974; Lindh et al., 2001). The Blekinge Province is dominated by the pervasively deformed 1.77-1.75 Ga Tving granitoids and “coastal gneisses” (Johansson et al., 2006; Johansson, 2016) implying that they were formed at deeper crustal levels and were subsequently uplifted (Kornfält, 1996; Johansson et al., 2006; Lindh et al., 2001).

Detrital zircons from the metasediments of the Bothnian basin cluster in two groups: Archaean (2.93-2.65 Ga) and Palaeoproterozoic (2.01-1.87 Ga), e.g. Skiöld, 1988; Claesson et al., 1993; Weihed et al., 2002). Detrital zircons in the metasedimentary rocks in the Bergslagen area include Archaean to earliest Palaeoproterozoic (2.97-2.45 Ga) and Palaeoproterozoic (2.08-1.87 Ga; e.g. Claesson et al., 1993; Andersson et al., 2006; Kathol et al., 2020). Also, an indication of a 4.0 Ga component was found in the Närkesberg-Hjortkvarn area in southern Bergslagen (Kathol et al., 2020).

2.2 Geological setting of the Baltic Sea and areas east of it

The Precambrian crust in the Baltic Sea area and to the east of it is a part of the East European Craton covered by Phanerozoic platform sediments. Knowledge about the Precambrian crust in this area is based on the drill core data and geophysical investigations (e.g. Berthelsen, 1992; BABEL Working Group, 1993; Wilde-Piórko and Grad, 2002).

Although several commercial companies and government organizations have drilled many hundreds of drill holes in the Baltic Sea region, with the main purpose to document the stratigraphy of the Palaeozoic sedimentary strata and explore the oil and gas potential, most of the drill holes never reached the Precambrian basement. Drill holes reached the Precambrian basement are summarized in Table 1.

Table 1. Drill holes reached the Precambrian basement in the Baltic Sea region

Site	Drilled by, year	Reference
Visby	SGU[1],1920s	Hedström, 1923
File Hajdar (Gotland)	Skånska Cement[2], 1937	Thorslund & Westergård, 1938
Böda hamn (Öland)	SGU[1], 1955	Hessland, 1949, 1955
Gotska Sandön	SGU[1], 1957	Thorslund, 1958; Gorbatschev, 1962
Grötlingbo (Gotland)	SGU[1], 1968	Anderegg et al., 1968
När (Gotland)	SGU[1], 1968	Anderegg et al., 1968
Öland onshore, 4 holes	OPAB[3], 1972-1973	-
Gotland onshore, 38 holes	OPAB[3], 1972-1992	-
Gotland offshore, 12 holes	OPAB[3], 1973-1976	-
P6-1	-	Pavlov, 1989; Grigelis, 1991
E7-1	Petrobalt[4], 1982	Grigelis, 1991
E6-1	Petrobalt[4], 1984	Grigelis, 1991
D1-1	Petrobalt[4], 1984	Grigelis, 1991

[1] Sveriges geologiska undersökning (Geological Survey of Sweden)
[2] Skånska Cementgjuteriet
[3] Oljeprospekterings AB (Petroleum exploration AB)
[4] RP–GDR–USSR Petrobalt consortium, 1982–1984

A summary of the Soviet investigations were published in 1991, however parts of the extensive material collected by OPAB became available only in mid-1990s allowing for the first studies of drill cores from the Precambrian basement on Gotland (Sundblad, 1996) and a detailed magnetometry study on south-central Gotland (Gyllencreutz, 1998).

Based on further drill core studies, including geochemical and isotopic investigations, Sundblad et al. (2003) inferred that the Precambrian basement beneath Gotland consisted of Svecofennian rocks in the northern and central parts and TIB granites in the southernmost part. This conformed to the results from the geophysical studies, which had recorded a significant decrease in crustal thickness in the central part of the Baltic Sea (BABEL Working Group, 1993; Lund et al., 2001).

The crystalline basement east of the Baltic Sea is composed of Palaeoproterozoic terranes, which accreted at ca. 1.83-1.80 Ga and 1.75-1.70 Ga to form a belt-like structure (Bogdanova et al., 2006). The metasedimentary (Alutaguse domain) and metavolcanic (Tallinn domain) rocks of ca. 1.90 Ga comprise the crystalline basement of northern Estonia (Puura et al., 1983; Kirs et al., 2009). Deposition of turbidites took place between 1.96 and 1.90 Ga (Lahtinen et al., 2010). The South Estonian granulite domain (SEG) is composed of mafic to felsic metaigneous granulites and grades into the Latvian-East Lithuanian domain (LEL). The latter comprises metavolcanic and associated metasedimentary rocks, metamorphosed in the amphibolite to granulite facies. Farther south, charnockites and mafic granulites of 1.86-1.82 Ga (Claesson et al., 2001; Motuza et al., 2008; Skridlaite et al., 2011) as well as gabbroic to granitic suites and their volcanic counterparts comprise the Mid-Lithuanian domain (MLD), which is interpreted to represent a one-time active continental margin. The West Lithuanian granulite domain (WLG) is dominated by metavolcanic and associated metasedimentary rocks intruded by granites. Volcano-sedimentary sequences of the WLG are interpreted to belong to an island arc similar to the 1.83-1.81 Ga volcanic belts in Poland (Bogdanova et al., 2015).

3 Material and Methods

3.1 Material

The main study area includes the central part of the Baltic Sea and southeastern Sweden. Altogether, 42 samples (Figure 2, Table 2): 23 drill cores and percussion-drilling cuttings from beneath the Swedish islands Gotland and Öland and the Baltic Sea area and 27 samples from the Valdemarsvik, Tiveden, Västervik and Fröderyd areas (southeastern Sweden). In the studied area, the Precambrian basement of the Baltic Sea is covered by up to 2600 m-thick sequence of Phanerozoic sedimentary rocks and seawater, and all access to the study material is retsricted to a drill core material (percussion-drilling cuttings and drill cores).

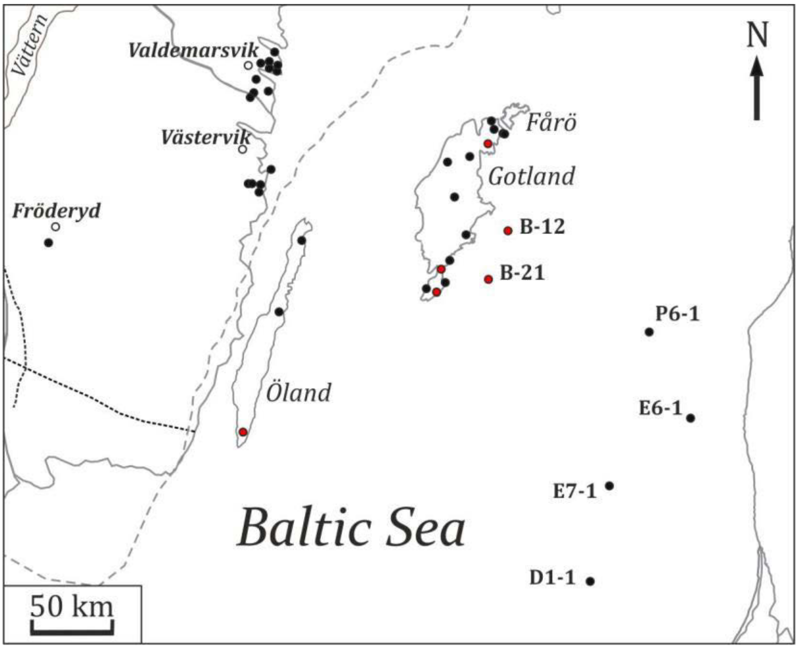


Figure 2. Map of sampling sites. Black dots – drill hole locations and sampling sites in outcrops. Red dots – percussion-drilling sites. Grey dashed line – northwestern limit of the Phanerozoic sedimentary cover.

Table 2. Samples used for the study and drill holes within Gotland and adjacent offshore area used for correlation with corresponding references

Location	Sampling site	Papers / References
Gotland	Arhagen (dc)[1]	Paper IV
	Stenstugu (dc)	Paper IV
	Audungs (dc)	Paper IV
	Sandviken (dc)	Paper IV
	Alby (pd)[2]	Paper IV
	File Hajdar (dc)	was used for correlation in Paper IV; Thorslund and Westergård (1938)
	Skäggs (dc)	Paper IV
	Viklau (dc)	Paper IV
	När (dc)	Paper IV
	Grötlingbo (dc)	Paper IV
	Frigsarve (pd)	Paper I
	Faludden (dc)	Paper IV
	Kvarne (dc)	Paper IV
	Hamra (pd)	was used for correlation in Paper IV; Salin et al. (2020)
Öland	Böda Hamn (dc)	Paper I
	Valsnäs (dc)	Paper I
	Kvinnsgröta (pd)	was used for correlation in Paper IV; Salin et al. (2020)
Baltic Sea (offshore Latvia/Lithuania)	B-12 (pd)	was used for correlation in Paper II; Salin (2014)
	B-21 (pd)	was used for correlation in Paper II; Salin (2014)
	P6-1 (dc)	was used for correlation in Paper IV; Pavlov (1989), Grigelis (1991)
	E6-1 (dc)	Paper II
	E7-1 (dc)	Paper I
	D1-1 (dc)	Paper I
Southeastern Sweden		
Tiveden	KS2005-KS2007	Paper IV
Valdemarsvik area	KS1923-KS1928	Paper IV
	Hulta (ES1908)	Paper IV

Västervik area	KS1914-KS1916 KS0507-KS0510	Paper IV
Fröderyd area	F90019- F90020, F90023, F90025- F90031	Paper III

[1] dc – drill core sample

[2] pd – percussion-drilling sample

3.1.1 Percussion-drilling cuttings

Percussion-drilling cuttings were available from Alby (northern Gotland), Frigsarve and Hamra (southern Gotland) and Kvinnsgröta (southern Öland). This sampling method implies that the rock is crushed by bit-rock impact and welled up from the drill hole by water flux. The loose rock fragments were collected at every 1 to 3 m depth interval, dried and put into a sample bag. In this way of sampling, each sample became contaminated by rock fragments from overlying rock units, and some minerals became lost. In this study, samples were collected at the depth intervals 477-479 m (Alby), 708-709 m (Frigsarve), 801-802 m (Hamra) and 272-273 m (Kvinnsgröta). These depth intervals are the deepest in the above-mentioned drill holes. They contain from 50 to 70 % (in Hamra and Frigsarve accordingly) of Precambrian granite fragments and loose feldspar, quartz and mica (biotite and muscovite) grains as well as 30 to 50 % of sedimentary components from the overlying Phanerozoic strata. Evident contamination is expressed by the presence of sandstone, limestone, schist and clay material, which were avoided during sampling. The Precambrian granite fragments differ significantly from the sedimentary material by coarser grain sizes and granitic mineral composition. These observations were considered when granitoid fragments for zircon separation were handpicked under the binocular microscope. Isolated zircon grains were not selected for age determination to avoid age discrepancies.

3.1.2 Rock samples

Twelve samples from beneath Gotland and Öland were collected from drill cores at the depths between 162 m (Böda Hamn) and 800 m (Kvarne) from the uppermost parts of the Precambrian basement immediately under the Cambrian sedimentary rocks. Three samples from the Baltic Sea offshore Latvia/Lithuania were collected at the depths between 1092 m (E6-1) and ~2600 m (D1-1). Samples contain metasedimentary and metaigneous rocks from northern and central Gotland as well as granitoids from southern Gotland (Kvarne), Öland (Böda Hamn and Valsnäs) and offshore Latvia/Lithuania.

Sixteen samples of metavolcanic rocks and one granitoid sample were collected in outcrops in the Tiveden, Valdemarsvik, Västervik and Fröderyd areas. Ten samples of mafic volcanic rocks, originally collected in 1990 and used by Sundblad et al. (1997) were re-evaluated in the current study.

3.2 Analytical methods

3.2.1 Geochemical analysis

Thirty-seven rock samples from the studied area were analysed for major, minor and trace elements, either at Actlabs, Ontario, Canada, or CAF, Stellenbosch University, South Africa. In addition, 119 geochemical analyses from the TIB 1 and Blekinge granites and the Pilsotas granodiorites in the WLG were selected from Ahl (1989), Mansfeld (1991), Wikman and Kornfält (1995), geochemical database of the Geological Survey of Sweden, Persson and Wikman (1986), Mansfeld (1991), Wikman (1998, 2000), Johansson et al. (2006) and Motuza et al. (2008; Paper I). The 27 geochemical analyses for the TIB 0 granitoides (Persson and Wikström, 1993), the granodiorites from the Kuršiai batholith in western Lithuania (Motuza et al., 2008) and the late Svecofennian granites in Sweden and Finland (Öhlander and Zuber, 1988; Nironen and Kurhila, 2008) were used (Paper II). The geochemical data from 21 mafic and felsic metavolcanic rocks, originally used by Sundblad et al. (1997), were re-evaluated for this study (Paper III). Six geochemical analyses for Västervik and Valdemarsvik metavolcanic rocks from Wik et al. (2005) were used for Paper IV.

3.2.2 Rb-Sr and Sm-Nd analyses

Seven samples from metavolcanic rocks were selected to provide information on the source of the igneous material in the Precambrian basement beneath Gotland and Valdemarsvik and Västervik areas in southeastern Sweden (Paper IV). The Rb-Sr and Sm-Nd analyses were conducted using a Thermo-Finnigan Triton thermal ionization mass spectrometry (TIMS) instrument.

3.2.3 U-Pb zircon geochronology

Zircon separates from rock samples were obtained using a conventional procedure including heavy liquid method, magnetic separation and subsequent handpicking under a binocular microscope. Rock fragments from percussion-drilling cuttings selected for zircon separation were handpicked under the binocular microscope. After samples were milled in mortar, magnetic minerals were separated only by a hand magnet due to the limited amount of rock material. Afterwards, zircon separation with conventional technique was applied.

Fifteen samples were selected for the zircon U-Pb age determination to constrain temporal variations of the igneous/metaigneous and metasedimentary rocks in the studied area. Age determination of ten samples was conducted using a large geometry Cameca IMS1280 Secondary Ion Mass Spectrometer (SIMS) at the Swedish Museum of Natural History in Stockholm (Nordsim facility; Papers I, II and IV). Zircon U-Pb dating analyses of five samples were performed using either an AttoM single collector ICP-MS connected to a Photon Machine Excite laser ablation system (Papers I and III), or a Nu Plasma HR multicollector ICP-MS, both at the Finnish Geosciences Research Laboratory, Geological Survey of Finland, Espoo.

Age calculations were performed using version 4.15 of the Isoplot software (Ludwig, 2003; Paper I-IV). Stacked diagrams for sedimentary rocks were performed using the jAgeDisplay software by Thomsen et al. (2016; Paper IV).

4 Summaries of the original papers

4.1 Paper I: The extension of the Transscandinavian Igneous Belt into the Baltic Sea region.

Until this project was initiated, all existing knowledge about the Precambrian basement in the Baltic Sea region was based on geophysical studies (Meissner et al., 1992; Lund et al., 2001; Bogdanova et al., 2006) and scarce petrological, geochronological and geochemical data summarized in an extended abstract by Sundblad et al. (2003). Paper I presents petrological, geochemical and geochronological data for five drill core or percussion-drilling samples from the Precambrian basement beneath southern Öland (Böda Hamn and Valsnäs), southern Gotland (Frigsarve) and the Baltic Sea area (E7-1 and D1-1). The aim of Paper I was to correlate observed features of these samples with existing knowledge on the Fennoscandian Shield in order to define crustal units formed between 1.90 and 1.75 Ga in the Baltic Sea region.

The correlation resulted in five crustal units, which could be traced from southeastern Sweden across the Baltic Sea towards its eastern coast.

These units include:

Unit 1: The Bergslagen district is a Svecofennian terrane dominated by 1.90-1.87 Ga granitoids, comagmatic felsic metavolcanic rocks and associated Fe, Cu, Zn, Pb and Ag ore bodies (Stephens et al., 2009), as well as intercalated metasedimentary rocks (e.g. Kumpulainen et al., 1996). This unit can be traced to southwestern Finland and the concealed Precambrian bedrock of Estonia. The Svecofennian metasediments south of Stockholm can be recognized beneath northern Gotland.

Unit 2: The Svecofennian border unit is composed of amphibolites intruded by the TIB 0 granitoids. This unit can be followed from the northern parts of lake Vättern to the Söderköping-Valdemarsvik region along the Baltic Sea coast. The amphibolites were correlated with similar rocks, identified in several drill cores on southern Gotland, including Viklau, Faludden and Kvarne (Sundblad et al., 2003). The study showed that the coarse-grained granitoid at Frigsarve (southern Gotland) is 1.85 Ga old, which is comparable with the 1.86-1.85 Ga granitoids belonging to the oldest generation of the Transscandinavian Igneous Belt (TIB 0).

Unit 3: TIB 1 is a well-established unit in southeastern Sweden. In Paper I, the TIB 1a subunit is introduced as a 1.81-1.79 Ga igneous complex (the Vimmerby Batholith) between the Vetlanda-Oskarshamn belt and the TIB 0 units. A quartz monzodiorite at Böda Hamn (northern Öland) yielded a U-Pb zircon age of 1.80 Ga, which together with the 1.81 Ga Kvarne granite (southern Gotland) shows that the TIB 1a granites can be followed into the Precambrian basement of the Baltic Sea.

Unit 4: Subunit TIB 1b (the Växjö Batholith) is another TIB population introduced in the Paper I. TIB 1b intruded at 1.79-1.77 Ga between the Vetlanda-Oskarshamn belt and the Blekinge Province. A 1.79 Ga quartz motzonite at Valsnäs (central Öland) can be correlated with these TIB 1b granites.

Unit 5: The Pomerania-Blekinge belt is composed of 1.77-1.75 Ga granitoids. Based on the deformational fabric as well as geochemical and geochronological data from the E7-1 and D1-1 granodiorites (offshore Lithuania and Latvia), the Pomerania-Blekinge belt was extended into the southeastern parts of the Baltic Sea.

4.2 Paper II: Tracing the SW border of the Svecofennian Domain in the Baltic Sea region: evidence from petrology and geochronology from a granodioritic migmatite.

Paper II presented petrographic, geochemical and geochronological features of a drill core sample collected from 1092-1093 m depth of the E6-1 drill hole located in the eastern part of the Baltic Sea, close to the Latvian/Lithuanian coast. The aim of the study was to trace the border of the Svecofennian Domain in the eastern part of the Baltic Sea.

Geochemical data from the E6-1 migmatitic orthogneiss showed that a palaeosome has a granodioritic composition and a leucosome has a granitic composition. The E6-1 protolith, represented by the palaeosome, was correlated with the TIB 0 Askersund granite, the oldest generation of the Transscandinavian Igneous Belt in southeastern Sweden. Both of them show volcanic arc features. In turn, the leucosome was formed due to a fluid-absent biotite dehydration of the granodioritic protolith. This is evidenced by higher contents of mobile elements, which tend to be enriched in the melt, lower contents of immobile elements staying in the restite and $(La/Yb)_{PM}$ ratios. Formation of a granitic leucosome from a TIB 0 type granodioritic protolith is also supported by a trace element model. In a model producing 40% melt, the trace element patterns are similar to what is observed in the leucosome granite. The leucosome composition is similar to other late Svecofennian granites.

A concordia age for two inherited zircon cores is 1854±15 Ma, which coincides with the emplacement age of the variably deformed and metamorphosed TIB 0 granitoids in southeastern Sweden. While this age was calculated from limited data and on its own it cannot give a robust evidence, it is supported by the geochemical correlation with the TIB 0 granitoids, which suggests that the observed age represents the igneous protolith age. The leucosome formed due to partial melting of the TIB 0 protolith at 1812±5 Ma, which coincides with the 1.83-1.81 Ga metamorphic event in southeastern Sweden.

Geochemical and geochronological data demonstrate that the E6-1 drill site is located within the continental margin of the Svecofennian Domain. Thus combined with the evidence from the E7-1 drill site (55 km southwest of the E6-1 drill hole) belonging to the Transscandinavian Igneous Belt, the southwestern border of the Svecofennian Domain is located between the E6-1 and E7-1 drill sites.

4.3 Paper III: A 1.85 Ga volcanic arc offshore the proto-continent Fennoscandia in southern Sweden.

Paper III presented petrological, geochemical and geochronological features of the metavolcanic rocks in the Fröderyd Group. The aim of Paper III was to see if there was any substance in the Svecofennian age and based on acquired data from the Fröderyd rocks to present an interpretation of the tectonic evolution including volcanic arc and rifted volcanic arc during the 1.87-1.77 Ga time interval with the relevance to the evolution of the southwestern margin of the proto-continent Fennoscandia.

The U-Pb zircon age of a felsic metavolcanic rock in the Fröderyd Group is 1853±11 Ma and geochemical data show that the group was formed in a rifted volcanic arc, southwest of the Fennoscandia proto-continent. Tectonic uplift and rapid erosion resulted in formation of lacustrine sediments in restricted basins, now found in the Vetlanda region. Simultaneously with the arc development, 1.86-1.85 Ga TIB 0 granitoids intruded the Fennoscandia proto-continent in an Andean-type active continental margin setting.

Based on age, sedimentation style and intercalated volcanic rocks, it can be inferred that the Västervik and Vetlanda metasedimentary successions formed in two different geological environments during two separate events. The 1.87-1.86 Ga Västervik quartzites were deposited along a continental margin and were intercalated with mafic volcanic rocks. While the ca. 1.82 Ga Vetlanda formation is dominated by quartz-plagioclase arkoses and conglomerates, indicating a shallow water environment; the absence of limestone may suggest a lacustrine environment. The Vetlanda metasedimentary rocks are intercalated with felsic metavolcanic rocks.

Although Röshoff (1975) proposed that all supracrustal rocks in the Nömmen and Vetlanda areas constituted one supergroup, geochemical and geochronological data presented by Mansfeld (1996), Mansfeld et al. (2005) and the current contribution, show that these two lithostratigraphic units do not record a coherent geological evolution of the area. Although there is no clear geochronological evidence, it is possible that the volcanic rocks in Nömmen and other sites in the Vetlanda-Oskarshamn belt represent alternative counterparts of the volcanic arc in Fröderyd. In turn, the Vetlanda formation should be restricted to the metasedimentary and felsic volcanic rocks in the Vetlanda and Björkö areas. Thus, it is implied that the Vetlanda supergroup has lost its meaning and should be abandoned. Also, it is recommended that the term "Oskarshamn-Jönköping belt" is abandoned and replaced by the original term "Vetlanda-Oskarshamn belt".

4.4 Paper IV: The Precambrian of Gotland, a key for understanding the Proterozoic evolution in southern Fennoscandia.

Paper IV presents data and arguments for correlations of the Precambrian beneath Gotland and adjacent areas of the Fennoscandian Shield. The correlations are based on petrographical, geochemical, geochronological and geophysical data. The aim of Paper IV is to model the complex crustal growth along the southwestern margin of the Svecofennian Domain.

The U-Pb zircon dating showed that the rocks in the Fårösund region (northern Gotland) can be divided into two groups representing different U-Pb age patterns. The first group (Stenstugu, Audungs and Sandviken) records 2.11-1.97 Ga and 2.95-2.63 Ga ages, whereas the Arhagen drill core sample mostly contains 2.11-1.96 Ga zircons. The youngest age (1.96 Ga) provides a maximum age for the deposition of the unmetamorphosed sediments. The Palaeoproterozoic age of 2.11-1.97 Ga identified in both groups is also observed in detrital zircons of supracrustal Svecofeninnian rocks of the Fennoscandian Shield. The Neoarchaean age of 2.95-2.63 Ga is well established both in the Fennoscandian Shield and worldwide. The oldest (3.29 Ga) crystal from the Arhagen drill core sample (northern Gotland) may indicate that this grain has undergone several erosional cycles.

The Viklau amphibolite (central Gotland), together with the amphibolites in the Tiveden and Valdemarsvik regions in southeastern Sweden, forms a distinct population with an island arc basalt affinity. These rocks are depleted in LREE and HREE relative to the Västevik amphibolites (southeastern Sweden), and either lack Eu anomaly or have a rather pronounced negative anomaly. The Västervik amphibolites have a steeper REE pattern with a moderate negative Eu anomaly. They plot close to the within-plate basalt field. Similar characteristics feature the Kvarne and Faludden amphibolites (southern Gotland).

Petrological and geochemical data as well as the U-Pb ages of the orthogneisses at Skäggs and När (central Gotland), show that they can be correlated with the

Svecofennian orthogneiss at Hulta (south of Valdemarsvik). The latter was collected in the same outcrop ("site 1" by Stephens and Andersson (2015)) as a grey granodioritic orthogneiss of 1880 Ma.

The 1811 Ma Kvarne granite (southern Gotland) is characterized by similar petrological and geochemical properties as the TIB 1a granitoids (e.g. at Böda Hamn, northern Öland; Äspö and Ramnebo, southeastern Sweden). Compared to the Skäggs-När-Hulta population, the Kvarne granite has a granitic compositions, but with significantly higher alkali contents.

Petrological and geochemical data show that the 1453 Ma Grötlingbo granite (southern Gotland) belongs to the 1.5 Ga population.

5 Results and Discussion

The U-Pb zircon dating showed that the rocks in the Fårösund region (northern Gotland) can be divided into two groups representing different U-Pb age patterns (Figure 3). The first group (Stenstugu, Audungs and Sandviken) records 2.95-2.63 Ga and 2.11-1.97 Ga ages, whereas the Arhagen drill core sample mostly contains 2.11-1.96 Ga zircons. The lowest age (1.96 Ga) provides a maximum age for deposition of sediments, which subsequently were metamorphosed. Neoarchaean and Palaeoproterozoic ages, identified in both groups, are also observed in detrital zircons of the Bothnian basin and the Bergslagen area of the Fennoscandian Shield (Claesson et al., 1993; Sultan et al., 2005; Bergman et al., 2008; Kathol et al., 2020).

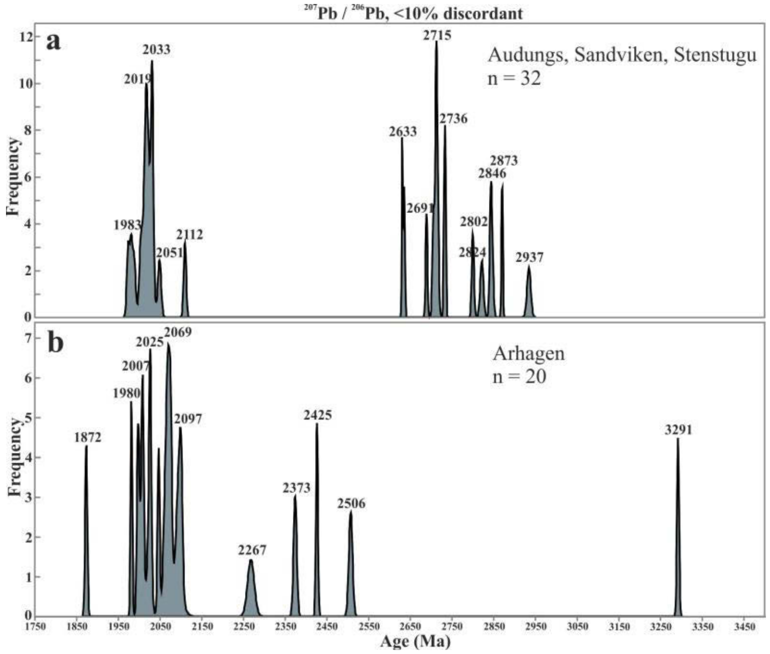


Figure 3. Probability-density distribution plots (PDP) in the 1750–3500 Ma interval from Gotland with calculated maximum probability ages for distinct distribution peaks of **a.** a combined zircon population from Audungs, Sandviken and Stenstugu and **b.** a zircon population from Arhagen, using ^{207}Pb/^{206}Pb single zircon ages. The diagrams include only <10% discordant spots. Frequency shows a number of analyses.

The oldest crystal (3.29 Ga), observed in the Arhagen drill core sample (northern Gotland, Figure 3), has a weak zonation within a homogeneous interior, which may indicate that this grain has undergone several erosional cycles. This age is not represented among the detrital zircons of the Svecofennian Domain, however sedimentary rocks in the WLG and NE Poland contain Archaean zircons ranging from 3.5 to 2.6 Ga, which triggered Bogdanova et al. (2015) to suggest a continental source somewhere in the present south (Sarmatia). However, the Sarmatian plate had been separated from the Svecofennian terranes by an ocean until the Fenno-Sarmatian collision at 1.82-1.80 Ga (Elming et al., 2010; Lahtinen et al., 2009). According to Mints et al. (2020) and Mints and Eriksson (2016), another palaeocontinent, Lauroscandia, was stable in the Neoarchaean and Palaeoproterozoic (2.5~1.8 Ga). It was composed of the Superior craton, Karelia, Kola, South-Baltia and Volgo-Uralia. The Wyoming Province, which is a part of the Superior craton, contains Palaeo- and Mesoarchaean TTG gneisses of 3.6–2.95 Ga, which could be a source for the 3.29 Ga zircon core. In this case, sedimentation could not have taken place from the present south, but from the west, along the coastline of the same continent.

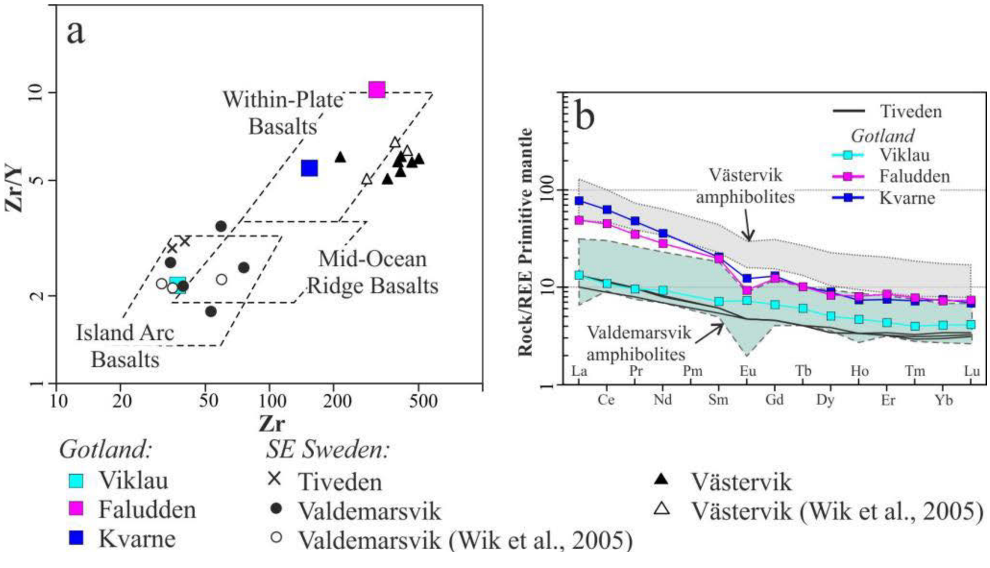


Figure 4. Selected geochemistry diagrams for amphibolite from Gotland and reference areas in southeastern Sweden. **a.** Zr/Y vs. Zr diagram after Pearce and Norry (1979). **b.** Primitive mantle-normalized REE abundances after McDonough and Sun (1995). Green area – Valdemarsvik amphibolites; grey area – Västervik amphibolites.

The Viklau amphibolite (central Gotland), together with the amphibolites in the Tiveden and Valdemarsvik regions (southeastern Sweden), forms a distinct population with an island arc basalt affinity (Figure 4a). These rocks are depleted in LREE and HREE and either lack Eu anomaly or have a rather pronounced negative anomaly (Figure 4b). In turn, petrological and geochemical data, as well as the U-Pb ages of the orthogneisses at Skäggs (1.90 Ga) and När (1.88 Ga) on central Gotland, show that they can be correlated with the Svecofennian orthogneiss south of Valdemarsvik in southeastern Sweden (Hulta; Figure 5a and b). The latter sample was collected in the same outcrop (“site 1” by Stephens and Andersson (2015)) as a grey granodioritic orthogneiss of 1.88 Ga. An amphibolite-granitoid complex can be traced from the Valdemarsvik area through central Gotland towards the drill hole P6-1 offshore the Latvian coast, but it is absent in the coastlands of Latvia (Paper IV).

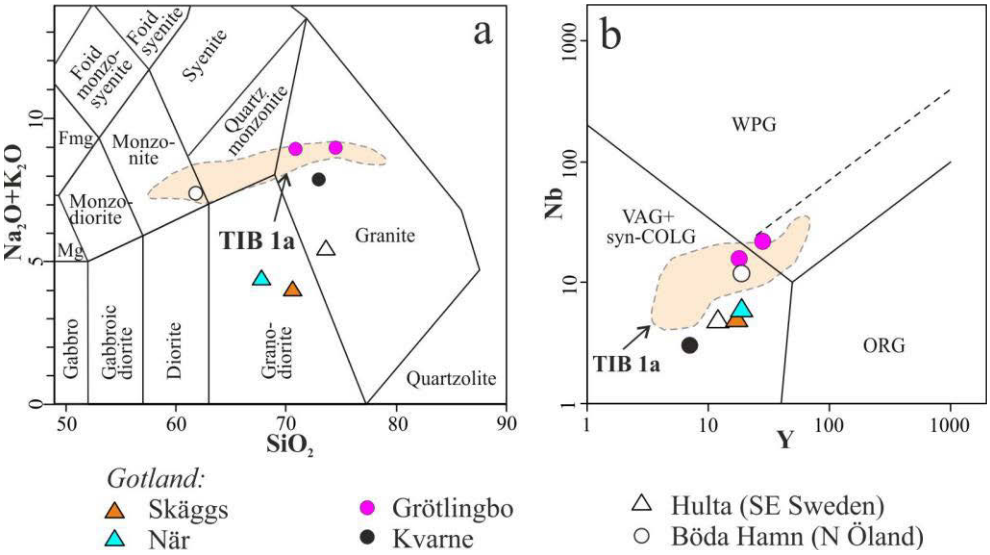


Figure 5. Selected geochemistry diagrams for granitoids from Gotland and reference areas in southeastern Sweden and northern Öland. **a.** TAS classification diagram after Middlemost (1994). **b.** Nb vs. Y diagram after Pearce et al. (1984). Fmg – foid monzogabbro; Mg – monzogabbro. Orange area – TIB 1a granites.

Two fine-grained amphibolites observed in the Faludden and Kvarne drill cores (southern Gotland) differ from the Valdemarsvik amphibolites, and can be correlated with the Västervik amphibolites in southeastern Sweden. The latter plot close to the within-plate basalt field and have a steep REE pattern with a moderate negative Eu anomaly (Figure 4a and b). Compared to the Västervik amphibolites, the Faludden and Kvarne amphibolites are significantly disturbed, which caused extensive remobilization of major (Si and K) and trace elements (Rb) and destruction of the Rb-Sr isotope system. This can be explained by infiltration of hydrothermal solutions from intrusions bordered by metamorphic rocks (Jiang et al., 2005). Alternatively, Si, K and Rb can be enriched during deformation (Condie and Sinha, 1996). Granitic rocks were observed in the same drill core as the Kvarne amphibolite, while Faludden is located close to the granitic intrusion at Hamra (Paper IV).

The study has shown that the coarse-grained granitoid at Frigsarve (southern Gotland) has an age of 1.85 Ga. This age is comparable with the 1.86-1.85 Ga felsic rocks belonging to the oldest generation of the Transscandinavian Igneous Belt (TIB 0; e.g. Åberg and Wikström, 1983; Andersson, 1997; Ahl et al., 2001). Inherited cores with 1.85 Ga ages were also observed in the 1.81 Ga Kvarne granite (15 km SW of Frigsarve), in the 1.48 Ga Grötlingbo granite (8 km NE of Frigsarve) and in the E6-1 migmatitic orthogneiss 30 km west of the Latvian coast. These observations suggest that the TIB 0 granitoids intruding the Västervik amphibollites dominate the area south of the Valdemarsvik amphibolite-granitoid complex. It is assumed that the LLDZ, separating the Valdemarsvik amphibolite-granitoid complex from the TIB 0 granitoids in Loftahammar in southeastern Sweden, can be traced in the Precambrian beneath southern Gotland and further southeast towards Liepaja along the Latvian coast (Papers I, II and IV).

Emplacement of the 1.85 Ga TIB 0 granitoids within an Andean-type active continental margin was simultaneous with the formation of the 1.85 Ga Fröderyd Group within the Vetlanda-Oskarshamn belt. The Fröderyd Group represents a rifted volcanic arc implied by the occurence of pillowed and massive mafic volcanic rocks with a mid-ocean ridge basalt affinity (Sundblad et al., 1997). An unusually high proportion of felsic volcanic rocks and lack of sheeted dykes and ultramafic rocks suggests a submarine rift distinct from an ophiolitic setting (Sundblad et al., 1997; Beunk and Page, 2001; Mansfeld et al., 2005). Subsequent development of the volcanic arc complex comprises emplacement of tonalites and granodiorites at Bäckaby, Eksjö and Virserum between 1.83 and 1.82 Ga (Mansfeld, 1991; Åhäll et al., 2002; Wik et al., 2003). Tectonic uplift and rapid erosion at ca. 1.82 Ga resulted in the formation of lacustrine sediments in restricted basins, now found in the Vetlanda region (Paper III).

Based on the age, sedimentation style and intercalated volcanic rocks, it can be inferred that the Västervik and Vetlanda metasedimentary sequences formed in two different geological environments during two separate events. The 1.87-1.86 Ga Västervik quartzites were deposited along a continental margin (Russell, 1967; Sultan and Plink-Björklund, 2006) and were intercalated with mafic volcanic rocks. While the ca. 1.82 Ga Vetlanda formation is dominated by quartz-plagioclase arkoses and conglomerates (Persson, 1989), indicating a shallow water (and not necessarily marine) environment; the absence of limestone may suggest a lacustrine environment. The Vetlanda metasediments are intercalated with felsic volcanic rocks (Paper III).

Continuous magmatic activity along the active continental margin caused intrusion of the TIB 1a granites at 1.81-1.79 Ga north of the Vetlanda-Oskarshamn belt (Vimmerby Batholith). A granite at Kvarne (southern Gotland) yielded a U-Pb zircon age of 1.81 Ga and a quartz monzodiorite at Böda Hamn (northern Öland) yielded a U-Pb zircon age of 1.80 Ga. Both granitoids are characterized by the similar petrological and geochemical properties as the TIB 1a granitoids at Äspö and Ramnebo. Furthermore, the Vimmerby Batholith is characterized by high magnetic anomalies on the regional magnetic field maps, which shows that the TIB 1a granites can be followed in the Precambrian basement of the Baltic Sea. Compared to the Skäggs-När-Hulta (south of Valdemarsvik) population, the Kvarne and Böda Hamn rocks have granitic and monzonitic compositions, but with significantly higher alkali contents. (Papers I and IV).

TIB 1b (the Växjö Batholith) intruded at 1.79-1.77 Ga between the Vetlanda-Oskarshamn belt and the Blekinge Province and can followed further to the north of lake Vättern into the Filipstad region. On regional magnetic field maps, a high magnetic anomaly, belonging to the Vimmerby Batholith, grades into an inhomogeneous pattern of the Växjö Batholith. Based on petrological and geochemical data, a 1.79 Ga quartz monzonite at Valsnäs can be correlated with the TIB 1b granites in the Växjö area, which shows that the TIB 1b granites can be followed in the Precambrian basement beneath central and southern Öland and further beneath the Baltic Sea (Paper I).

The Pomerania-Blekinge belt is composed of 1.77-1.75 Ga deformed granitoids (Krzemińska et al., 2017; 2018). Geochemical and geochronological data, together with the deformation observed in the E7-1 and D1-1 granodiorites, suggest that this region can be extended into the eastern parts of the Baltic Sea towards the Lithuanian coast (Paper I).

Petrological and geochemical data show that the 1.45 Ga Grötlingbo and 1.47 Ga Hamra granites belong to the 1.5 Ga population, represented by the Götemar, Figeholm and Blå Jungfrun granites (Paper IV) related to the Danopolonian orogeny.

In general, the evolution of the southwestern margin of the Svecofennian Domain can be summarized as a sequence of a schematic profiles depicted in Figure 6 (Paper III).

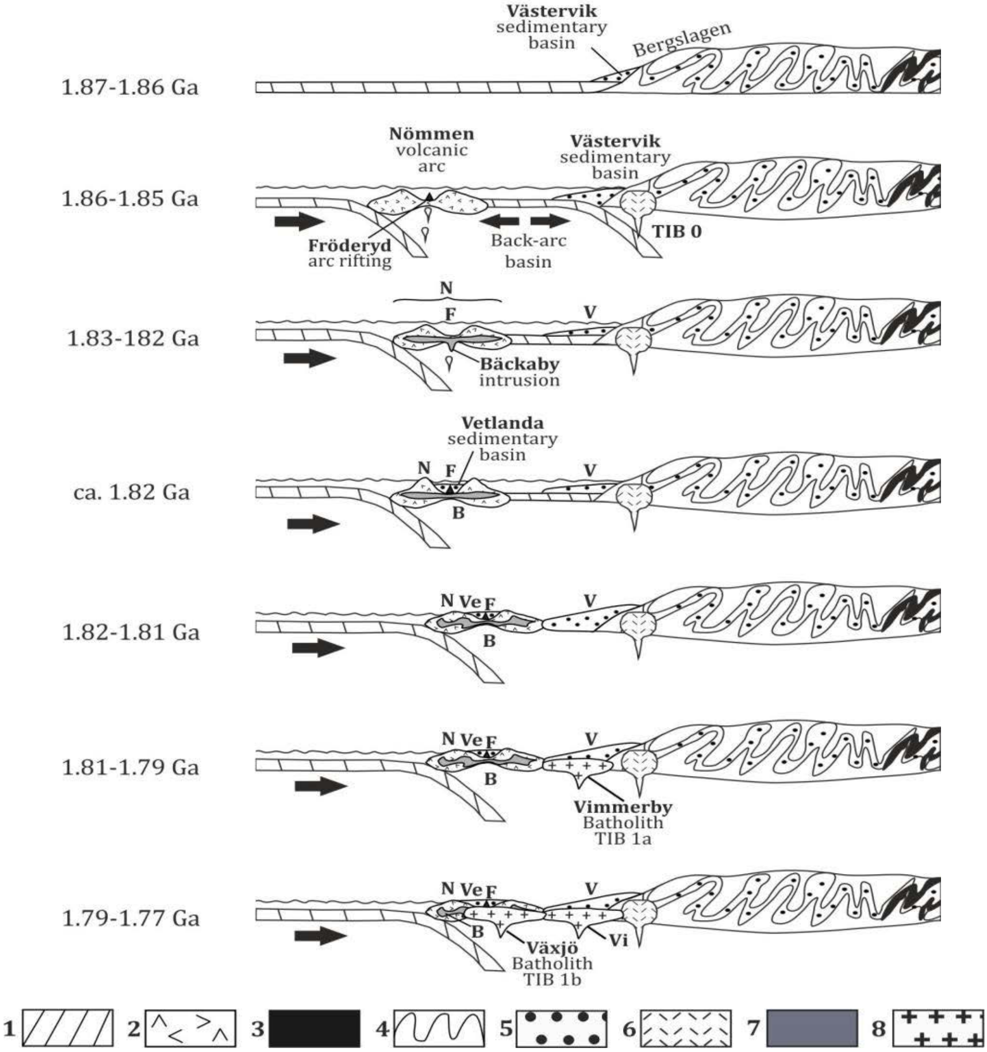


Figure 6. Schematic profiles depicting the 1.87-1.77 Ga evolution of the southwestern active margin to the Fennoscandia proto-continent (not to scale). 1 – oceanic crust, 2 – andesitic and basaltic volcanic rock and amygdaloidal lava, 3 – basaltic volcanic rock and/or pillow lava, 4 – metamorphosed and affected by polyphase ductile deformation crust, 5 – sedimentary rock, 6 – TIB 0 granitoid, 7 – Bäckaby tonalite, 8 – TIB 1 granitoid. B – Bäckaby tonalite, F – Fröderyd volcanic arc rifting, N – Nömmen volcanic arc, TIB – Transscandinavian Igneous Belt, Ve – Vetlanda sedimentary rock, V – Västervik quartzite, Vi – Vimmerby Batholith.

6 Summary

The evolution of the southwestern margin of the Svecofennian Domain can be represented by a sequence of belts formed within various tectonic environments. These belts are traced from well-exposed parts of the Svecofennian Domain in southeastern Sweden through the concealed basement beneath the Baltic Sea towards Latvia, Lithuania and Poland. These belts include:

1. A metasedimentary unit can be traced from the coastal areas south of Stockholm to northern Gotland and to western Estonia.
2. An amphibolite-granitoid volcanic arc unit can be traced from the Valdemarsvik area through central Gotland towards the Latvian offshore regions. Its southern limit is confined to the Linköping-Loftahammar Deformation Zone.
3. The Västervik unit is composed of metasedimentary rocks intercalated with the metabasalts. It is located between the LLDZ in the north and the TIB 1a granitoids in the south and can be followed from the Västervik area through southern Gotland.
4. The TIB 0 granitoids were emplaced into the Västervik unit in an Andean-type active continental margin setting. This magmatic activity took place simultaneously with magmatic activity within the Fröderyd/Nömmen volcanic arc located outboard the southwestern margin of the Svecofennian Domain.
5. The area south of the Västervik unit is occupied by the TIB 1 generation of granitoids (a, b and c), emplaced within a continued Andean-type active continental margin setting.
6. The Transscandinavian Igneous Belt units are stiched by the younger granitic plutons related to the Danopolonian orogeny.

Acknowledgements

It is a pleasure for me to thank all those people who made this dissertation possible and who helped to take one more step towards a mature science. First of all, I would like to thank my supervisor, Prof. Krister Sundblad, who initiated this project and suggested such an interesting study area for my research. I really appreciate his inspiration and support without which my work, which started with a pile of dusty boxes and the words “they were waiting for you for twenty years” would have never been done. I would also like to thank my co-supervisor, Jeremy Woodard, for great encouragement and assistance from the technical and analytical point of view. Some of our ideas (like air abrasion of biotites), which I enthusiastically tried to bring to life, would be easily accepted to a *Journal of failed experiments*, if such existed, but in overall this did not obstruct from the final result, instead made the whole research process more exciting and intriguing.

My colleagues (and friends) at the Department of Geography and Geology, University of Turku, are thanked for heartwarming atmosphere. Particularly, Arto Peltola who always eagerly prepared thin sections in spite of permanent workload is acknowledged, and Markku Väisänen who taught me how to separate zircons. Without zircons, I would still waiting for Ar-Ar results from K-feldspars and biotites, which were sent six years ago to a laboratory for an analysis. My special thanks to my office mates Heider Al Humadi, Jaakko Kara and Satu Koivisto (archeology) for help and interesting conversations on geologic (and not only) topics.

Geological Survey of Latvia, Lithuania and Sweden are acknowledged for providing study material, and especial thanks to Gedeminas Motuza and Gražina Skridlaitė (Vilnius University). The Geological Survey of Finland (GTK) is acknowledged for support and providing access to the laboratory facilities, and especially I would like to thank Hugh O’Brien, Yann Lahaye, Bo Johansson, Marja Lehtonen, Sari Lukkari and Irmeli Mänttäri. I would like to acknowledge Martin Whitehouse and Kerstin Lindén from the NORDSIMS facility for assistance before and during the laboratory work.

I would like to thank all reviewers (anonymous and not) who provided “substantial and exhaustive reviews” of the articles and especially editors finding reviewers, when a suggested list was already not enough. Without these people, any study would be too easy.

At the end, I would like to thank my family, and especially my granny who unintentionally pushed me to finish this work. I am extremely grateful to my mother-in-law, who was ready to help at any moment when needed. I cannot overemphasize my deep gratitude to my husband, Alexander, who stayed with our daughters, Riikka and Agata, when I was absent, and who always supported, encouraged and believed in me, sometimes even more than I did.

Turku, 30 June 2021 Evgenia Salin

Evgenia Salin

List of References

Åberg, G. & Wikström, A., 1983. Radiometric dating of the postorogenic Graversfors granite, south central Sweden. *Geologiska Föreningens i Stockholm Förhandlingar,* 104, p. 225–230.

Åhäll, K.-I., Connelly, J.N. & Brewer, T.S., 2002. Transitioning from Svecofennian to Transcandinavian Igneous Belt (TIB) magmatism in SE Sweden: implications from the 1.82 Ga Eksjö tonalite. *GFF*, 124, p. 217–224.

Ahl, M., 1989. Zn-Pb-Cu-mineraliseringarna vid Ramnebo, sydöstra Sverige, och deras genetiska relation till Smålandsgraniten. Stockholm Univ., Sweden, 26 pp. [MSc thesis]

Ahl, M., Bergman, S., Bergström, U., Eliasson, T., Ripa, M. & Weihed, P., 2001. Geochemical classification of plutonic rocks in central and northern Sweden. *Sveriges Geologiska Undersökning*, Rapporter och Meddelanden 106, 82 pp.

Ahl, M., Sundblad, K. & Schöberg, H., 1999. Geology, geochemistry, age and geotectonic evolution of the Dala granitoids, central Sweden. *Precambrian Research,* 95, p. 147-166.

Allen, R.L., Weihed, P. & Svenson, S.A., 1996a. Setting of Zn-Cu-Au-Ag massive sulfide deposits in the evolution and facies architecture of a 1.9 Ga marine volcanic arc, Skellefte District, Sweden. *Economic Geology*, 91, p. 1022–1053.

Allen, R.L., Lundström, I., Ripa, M., Simeonov, A., Christofferson, H., 1996b. Facies analysis of a 1.9 Ga, continental margin, back-arc, felsic caldera province with diverse Zn-Pb-Ag-(Cu-Au) sulfide and Fe oxide deposits, Bergslagen region, Sweden. *Economic Geology*, 91, p. 979–1008.

Anderegg, H.J., Skoglund, R., Norling, E. & Kjellström, G., 1968. Outline of the Swedish exploration venture for hydrocarbons, Unpublished report. *Geological Survey of Sweden*, pp. 21.

Andersson, U.B., 1997. Petrogenesis of some Proterozoic granitoid suites and associated basic rocks in Sweden (geochemistry and isotope geology). *Sveriges Geologiska Undersökning*, Rapporter och Meddelanden 91, 216 pp.

Andersson, U.B., Högdahl, K., Sjöström, H. & Bergman, S., 2006. Multistage growth and reworking of the Palaeoproterozoic crust in the Bergslagen area, southern Sweden: evidence from U-Pb geochronology. *Geological Magazine*, 143, p. 679–697.

BABEL Working group, 1993. Deep seismic reflection/refraction interpretation of crustal structure along BABEL profiles A and B in the southern Baltic Sea. *Geophysical Journal International,* 112, p. 325–343.

Berthelsen, A., 1992. Mobile Europe. In: Blundell, D., Freeman, R., Mueller, S. (Eds.), A Continent Revealed: The European Geotraverse. Cambridge University Press, pp. 17–33.

Beunk, F.F. & Page, L.M., 2001. Structural evolution of the accretional continental margin of the Paleoproterozoic Svecofennian orogen in southern Sweden. *Tectonophysics*, 339, 67–92.

Bogdanova, S., Gorbatschev, R., Grad, M., Janik, T., Guterch, A., Kozlovskaya, E., Motuza, G., Skridlaite, G., Starostenko, V. & Taran, L., 2006. EUROBRIDGE: new insight into the geodynamic evolution of the East European Craton. In: Gee, D.G., Stephenson, R.A. (Eds.), European Lithosphere Dynamics. Geol. Soc. Lond., Memoirs, pp. 599–625.

Bogdanova, S., Gorbatschev, R., Skridlaite, G., Soesoo, A., Taran, L. & Kurlovich, D., 2015. Trans-Baltic Palaeoproterozoic correlations towards the reconstruction of supercontinent Columbia/Nuna. *Precambrian Research*, 259, p. 5–33.

Claesson, S., Bogdanova, S.V., Bibikova, E.V. & Gorbatschev, R., 2001. Isotopic evidence of Palaeoproterozoic accretion in the basement of the East European Craton. *Tectonophysics*, 339, p. 1–18.

Claesson, S., Huhma, H., Kinny, P.D. & Williams, I.S., 1993. Svecofennian detrital zircon ages–implications for the Precambrian evolution of the Baltic Shield. *Precambrian Research*, 64, p. 109–130.

Claesson, S. & Lundqvist, T., 1995. Origins and ages of Proterozoic granitoids in the Bothnian Basin, central Sweden; isotopic and geochemical constraints. *Lithos*, 36, p. 115–140.

Condie, K.C. & Sinha, A.K., 1996. Rare earth and other trace element mobility during mylonitization: a comparison of the Brevard and Hope Valley shear zones in the Appalachian Mountains, USA. *Journal of Metamorpic Geology*, 14, p. 213–226.

Eliasson, T. & Sträng, T., 1998. Kartbladen 23H Stensele. In C.-H. Wahlgren (ed.): Regional berggrundsgeologisk undersökning, Sammanfattning av pågående undersökningar 1997. *Sveriges geologiska undersökning*, Rapporter och Meddelanden 97, p. 55–59. [In Swedish]

Elming, S.Å., Shumlyanskyy, L., Kravchenko, S., Layer, P. & Söderlund, U., 2010. Proterozoic Basic dykes in the Ukrainian Shield: A palaeomagnetic, geochronologic and geochemical study – The accretion of the Ukrainian Shield to Fennoscandia. *Precambrian Research*, 178, p. 119–135.

Gaál, G. & Gorbatschev, R., 1987. An outline of the Precambrian evolution of the Baltic Shield. *Precambrian Research*, 35, p. 15–52.

Gorbatschev, R., 1962. The Pre-Cambrian sandstone of the Gotska Sandön boring core. *Geological Institutions of the University of Uppsala*, Bulletin 39, 32 pp.

Gorbatschev, R., 2004. The Transscandinavian Igneous Belt-introduction and background. In: Högdahl, K., Andersson, U. & Eklund, O., (eds.): The Transscandinavian Igneous Belt (TIB) in Sweden: a review of its character and evolution. *Geological Survey of Finland*, Special Paper, 37, p. 9–15.

Gorbatschev, R. & Bogdanova, S., 1993. Frontiers in the Baltic shield. *Precambrian Research*, 64, p. 3–21.

Grigelis, A. (Ed.), 1991. Geology and Geomorphology of the Baltic Sea: Explanatory Note of the Geological Maps, Scale 1: 500000. Nedra, Leningrad, 420 pp. [In Russian]

Guggisberg, B., Kaminski, W. & Prodehl, C., 1991. Crustal structure of the Fennoscandian Shield: a traveltime interpretation of the long-range FENNOLORA seismic refraction profile. *Tectonophysics*, 195, p. 105–137.

Gyllencreutz, R., 1998. A ground magnetometric survey on south-central Gotland, Sweden. In: Stockholm University, Sweden, 29 pp. [M.Sc. thesis]

Hedström, H., 1923. Remarks on some fossils from the diamond boring at the Visby cement factory. *SGU* C 314, 26 pp.

Hessland, I., 1949. Investigations of the Lower Ordovician of the Siljan district Sweden. 4. Lithogenesis and changes of level in the Siljan district during a period of the Lower Ordovician. Bulletin of the Geological Institution of the University of Upsala, 33, p. 437–510.

Hessland, I., 1955. Studies in the lithogenesis of the Cambrian and basal Ordovician of the Böda Hamn sequence of strata. Bulletin of the Geological Institution of the University of Upsala, 35, p. 35–109.

Högdahl, K., Andersson, U. & Eklund, O., 2004. The Transscandinavian Igneous Belt (TIB) in Sweden: a review of its character and evolution. *Geological Survey of Finland*, Special Paper 37, 125 pp.

Jarl, L.-G. & Johansson, Å., 1988. U-Pb zircon ages of granitoids from the Småland-Värmland granite-porphyry belt, southern and central Sweden. *Geologiska Föreningens i Stockholm Förhandlingar*, 110, p. 22–28.

Johansson, Å., 2016. U-Pb SIMS dating of some granitoids from eastern Blekinge, southern Sweden. *GFF*, 138, p. 430–444.

Johansson, Å., Bogdanova, S. & Čečys, A., 2006. A revised geochronology for the Blekinge province, southern Sweden. *GFF*, 128, p. 287–302.

Kathol, B., Hansen Serre S. & Thomsen T.B., 2020. Provenance of Svecofennian sedimentary rocks in Bergslagen and surrounding areas. *SGU* report 2020:22.

Kähkönen, Y., 2005. Svecofennian supracrustal rocks. In: Lehtinen, M., Nurmi, P.A.,Rämö, O.T. (Eds.), Precambrian Geology of Finland – Key to the Evolution of theFennoscandian Shield. Elsevier, Amsterdam, pp. 343–406.

Kirs, J., Puura, V., Soesoo, A., Klein, V., Konsa, M., Koppelmaa, H., Niin, M & Urtson, K., 2009. The crystalline basement of Estonia: rock complexes of the Palaeoproterozoic Orosirian and Statherian and Mesoproterozoic Calymmian periods, and regional correlations. *Estonian Journal of Earth Science*, 58, p. 219–228.

Kornfält, K.-A., 1996. U-Pb zircon ages of six granite samples from Blekinge County, south-eastern Sweden. In: Lundqvist, T. (Ed.), Radiometric Dating Results 2. *Sveriges Geologiska Undersökning C*, pp. 15–31.

Kornfält, K.-A., Persson, P.-O. & Wikman, H., 1997. Granitoids from the Äspö area, southeastern Sweden – geochemical and geochronological data. *GFF*, 119, p. 109–114.

Kleinhanns, I.C., Whitehouse, M.J., Nolte, N., Baero, W., Wilsky, F., Hansen, B.T. & Schoenberg, R., 2015. Mode and timing of granitoid magmatism in the Västervik area (SE Sweden, Baltic Shield): Sr–Nd isotope and SIMS U-Pb age constraints. *Lithos*, 212–215, p. 321–337.

Krzemińska, E., Krzemiński, L., Petecki, Z., Wiszniewska, J., Salwa, S., Żaba, J., Gaidzik, K., Williams, I.S., Rosowiecka, O., Taran, L., Johansson, Å., Pécskay, Z., Demaiffe, D., Grabowski, J. & Zieliński, G., 2017. Geological map of crystalline basement in the Polish part of the East European Platform 1:1 000 000. *Polish Geological Institute*, Warsaw.

Krzemińska, E., Krzemiński, L., Wiszniewska, J., Johansson, Å. & Williams, I.S., 2018. Analogous Late Paleoproterozoic basement in Pomerania (N. Poland) and Blekinge (S. Sweden) – the isotopic evidences. The 33rd Nordic Geological Winter Meeting, Copenhagen.

Lahtinen, R., Huhma, H., Kontinen, A., Kohonen, J. & Sorjonen-Ward, P., 2010. Newconstraints for the source characteristics, deposition and age of the 2.1–1.9 Ga metasedimentary cover at the western margin of the Karelian Province. *Precambrian Research*, 176, p. 77–93.

Lahtinen, R., Korja, A., Nironen, M. & Heikkinen, P., 2009. Palaeoproterozoic accretionary processes in Fennoscandia. *Geological Society of London*, Special Publication, 318, p. 237–256.

Larson, S.Å. & Berglund, J., 1992. A chronological subdivision of the Transscandinavian Igneous Belt – three magmatic episodes? *Geologiska Föreningens i Stockholm Förhandlingar*, 114, p. 459–461.

Lindh, A., Krauss, M. & Franz, K.-M., 2001. Interpreting the Småland-Blekinge deformation zone from chemical and structural data. *GFF*, 123, p. 181–191.

Ludwig, K.R., 2003. User's manual for Isoplot 3.00: a geochronlogical toolkit for Microsoft Excel. *Berkeley Geochronlogy Center*, Special Publication, 4, p. 25–32.

Lund, C.-E., Gorbatschev, R. & Smirnov, A., 2001. A seismic model of the Precambrian crust along the coast of southeastern Sweden: the coast profile wide-angle airgun experiment and the southern part of FENNOLORA revisited. *Tectonophysics*, 339, p. 93–111.

Lundqvist, T., Vaasjoki, M. & Persson P.-O., 1998. U–Pb ages of plutonic and volcanic rocks in the Svecofennian Bothnian Basin, central Sweden, and their implications for the Palaeoproterozoic Evolution of the Basin. *GFF*, 120, p. 357–363.

Mansfeld, J., 1991. U-Pb age determinations of Småland-Värmland granitoids in Småland, southeastern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar*, 113, p. 113–119.

Mansfeld, J., 1996. Geological, geochemical and geochronological evidence for a new Palaeoproterozoic terrane in southeastern Sweden. *Precambrian Research*, 77, p. 91–103.

Mansfeld, J., Beunk, F.F. & Barling, J., 2005. 1.83–1.82 Ga formation of a juvenile volcanic arc – implications from U–Pb and Sm–Nd analyses of the Oskarshamn-Jönköping Belt, southeastern Sweden. *GFF*, 127, p. 149–157.

McDonough, W.F. & Sun, S.S., 1995. The composition of the Earth. *Chemical Geology*, 120, p. 223–253.

Meissner, R., Snyder, D., Balling, N. & Staroste, E. (Eds.), 1992. The BABEL Project: First Status Report. Commission of the European Communities, Directorate-General Science, Research and Development, Brussels, pp. 155.

Middlemost, E.A., 1994. Naming materials in the magma/igneous rock system. *Earth-Science Reviews*, 37(3-4), p. 215–224.

Mints, M.V., & Eriksson, P.G., 2016. Secular changes in relationships between plate-tectonic and mantle-plume engendered processes during Precambrian time. *Geodynamics & Tectonophysics*, 7(2), p. 173–232.

Mints, M.V., Glaznev, V.N., Muravina, O.M. & Sokolova, E.Y., 2020. 3D model of Svecofennian Accretionary Orogen and Karelia Craton based on geology, reflection seismics, magnetotellurics and density modelling: Geodynamic speculations. *Geoscience Frontiers*, 11(3), p. 999–1023.

Motuza, G., Motuza, V., Salnikova, E. & Kotov, A., 2008. Extensive charnockitic-granitic magmatism in the crystalline crust of West Lithuania. *Geologija*, 50, p. 1–16.

Nyström, J.O., 1982. Post-Svecokarelian andinotype evolution in central Sweden. *Geologische Rundschau*, 71, p. 141–157.

Nironen, M. & Kurhila, M., 2008. The Veikkola granite area in southern Finland: emplacement of a 1.83-1.82 Ga plutonic sequence in an extensional regime. *Geological Survey of Finland*, Bulletin 80, p. 39–68.

Öhlander, B. & Zuber, J., 1988. Genesis of the Fellingsbro-type granites: evidence from gravity measurements and geochemistry. *Geologiska Föreningens i Stockholm Förhandlingar*, 110, p. 39–54.

Patchett, P.J., Todt, W. & Gorbatschev, R., 1987. Origin of Continental Crust of 1.9-1.7 Ga age: Nd isotopes in the Svecofennian orogenic terrains of Sweden. *Precambrian Research*, 35, p. 145–160.

Pavlov, L.A., 1989. Results of parametrical drilling of borehole #1 within the Grigorievskaya area (Baltic Sea). State Geology Archive, Latvian environment, geology and meteorology centre, unpublished report 11378, 207 pp.

Pearce, J.A., Harris, N.B., & Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology*, 25(4), p. 956–983.

Pearce, J.A. & Norry, M.J., 1979. Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. *Contributions to Mineralogy and Petrology*, 69, p. 33–47.

Persson, L., 1989. Beskrivning till berggrundskartorna Vetlanda SV och SO. *Geological Survey of Sweden*, Af 170-171, 130 pp.

Persson, L. & Wikman, H., 1986. Provisoriska översiktliga berggrundskartan Jönköping. *Sveriges Geologiska Undersökning*, Ba 39. Map in the scale 1:250 000.

Persson, P.-O. & Wikström, A., 1993. A U-Pb dating of the Askersund granite and its marginal augen gneiss. *Geologiska Föreningens i Stockholm Förhandlingar*, 115, p. 321–329.

Puura, V., Vaher, R., Klein, V., Koppelmaa, H., Niin, M., Vanamb, V. & Kirs, J., 1983. The crystalline basement of Estonia. [Kristallicheskij fundament Estonii]. Nauka, Moscow, 208 pp. [in Russian]

Röshoff, K., 1975. Some aspects of the Precambrian in southeastern Sweden in the light of a detailed geological study of the Lake Nömmen area. *Geologiska Föreningens i Stockholm Förhandlingar*, 97, p. 368–378.

Russell, R.V., 1967. Paleocurrent analysis in deltaic Precambrian meta-sedimentary rocks from Västervik. Sweden. *Geologiska Föreningens i Stockholm Förhandlingar*, 89, p. 105–115.

Salin, 2014. Petrology and lead isotopic composition of rocks of the Precambrian basement under Gotland and adjacent offshore regions of the Baltic Sea. University of Turku, Master's thesis

Salin, E., Sundblad, K. & Woodard, J., 2020. Distribution, age, geochemistry and origin of "anorogenic" granites in the Baltic Sea region. Abstract volume, 34th Nordic Geological Winter Meeting, Oslo, 189–190.

Skiöld, T., 1988. Implications of new U-Pb zircon chronology to early Proterozoic crustal accretion in northern Sweden. *Precambrian Research*, 38, p. 147–164.

Skridlaite, G.,Whitehouse,M., Bogdanova, S. & Taran, L., 2011. The 1.86–1.84 Ga magmatism in the Western East European Craton (Lithuania): implications for a convergent continental Margin. Mineralogical Magazine, Goldschmidt Conference Abstracts, vol. 75 (3), p. 1890.

Stephens, M.B. & Andersson, J., 2015. Migmatization related to mafic underplating and intra- or back-arc spreading above a subduction boundary in a 2.0–1.8 Ga accretionary orogen. Sweden. *Precambrian Research*, 264, p. 235–257.

Sultan, L. & Plink-Björklund, P., 2006. Depositional environments at a Palaeoproterozoic continental margin, Västervik Basin. SE Sweden. *Precambrian Research*, 145, p. 243–271.

Sundblad, K., 1996. The Precambrian crust underneath Gotland. Abstract, Eurobridge workshop, Oskarshamn, Sweden, June 1996.

Sundblad, K., Claesson, S. & Gyllencreutz, R., 2003. The Precambrian of Gotland - a key to the understanding of the geologic environment for granitoids in the Baltic Sea region. In: Granitic Systems - State of the Art and Future Avenues, Helsinki, Abstract Volume, pp. 102–106.

Sundblad, K., Mansfeld, J. & Särkinen, M., 1997. Palaeoproterozoic rifting and formation of sulphide deposits along the southwestern margin of the Svecofennian Domain, southern Sweden. *Precambrian Research*, 82, p. 1–12.

Thomsen, T.B., Heijboer, T., & Guarnieri, P., 2016. jAgeDisplay: software for evaluation of data distributions in U-Th-Pb geochronology. *Geological Survey of Denmark and Greenland (GEUS)*, Bulletin 35, p. 103–106.

Thorslund, P., 1958. Djupborrningen på Gotska Sandön. *Geologiska Föreningens i Stockholm Förhandlingar*, 80, 190–197. [In Swedish, with English abstract]

Thorslund, P. & Westergård, A.H., 1938. Deep boring through the Cambro-Silurian at File Hajdar, Gotland. *SGU*, C 415, 48 p.

Vivallo, W. & Rickard, D., 1984. Early Proterozoic ensialic spreading-subsidence: evidence from the Garpenberg enclave, Central Sweden. *Precambrian Research*, 26, 203–221.

Wasström, A., 2005. Petrology of a 1.95 Ga granite–granodiorite–tonalite–trondhjemite complex and associated extrusive rocks in the Knaften area, northern Sweden. *GFF*, 127, p. 67–82.

Weihed, P., Billström, K., Persson, P.-O. & Bergman Weihed, J., 2002. Relationship between 1.90–1.85 Ga accretionary processes and 1.82–1.80 Ga oblique subduction at the Karelian craton margin, Fennoscandian Shield, *GFF*, 124(3), p. 163–180.

Wik, N.-G., Bergström, U., Bruun, Å., Claeson, D., Jelinek, C., Juhojuntti, N., Kero, L., Lundqvist, L., Stephens, M.B., Sukotjo, S. & Wikman, H., 2005. Beskrivning till regional berggrundskarta över Kalmar län. *Geological Survey of Sweden* Ba 66.

Wik, N.-G., Bergström, U., Claeson, D., Juhojuntti, N., Kero, L., Lundqvist, L., Petersson, J., Sukotjo, S., Wedmark, M. & Wikman, H., 2003. Regionala kartor 1:250 000. Projekt Småland regional berg. In Delin, H. (Ed.): Berggrundsgeologisk undersökning. Sammanfattning av pågående verksamhet 2002. *Geological Survey of Sweden*, Rapporter och Meddelanden 112, 96–116.

Wiklander, U., 1974. Precambrian petrology, geochemistry and age relations of northeastern Blekinge, southern Sweden. *Sveriges Geologiska Undersökning*, C 704, 142 pp.

Wikman, H., 1993. U-Pb ages of Småland granites and a Småland volcanite from the Växjö region, southern Sweden. In: Lundqvist, T. (Ed.), Radiometric Dating Results, *Sveriges Geologiska Undersökning C*, pp. 65–72.

Wikman, H., 1998. Beskrivning till berggrundskartorna Växjö SV och SO, 1:50 000. *Sveriges Geologiska Undersökning*, Af 188, Af 200 90.

Wikman, H., 2000. Beskrivning till berggrundskartorna 5E Växjö NO och NV. *Sveriges Geologiska Undersökning*, Af 201, Af 216 108.

Wikman, H. & Kornfält, K.-A., 1995. Updating of a lithological model of the bedrock of the Äspö area. *Geological Survey of Sweden*, Progress Report 25-95-04, 105 pp.

Wikström, A., 1991. Structural features of some younger granitoids in central Sweden and implications for the tectonic subdivision of granitoids. *Precambrian Research*, 51, p. 151–159.

Wikström, A. & Persson, P.-O., 2002. A c. 1845 Ma ("Askersund") age of the Hälla augen gneiss in south-eastern Östergötland, south-east Sweden. In: Bergman, S. (Ed.), Radiometric Dating Results 5. *Sveriges Geologiska* Undersökning C, pp. 58–61.

Wilde-Piórko, M. & Grad, M., 2002. Crustal structure variation from the Precambrian to Palaeozoic platforms in Europe imaged by the inversion of teleseismic receiver functions – Project TOR. *Geophysical Journal International*, 150, p. 261–270.

TURUN
YLIOPISTO
UNIVERSITY
OF TURKU

Painosalama, Turku, Finland 2021

ISBN 978-951-29-8509-8 (PRINT)
ISBN 978-951-29-8510-4 (PDF)
ISSN 0082-6979 (Print)
ISSN 2343-3183 (Online)