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UNIVERSITY OF TURKU

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Unravelling the evolution and properties of fault and fracture systems and their prediction at different scales

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Cover image: Photo taken from a faulted bedrock outcrop on Flatö in Åland. Photo taken by Nicklas Nordbäck on June 25th, 2020

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ABSTRACT

The aim of this thesis is to improve the understanding of the brittle tectonic evolution in Fennoscandia, which is known to be complex and contain multiple stages of fault nucleation and reactivation. Building on prior work, this work provides new structural descriptions and temporal constraints of fractures and faults from the Paleoproterozoic bedrock of southwestern Finland. Integration of structural and isotopic data from Olkiluoto, the site of planned nuclear waste disposal, allowed constraining the geometric and temporal relationships of specific sets of brittle faults within the fault network at local scales. However, the Olkiluoto dataset leaves a substantial period of uncertainty in crustal evolution at 1.6–1.3 Ga, and this thesis aims to close this gap through examining novel regional structural datasets from the 1.58 Ga Åland rapakivi batholith for paleostress analysis. Moreover, this work displays the results of multiscale lineaments mapped from southern Finland, providing information on the scalability of brittle structures, localization of regional deformation, and insights into the evolution of the brittle crust under various stress conditions.

According to the results of this study, the tectonic development of the brittle crust within southwestern Finland includes at least six major tectonic stages: 1) brittle deformation initiated under NW–SE to NNW–SSE compression at the brittle-ductile transition at around 1.75 Ga. Two successive stages of regional extension followed: 2) N–S extension at around 1.64 Ga during the emplacement of the pre-1.6 Ga rapakivi granites, and 3) E–W to NW–SE extension during the intrusion of the 1.58 Ga Åland rapakivi, diabase dykes, and the onset of the development of a sedimentary basin where the Bothnian Sea is now located. This extensional period was succeeded by strike-slip tectonics including 4) WNW–ESE to NNW–SSE compression between 1.55–1.4 Ga and 5) NE–SW compression at around 1.3–1.2 Ga. 6) NE–SW to ENE–WSW compression during the early phases of the 1.1 Ga Sveconorwegian orogeny resulted in the formation of low-angle faults in Olkiluoto. Any later tectonic events were restricted to reactivations of previously formed faults. The absolute age of the overprinting regional joints remains unknown, but a minimum age of ca. 540 Ma can be inferred from Cambrian sedimentary infillings observed within some of the joints.

KEYWORDS: Tectonics, brittle deformation, structural geology, faulting stages, fracture network, geochronology, paleostress, remote sensing

TURUN YLIOPISTO
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TIIVISTELMÄ

Tämän opinnäytetyön tavoitteena on kehittää ymmärrystä Fennoskandian kilven hauraasta tektonisesta evoluutiosta, jonka tiedetään olevan sekä monimutkainen että sisältävän useita siirrosten synty- ja reaktivoitumisvaiheita. Tämä työ täydentää aiempia julkaisuja Lounais-Suomen kallioperän rakennekehityksestä uusien rako- ja siirrossystemien karakterisoinnin ja ikämääritysten muodossa. Olkiluotoon sijoitettavan ydinjätteen loppusijoituspaikan kallioperän osalta näiden uuden tulosten keskinäisen integroinnin perusteella kyettiin määrittämään sekä hauraiden siirrosten suhteelliset ikäsuhteet että absoluuttiset iät. Olkiluodon aineisto ei kuitenkaan kata ajallisesti maankuoren evoluutiota mesoproterotsooisen kauden alkuosassa, jonka vuoksi ajanjaksoon 1,6–1,3 Ga liittyy merkittäviä epävarmuuksia. Tällä opinnäytetyöllä pyritään edellä mainitusta syystä täyttämään tätä aukkoa tietämyksessä laatimalla uusiin alueellisiin rakenneaineistoihin perustuvia malleja paleojännityskentästä 1,58 Ga Ahvenanmaan rapakivibatoliitista. Lisäksi tässä työssä esitellään Etelä-Suomesta kartoitettujen monimittakaavaisten lineamenttitukintojen tulokset, jotka antavat tietoa hauraiden rakenteiden skaalautumisesta, alueellisten muodonmuutosten lokalisoitumisesta sekä ymmärrystä hauraan kuoren kehityksestä erilaisissa jännitysolosuhteissa.

Tämän tutkimuksen tulosten perusteella maankuoren hauraan tektonisen kehityksen vaiheet Lounais-Suomessa ovat seuraavat: 1) hauras muodonmuutos alkoi NW–SE - NNW–SSE puristuksessa noin 1,75 Ga sitten, kun kallioperä oli jäähtynyt ja hauraiden rakenteiden muodostuminen oli mahdollista. Tätä puristusta seurasi kaksi peräkkäistä ekstensiovaihetta: 2) N–S ekstensio vaikutti yli 1,6 Ga ikäisten rapakivigraniittien asettumiseen ja 3) E–W - NW–SE ekstensio 1,58 Ga Ahvenanmaan rapakiven paikoilleen asettumiseen sekä, diabaasijuonten ja sedimenttialtaan kehitykseen. Näitä vaiheita seurasi kulkusiirrostektoniikka, mukaan lukien 4) WNW–ESE - NW–SSE puristus välillä 1,55–1,4 Ga ja 5) NE–SW puristus noin 1,3–1,2 Ga. 6) 1,1 Ga Svekonorjalaisen orogenian alkuvaiheessa NE–SW - ENE–WSW puristus johti kaateiltaan loiva-asentoisten siirrosten muodostumiseen Olkiluodossa. Kaikki tätä myöhäisemmät tektoniset tapahtumat rajoittuivat jo aiemmin muodostuneiden siirrosten uudelleenaktivoitumiseen. Kallioperästä havaittujen tensiorakojen absoluuttinen ikä on tuntematon, mutta niiden vähimmäisiäksi voidaan päätellä n. 540 Ma perustuen niissä esiintyviin kambrikautisiin sedimenttitäytteisiin.

AVAINSANAT: Tektoniikka, hauras muodonmuutos, rakennegeologia, siirrostumisvaiheet, rakoverkosto, geokronologia, paleojännitys, kaukokartoitus

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 Nordbäck, N. Mattila, J. Zwingmann, H. Viola, G. Precambrian fault reactivation revealed by structural and K-Ar geochronological data from the spent nuclear fuel repository in Olkiluoto, southwestern Finland. *Tectonophysics*, 2022; 824, 229208.

II Nordbäck, N., Ovaskainen, N., Markovaara-Koivisto, M., Skyttä, P., Ojala, A., Engström, J., Nixon, C. Multiscale mapping and scaling analysis of the censored brittle structural framework within the crystalline bedrock of southern Finland. *Bulletin of the Geological Society of Finland*, 2023; 95 (1), 532.

III Nordbäck, N., Skyttä, P., Engström, J., Ovaskainen, N., Mattila, J., Aaltonen, I. Mesoproterozoic strike-slip faulting within the Åland rapakivi batholith, southwestern Finland. *Tektonika, 2024; 2 (1).*

The original publications have been reproduced with the permission of the copyright holders. The main contribution of N. Nordbäck to the original papers was as follows:

Paper I: Structural mapping and analysis of structural datasets. Development of the hierarchical and structural geochronological models (together with Jussi Mattila). Preparation of figures and manuscript. The isotopic part was handled mostly by Horst Zwingmann and Giulio Viola.

Paper II: Field work and photogrammetric UAV surveys at Kopparnäs. Lineament and UAV fracture mapping at different scales. Data analysis together with Nikolas Ovaskainen. Preparation of figures and writing of most parts of the manuscript.

Paper III: Structural mapping and photogrammetric UAV surveys of outcrops on Åland Islands together with the KYT KARIKKO research team. All data analyses, preparation of most figures and writing most of the manuscript.

1 Preface

The understanding of brittle deformation of Earth's crust is important as brittle structures play a major role in controlling the fluid flow and stability of the bedrock. These properties are essential for analysing the suitability of bedrock volumes for different types of applications, including bedrock construction, groundwater management, energy storage, geothermal potential, storage of spent nuclear fuel, carbon dioxide storage and extraction of hydrocarbons. During the past, geological investigations within Fennoscandia were mainly focussed on studying the ductile structural development and the mineral potential of the crystalline basement. However, due to the recently increased utilisation of the bedrock in the Fennoscandian shield, with specific reference to underground applications, the need to understand the evolution, properties, and hydrogeology of brittle structures has become essential. Research activities associated with the site selection and characterisation of repositories for spent nuclear fuel have had a significant role in boosting the research activities within the field of brittle structural geology in both Finland and Sweden. Despite this development, the currently available information and understanding on e.g., the geochronology of brittle structures is still both incomplete and uncertain. Furthermore, the data and models are spatially limited to the selected sites for storage of spent nuclear fuel and, hence, their regional representativity is also uncertain.

Due to the complex crustal evolution of old crystalline terrains, often including multiple overprinting deformation phases within both the ductile and brittle regimes, unravelling all past brittle tectonic events requires that bedrock areas of different ages are studied, and that the studies are conducted in multiple scales. Therefore, to increase the knowledge on structural evolution of the crystalline bedrock in southern Finland, this thesis includes detailed investigations of brittle structures from different lithostratigraphic units and areas, and integrates the use of UAV photogrammetry, remote mapping, and traditional structural mapping to enable the surveying of large outcrop areas with high resolution and correlations of brittle structures at different scales. The smallest scales that were studied include down to centimetre-scale fracture data, while the largest area studied include up to 300 km long lineaments from the area of southern Finland.

The work on this thesis started in 2018 with the mapping of brittle structures in the ONKALO™ underground research facility in Olkiluoto (Figure 1), as a collaboration between Posiva Oy and the Geological Survey of Finland (GTK). For the integration of this structural dataset with available isotopic fault dating results and preparation of the manuscript for Paper I, a collaboration was initiated in 2020 with University of Bologna and Kyoto University. The following research activities related to Paper II and III were conducted as part of the KYT KARIKKO[1] project (GTK and University of Turku), which was a part of the Finnish Research Programme (KYT) on Nuclear Waste Management (2019-2022). The area of Inkoo (Figure 1) and outcrops at Kopparnäs, where previous fracture studies and methodological developments had already been conducted by GTK, was selected as a study area for paper II. The inspiration for fracture network characterisation in Paper II was gained during the Tectonic Studies Group (TSG) meeting at the Bergen University in January 2019. The structural dataset for Paper III was gathered during extensive fieldwork on Åland islands (Figure 1) during summers of 2020 and 2021. The work on Åland was a team effort by the KYT KARIKKO research team and the Structural Geology Group Turku-Åbo (SGG).

[1] The KYT KARIKKO-project (2019–2022), managed by the Geological Survey of Finland, examined the multiscale characterization and modelling of brittle structures (fractures and faults) of the Finnish bedrock. The main motivation for this research was the inherent uncertainty related to multiscale datasets and assumptions regarding the scalability of brittle structures in 3D and Discrete Fracture Network (DFN) modelling.

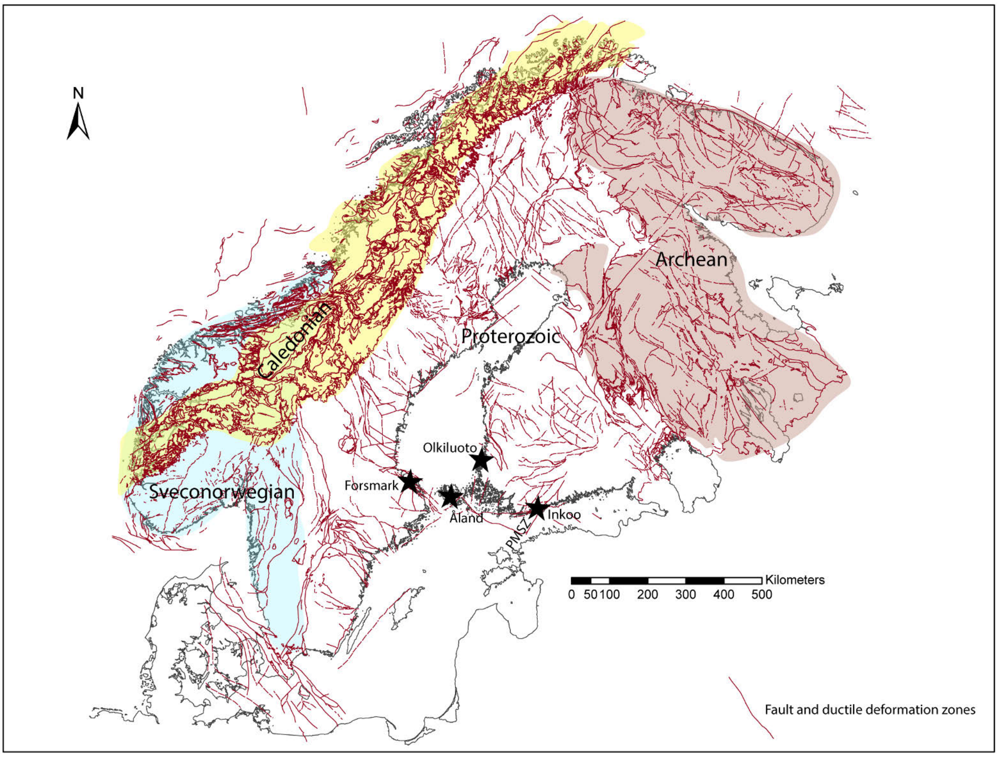

Figure 1. Major geological provinces and structures of the Fennoscandian shield. PMSZ = Porkkala-Mäntsälä shear zone. The figure is based on the Geological map of the Fennoscandian shield 1:000 000 (Geological Survey of Finland, 2001).

2 Introduction

2.1 Brittle deformation and brittle structures

Depending on temperature and pressure conditions, rocks can deform in ductile or brittle manner. Within the brittle regime, when the stress exceeds the mechanical strength of the rock, brittle deformation results either in the formation of new brittle structures (fractures and faults) or in reactivation of pre-existing discontinuities (e.g., Sibson, 1985; Morris et al., 1996). Since later brittle reactivations may erase the evidence of previous faulting events, the unravelling of such complex deformation histories is challenging. Nevertheless, previous studies have shown that by combining structural, kinematic and isotopic methods, also very complex tectonic histories can be depicted (Saintot et al., 2011; Mattila and Viola, 2014; Torgersen and Viola, 2014; Elminen et al., 2018; Scheiber and Viola, 2018).

Brittle structures within the crystalline bedrock in southern Finland are typically more eroded than the more intact parts of the surrounding bedrock (Krabbendam and Bradwell, 2014; Skyttä et al., 2023), mainly because of past glaciations and the associated bedrock erosion. As a consequence, large-scale fault zones, particularly those buried beneath thick overburden, pose a challenge for field investigations. Despite of the difficulty of direct field investigations, these fault zones can still be traced from linear topographic depressions or as geophysical anomalies (O'Leary et al., 1976; Meixner et al., 2018). Fortunately, the natural fracture systems are known to have fractal or scale-invariant properties (Tchalenko, 1970; Bonnet et al., 2001), which implies that regardless of the scale of observation and the size of the studied structures, they can reveal information across multiple scales, given that sufficient size range is investigated. Thus, small structures observed in outcrops can reveal information that can be upscaled to explain the properties of large deformation structures. Nevertheless, all brittle systems in nature must have upper and lower limits where fractal behaviour and scaling laws remain valid (Bonnet et al., 2001; Davy et al., 2010).

2.2 Brittle tectonic evolution of Fennoscandia

The Fennoscandian shield exhibits several generations of superimposed structures (Figure 1), representing both ductile to brittle tectonic stages (Nironen, 1997; Hermansson et al., 2008; Lahtinen et al., 2009; Mattila and Viola, 2014; Torvela and Kurhila, 2020). The brittle deformation in southern Finland was predated by metamorphism, partial melting and intense ductile deformation during the 1.9–1.8 Ga Svecofennian orogeny (Ehlers et al., 1993; Lahtinen et al., 2009). The Svecofennian deformation and late-Svecofennian shear zones (Väisänen and Skyttä, 2007; Torvela and Ehlers, 2010) contributed to the generation of variably penetrative anisotropies and localized weaknesses within the bedrock, which were later exploited and selectively reactivated during the following multiple deformation stages within the brittle regime (Mattila and Viola, 2014).

According to isotopic Ar–Ar ages the rocks within southwestern Finland entered the brittle-ductile transition zone after ~1.79 Ga (Torvela et al., 2008) while Ar–Ar age results from Olkiluoto in southwestern Finland (Figure 1) constrain the transition to brittle regime between 1.79–1.72 Ga (Aaltonen et al., 2016). Evidence from Forsmark (Figure 1) in southeastern Sweden similarly infer the shift to brittle regime at 1.8–1.7 Ga (Söderlund et al., 2009). Microstructural, fluid inclusion and geochemical studies in Olkiluto show that the first brittle faults were formed already at the brittle-ductile transition at ~1.75 Ga (Marchesini et al., 2019; Prando et al., 2020).

After the transition to brittle deformation regime, several different brittle deformations events that took place in the bedrock of southern Finland have been identified. Paleostress inversion studies from Olkiluoto by Mattila and Viola (2014) revealed similar paleostress regimes and faulting stages as a corresponding study by Saintot et al. (2011) from Forsmark. Based on the results from Olkiluoto (Mattila and Viola, 2014) the following conceptual tectonic model comprising seven fault stages was proposed: 1) NW–SE to NNW–SSE transpression during the formation of subvertical roughly N–S trending strike-slip faults (later constrained to the ductile-brittle transition by Marchesini et al. (2019) and Prando et al. (2020)), 2) N–S to NE–SW transpression that caused partial reactivation of Stage 1 structures (within brittle conditions; Marchesini et al., 2019), 3) regional NW–SE extension during approximately 1.6 Ga rapakivi magmatism, 4) NE–SW transtension between 1.6–1.3 Ga at time of the development of the Satakunta graben, 5) NE–SW compression postdating 1.27 Ga diabase sills, 6) E–W transpression during the initial stages of the Sveconorwegian orogeny (Bingen et al., 2008) and 7) E–W extension during the Sveconorwegian orogenic collapse. Furthermore, results from Mattila and Viola (2014) and Saintot et al. (2011) showed that no new brittle structures were generated after the Sveconorwegian orogeny at around 1.0 Ga, but pre-existing structures were reactivated instead.

Available K–Ar illite data from faults in Finland point dominantly towards Sveconorwegian ages for fault generation and reactivation (Mänttäri et al., 2007; Viola et al., 2013; Elminen et al., 2018) while Ar–Ar results from within the Porkkala-Mäntsälä shear zone (PMSZ; Figure 1) reveal a wider scatter from reactivation ages between 1.3–0.95 Ga (Heeremans and Wijbrans, 1999). Rb–Sr ages by Tillberg et al. (2020, 2021) from veins and faults within Paleoproterozoic crystalline bedrock in southeastern Sweden, reveals a large span of ages between 1.75 and 0.35 Ga that to some extent coincide with the timing of the described faulting stages in Finland.

2.3 Objectives of this study

The objective of this thesis is to improve the understanding on the brittle tectonic evolution within Fennoscandia by providing new time-constraints and structural information on brittle structures (fractures and faults). The work builds upon earlier work by Mattila and Viola (2014) regarding the long, multistage, and complex brittle tectonic evolution within the Paleoproterozoic bedrock of southwestern Finland. As part of this thesis, new structural and isotopic data from Olkiluoto (Figure 2) are provided, which contributes towards a better description of the tectonic evolution within the Paleoproterozoic domains and validation of the previous models (Saintot et al., 2011; Mattila and Viola, 2014). Due to the complexity of deformation in Olkiluoto, including multiple stages of fault reactivations, the isotopic record from Olkiluoto is mostly limited to ages representing late Mesoproterozoic reactivations (1.3–1.0 Ga) and possibly lacking information on earlier events, perhaps overprinted by younger fault reactivations. In particular, to provide information on the relatively uncertain Mesoproterozoic tectonic evolution during the apparently quiet stage of crustal evolution at 1.6–1.3 Ga, novel brittle structural datasets from the 1.58 Ga Åland rapakivi batholith (Figure 2; Suominen, 1991) were collected and analysed for paleostress interpretations. In addition, lineaments within southern Finland were mapped in diverse geological settings and at different resolutions. The collected lineament and outcrop datasets provided data on the scalability of the properties of brittle structures, localisation of large-scale brittle structures and a basis to evaluate the evolution of the brittle crust within different stress fields and scales.

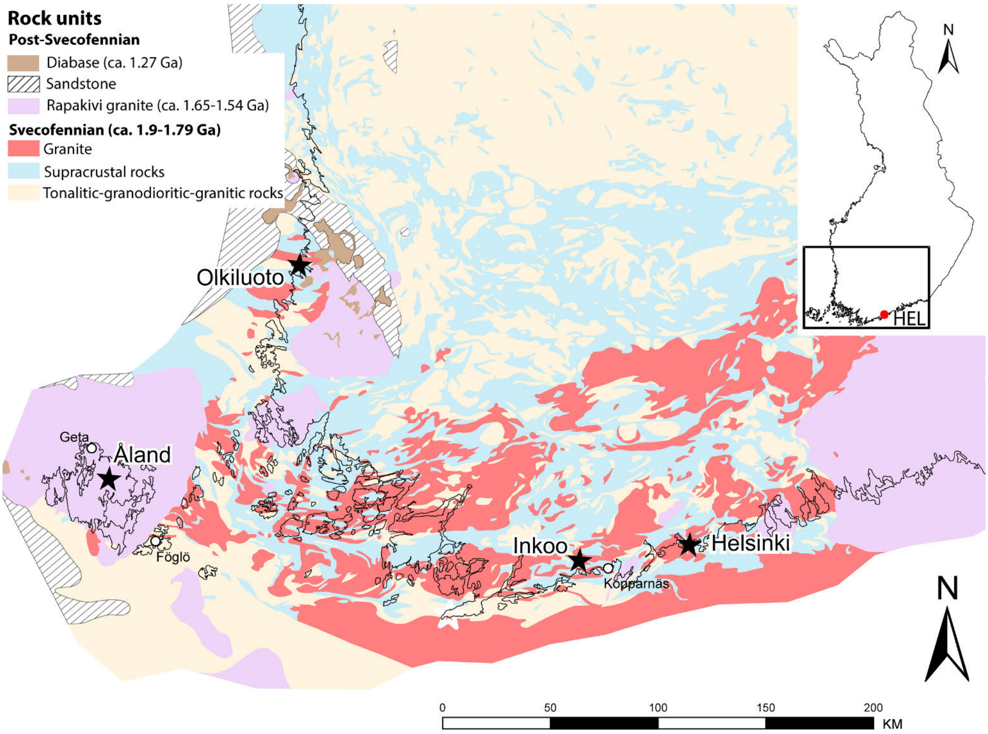

Figure 2. Generalised geological map of southern Finland. The locations of Olkiluoto, Åland, Inkoo and Helsinki are shown with black stars and locations of Geta and Kopparnäs with white circles. The figure is based on the geological bedrock map of Finland – Bedrock of Finland 1:1 000 000 (Geological Survey of Finland, 2016).

3 Materials, methods, and data collection

3.1 Remote sensing

3.1.1 Lineament interpretation

Since major brittle structures typically occur as sedimentary-filled depressions within the bedrock, they are rarely observable in outcrops. However, lineaments can be mapped from remote sensing datasets, which can be used as proxies for brittle structures (O'Leary et al., 1976; Meixner et al., 2018). In this study lineaments were interpreted using topographic LiDAR (0.5 points/m^2; National Land Survey of Finland, 2019) integrated with bathymetric (EMODnet Bathymetry Consortium, 2018) and aerogeophysical data (Hautaniemi et al., 2005). Lineaments were interpreted at three different resolutions: 1:500 000, 1:200 000 and at the full resolution of the LiDAR dataset.

3.1.2 UAV Photogrammetry

UAV photogrammetry (Bemis et al., 2014; James et al., 2019; Ovaskainen et al., 2022) was used for documentation of well-exposed and polished outcrops along the shorelines in Inkoo (Kopparnäs; Figure 2) and Åland Islands. The equipment included a Phantom 4 Pro quadcopter equipped with a 20 MP camera and a VRS-GPS for measuring the position of ground control points. The acquired photographs were processed into georeferenced high-resolution 2D orthomosaic images using the photogrammetry processing software *Agisoft Metashape*. The orthomosaics were analysed in *ArcGIS*, and polylines representing fracture traces, lithology and glacial striations were mapped from the images. To allow for topological analysis (Sanderson and Nixon, 2018) of both fractures and lineaments, the polylines that abut to other polylines were mapped using the snapping function in ArcGIS.

3.2 Field mapping

To complement the pre-existing brittle structural datasets in Olkiluoto, geological mapping was carried out from accessible tunnel and shaft sections of ONKALO™ between 2018 and 2019 (Paper I). This work included detailed structural characterisation of fault zone intersections and the integration of information from older structural datasets containing systematically collected photographic and fracture trace datasets from along the tunnel walls. During the structural mappings in ONKALO™, special emphasis was placed upon fault kinematics, fault-rock products and relative age relationships between brittle structures.

The field work in Inkoo (Paper II) was conducted on well-exposed outcrops in Kopparnäs between 2018 and 2020 and included UAV photogrammetric surveying, compass measurements of foliation and fractures, and validation of the orientation, topology, and length of remotely mapped lineaments and fractures.

The field work campaigns on Åland Islands (Paper III) were carried out during field seasons of 2020 and 2021. The field work during 2020 included extensive UAV photogrammetric surveying around the main Island of Åland, including also the Föglö area (Figure 2). Simultaneously with the UAV documentation, sparse field mapping datasets including main joint sets and brittle fault structures were collected from all the surveyed areas. During 2021 the focus of the field mapping was directed to the large and continuous outcrops on the northern shores of the Åland main Island, within the municipality of Geta (Figure 2). For field mapping of the Geta outcrops, the UAV orthomosaics, covering a several kilometres wide and well-exposed area, were used to locate and verify the traces of remotely mapped joints, shear fractures and fault zones. During the field mapping, fracture types were registered for all mapped fractures and structural orientation measurements collected. For all mapped shear structures, detailed parameters including kinematics, length and width were registered and stored as digital attribute information in the ArcGIS geodatabase.

3.3 Fracture scaling

The remote sensing datasets (Paper II), including lineament and outcrop fracture traces, were analysed for their length scalability. The trace length data was analysed using a Python library, *powerlaw* (Alstott et al., 2014), to fit the length data with power law, lognormal and exponential distributions. Due to limitations in the resolution of each dataset, a cut-off below which the outcrop structures could not be mapped in a statistically consistent way was determined automatically with *powerlaw*. To resolve the best fitting distribution (power law, lognormal and exponential distribution) for each individual dataset, the log-likelihood ratio, R, and the significance value, p, were compared between the fitted distributions.

Multiscale analysis of length data from different scales required normalisation of the datasets (Bonnet et al., 2001). Area normalisation was used by dividing the complementary cumulative distribution of the traces by the size of the area from within the traces were mapped (e.g., Bossennec et al., 2021; Chabani et al., 2021). Using the *fractopo* Python library (Ovaskainen et al., 2022), a common power law distribution for the multiscale datasets was calculated using a first-degree polynomial least squares fit algorithm.

3.4 Paleostress analysis

Paleostress analysis based on kinematic observations from brittle deformation structures can be used to reconstruct the stress fields that affected the bedrock during the formation or reactivation of brittle structures. Typically, a kinematic observation includes the sense of slip, orientation of the fault plane and orientation of the slip vector but e.g., fault planes with kinematically associated tension fractures can also be used. The basis for such analysis is the Wallace-Bott hypothesis (Wallace, 1951; Bott, 1959) which states that the slip on a fault plane is parallel to the maximum shear stress (assuming mechanically isotropic material). For kinematic fault data, the *Wintensor* paleostress inversion software (Delvaux and Sperner, 2003) was used to calculate directions of principal stress axes ($\sigma_1 \geq \sigma_2 \geq \sigma_3$) and their relative magnitudes, described by the stress ratio R, which is defined as: $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$. The results from a paleostress analysis can be further used in the determination of stress regime, which is defined by first determining which of the principal stress axes is vertical: σ_1 vertical = extensional, σ_2 vertical = strike-slip and σ_3 vertical = compressional. Within these main types, stress regime can further vary depending on the stress ratio R. For example in strike-slip stress regimes: in transpression $R < 0.25$, in strike-slip $R = 0.5$ and in transtension $R > 0.75$ (Figure 3; Delvaux et al., 1997). The *Wintensor* workflow included initial sorting of the fault data into sub-sets with the right dihedron method (Angelier and Mechler, 1977), followed by more detailed analysis using the rotational optimisation method (Delvaux, 1993). The kinematic fault data from Åland Islands, which was analysed in *Wintensor*, included both striations on slickensides and slip planes with associated tension fractures.

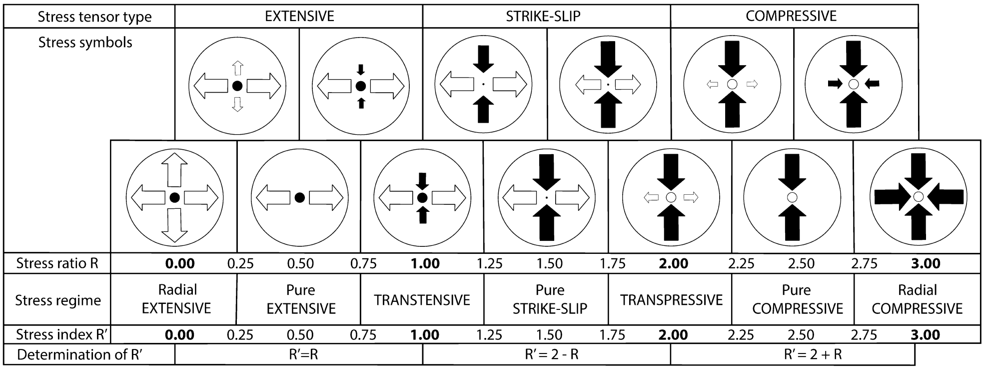

Figure 3. Illustration by Delvaux et al. (1997) of the stress regime index R' versus stress ratio R and orientation of the principal stress axes.

Since joints can be assumed to have propagated perpendicular to the minimum principal stress (σ_3), they can also reveal information about paleostress during their formation (Dyer, 1988). In addition, the clustering of three-dimensional joint orientation data can reveal information on the orientation of all principal stress orientations. In the paleostress analysis of joints from the Geta area, the *GArcmB* software (Yamaji, 2016) was used for fitting mixed Bingham distributions (Jolly and Sanderson, 1997) and principal stress axes (Baer et al., 1994; Yamaji et al., 2010) to each joint set.

3.5 K–Ar dating

The potassium-argon (K–Ar) geochronometer can be used to date synkinematic illite that formed authigenetically during faulting (Dalrymple and Lanphere, 1970; Viola et al., 2013; Scheiber et al., 2019; Tartaglia et al., 2020). The interpretation of K–Ar ages depends on the illite polytype and, for example in sedimentary rocks, the $1M/1M_d$ illite end member represents the age of faulting while the $2M_1$ is considered detrital (Haines and van der Pluijm, 2008). However, since the temperature in crystalline rocks can allow for authigenic $2M_1$ formation during faulting (Zwingmann et al., 2010; Viola et al., 2013) the same assumption is not valid. Thus, to interpret the age data from $2M_1$ illite, in this study we use the "Age Attractor Model" by Torgersen et al. (2015) according to which the coarsest grain size of clay samples within the fault gouge contain large amounts of protolithic clay while the smallest illite fraction (< 0.1 μm) yield more reliable results on the age of brittle faulting.

4 Review of the original publications

4.1 Paper I

This paper investigated the geochronology and tectonic evolution of brittle fault structures intersecting the ONKALO^{TM} spent nuclear waste repository in Olkiluoto, southwestern Finland. The study builds upon the conceptual brittle tectonic model based on fault kinematic paleostress analysis by Mattila and Viola (2014). Paper I included structural characterization and classification of fault structures into fault systems, each of which represents faults with similar geological and mechanical properties (reactivation potential), kinematics and tectonic histories. Based on the structural characterization, four different fault systems were defined. The relative age relationships between these Fault systems I–IV, from oldest to youngest, were determined based on observed crosscutting relationships, observed alterations, and mineralogy. The roughly N–S trending strike-slip faults belonging to Fault systems I and II are systematically offset by the younger E–W trending oblique dextral/normal Fault system III and the low-angle thrust Fault system IV. Furthermore, geological characteristics of the different fault systems can be used to strengthen the interpretation of their relative age relationships. Although the relative age relationship between Fault system III and IV was not observed in Olkiluoto, the lack of hydrothermal alteration and quartz infills in Fault system IV indicates that this fault system post-dates the hydrothermal activity which is observed in all the other three fault systems. In addition, the broad range of fault products within the Fault systems I and II, including e.g., mylonite, is proof of a long and multistage development.

Furthermore, the potassium-argon (K–Ar) dating method on fault gouge illite samples from different fault systems was used to determine the absolute ages of fault formation and reactivation. The generation of brittle faults in Olkiluoto was guided by pre-existing weaknesses, such as ductile Svecofennian shear zones. Fault systems I and II were interpreted to have formed already at the brittle-ductile transition zone at ca. 1.75 Ga under NW–SE to NNW–SSE compression. Fault system III was estimated to have formed at around 1.6 Ga in a previously undefined stress field and Fault system IV in E–W compression during the 1.1–0.9 Ga Sveconorwegian orogeny. In addition, the isotopic data revealed reactivations of Fault systems I and

III between 1.3–1.2 Ga, linked to NE–SW compression, and further reactivations of Fault systems II and III during E–W to ENE–WSW compression during the initial stages of the Sveconorwegian orogeny (1.1–1.0 Ga) and even further reactivations of Fault system III and IV during the Sveconorwegian orogenic collapse (0.97–0.87 Ga).

4.2 Paper II

The aim of this paper was to investigate the suitability of different remote sensing methods for multiscale mapping and scaling analysis (topology, orientation, and length distribution) of brittle structures within the partly sedimentary covered bedrock of southern Finland. The size of study areas varied from the entire southern Finland (90 429 km^2), to the 1 km^2 Kopparnäs outcrop area within the municipality of Inkoo. Large-scale structures were investigated using lineament interpretation based on LiDAR, bathymetry and aerogeophysical source data at three different resolutions. Small-scale outcrop joints were mapped based on UAV-derived photogrammetric data at two different resolutions. From a methodological perspective, Paper II contributes towards a better understanding about the different sources of uncertainty associated with the different remote methods and data resolutions. For example, topological properties for lineaments were found to be highly uncertain due to the limited resolution of source datasets while the orientation of lineaments provided more reliable results, although subject to uncertainties related to glacial erosion. For smaller fault zones, precursors such as ductile structures and lithological contacts were found to influence the localisation of brittle structures.

When assessing the scalability of lineament orientation data from areas with contrasting sizes, these areas are not geologically comparable due to the variations in e.g., lithology and ductile precursors. These geological variations are observed to affect lineament orientation, e.g., when comparing the 1:500 000 resolution lineaments from southern Finland (scattered orientations) with the 1:200 000 resolution lineaments from the Inkoo study area (dominated by ENE–WSW and NNW–SSE orientations). However, different resolution lineament datasets from the Inkoo area showed similar orientations. Compared to the lineaments, the variation in outcrop joint orientation data is more subject to the spatial selection of the sampling site as jointing is heavily controlled by ductile precursors. Length distribution parameters of lineaments were observed, to a varying degree, to be affected by truncation and censoring effects of source datasets. Nevertheless, for the most reliable datasets (1:200 000 lineaments and UAV-fracture data) differences in length scalability were still observed, as displayed by the -1.92 power law exponent for the 1:200 000 resolution lineaments and the -2.26 exponent for > 2 m long outcrop fractures. Furthermore, < 2 m outcrop fractures could only be described by a lognormal length distribution. These differences can be attributed to the possible effects caused by i) bedrock anisotropies and strain localisation, ii) limited thickness of lithological domains or the brittle crust, iii) and variations in the propagation and interactions of brittle structures of different types and ages. As such, the results from Paper II also underline the complexity and multistage evolution of the bedrock of southern Finland, as described in Paper I.

4.3 Paper III

The objective of Paper III was to improve the understanding regarding the Mesoproterozoic brittle tectonic evolution within Fennoscandia. The study was focussed on the 1.58 Ga Åland rapakivi batholith which constrains the maximum age of observed brittle structures to Mesoproterozoic times. Data on outcrop scale brittle structures were collected using UAV-photogrammetric datasets integrated with structural field mapping of fault zones, shear fractures and joints. In addition, the large-scale structures of the rapakivi batholith and surrounding regions of SW Finland were investigated by lineament interpretations.

Results indicate that dextral E–W trending strike-slip faults predate E–W trending sinistral and N–S trending dextral strike-slip fault structures. Based on the observed relative age relationships, paleostress results, and correlations to previous results, the following chronological model is proposed: 1) The Åland rapakivi batholith was affected by a strike-slip stress regime with WNW–ESE to NW–SE compression at around 1.55–1.4 Ga (Stage 1). This stage is correlated to the formation of E–W trending oblique dextral/normal faults in Olkiluoto, previously proposed as ca. 1.6 Ga (Paper I). 2) At ca. 1.3–1.2 Ga, corresponding to the time of post-Jotnian diabases and reactivation of Fault systems I and III in Olkiluoto (Paper I), the rapakivi intrusion was deformed by NE–SW compression within a strike-slip or transtensional stress-regime (Stage 2). 3) These two faulting stages are post-dated by regional joints, which timing is uncertain but can be inferred to be older than 540 Ma from the occurrence of Cambrian clastic sediments in some of the joints (Bergman et al., 1982). Results indicate that two subvertical joint sets (E–W to ESE–WNW trending and N–S to NE–SW trending) were formed simultaneously in an extensional stress field (vertical $\sigma 1$) and that subhorizontal joints were formed in a later compressional stress field (horizontal $\sigma 1$). Based on the lineament interpretations, emplacement of the rapakivi granites in SW Finland was most likely facilitated by reactivations of roughly N–S trending Paleoproterozoic structures within E–W extension, pre-dating Stage 1. This period is also likely related to the initial development of the sedimentary basin beneath the Bothnian Sea. The NW–SE orientation of major lineaments within the rapakivi also indicate that Svecofennian NW–SE trending ductile shear zones were further reactivated within the brittle regime during Mesoproterozoic times, most likely during Stage 1.

5 Discussion

5.1 Brittle structural evolution within southern Finland

The geochronological results from Olkiluoto in Paper I, show that the bedrock in southern Finland was affected by at least five stages of faulting between ca. 1.75 Ga and 0.9 Ga. These results agree with the conceptual scheme by Mattila and Viola (2014) regarding the paleostress stages of brittle faulting in southwestern Finland, but also add new information concerning the absolute age of reactivations of individual fault systems. The NNE–SSW trending sinistral strike-slip faults of Fault system I and NNW–SSE trending dextral strike-slip faults of Fault system II are compatible with the NW–SE to NNW–SSE compression proposed by Mattila and Viola (2014) for Stage I and N–S to NNE–SSW transpression for Stage II, respectively (Figure 4). The suggested 1.75 Ga timing of formation of Fault system I and II is also in agreement with other published results from Olkiluoto (Marchesini et al., 2019; Prando et al., 2020), with the character of the included fault-rocks (speficically the mylonites) and the observed crosscutting relationships with Fault systems III and IV. This period of roughly N–S compression at around 1.75 Ga is also compatible with sinistral brittle reactivations of major NE–SW trending ductile shear zones (Ploegsma and Westra, 1990) and dextral reactivation of the NW–SE trending Sottunga–Jormua ductile shear zone (Torvela and Ehlers, 2010) in southern Finland.

Due to the lack of isotopic information and difficulties in assigning Fault system III in Olkiluoto to the scheme by Mattila and Viola (2014), the formation of this fault system was in Paper I first tentatively assigned to a previously undefined transtensional palostress stage during the period of rapakivi magmatism at around 1.6 Ga. However, according to the results and interpretations of Paper III, the bedrock in southern Finland could rather have been affected by a period of extension and reactivation of previously formed brittle structures during the 1.64–1.54 Ga period of rapakivi magmatism and associated diabase dykes (Haapala and Rämö, 1992; Rämö and Haapala, 2005; Figure 4). As further evidence of extensional tectonics, Mesoproterozoic sedimentary rocks are preserved in the offshore basin between Finland and Sweden (Luosto et al., 1990; Korja and Heikkinen, 1995;

Kohonen and Rämö, 2005) and in the Satakunta graben (Kohonen et al., 1993). The exact age of the sedimentary sequence is uncertain, but the minimum age is constrained by crosscutting 1.27 Ga diabase sills (Suominen, 1991). Moreover, based on results of Paper III, the 1.58 Ga Åland rapakivi was affected by similar strike-slip faulting as Fault system III in Olkiluoto under WNW–ESE to NNW–SSE compression (Figure 4). This newly recognized paleostress stage, which was inferred to 1.55–1.4 Ga, could thus be used to explain that the nucleation of Fault system III in Olkiluoto took place somewhat later than previously thought. Based on Ar–Ar ages from the Obbnäs rapakivi in the vicinity of the Porkkala–Mäntsälä shear zone (Heeremans and Wijbrans, 1999), and the inferred post-rapakivi reactivation of the Sottunga-Jormua shear zone (Torvela et al., 2008), it is possible that suitably oriented pre-existing brittle structures were further reactivated at ca. 1.55–1.4 Ga. A younger palostress stage characterized by NE–SW compression was observed from E–W trending sinistral and N–S trending dextral strike-slip faults within the Åland rapakivi (Figure 4). This faulting stage can be correlated to Stage 5 of Mattila and Viola (2014) and the isotopically dated fault reactivations in Olkiluoto at around 1.3–1.2 Ga (Paper I). The 1.3–1.2 Ga period coincides with the intrusion of Postjotnian diabases (Suominen, 1991) and Ar–Ar reactivation ages from the Porkkala-Mantsäla shear zone (Heeremans and Wijbrans, 1999). The low-angle faults (Fault system IV) in Olkiluoto show isotopic ages between 1.1–0.9 Ga (Paper I). Based on the mineralogy and crosscutting relationships, the oldest isotopic ages of low-angle faults are interpreted to represent nucleation ages and these structures are interpreted to have formed in E–W compression during the initial stages of the Sveconorwegian orogeny and later reactivated due to E–W extension (Mattila and Viola, 2014) during subsequent collapse of the thickened orogen (Figure 4). Based on previous results (Munier, 1993; Saintot et al., 2011; Mattila and Viola, 2014) and the results of this thesis, all the observed fault systems were formed already by late Mesoproterozoic times.

Due to the absence of absolute time-constraints for joint formation, the timing of jointing is still relatively uncertain. However, based on observed crosscutting relationships to the supposedly Mesoproterozoic faults (Paper III) and due to the presence of Cambrian aged clastic material in joints (Bergman et al., 1982), their age can be loosely constrained to be younger than the strike-slip faulting on Åland and older than the Cambrian sedimentary sequences (Figure 4). Since no new brittle structures were formed after Precambrian times and since the tectonic events of the Caledonian orogeny (Roberts, 2003) and paleostress conditions during postglacial faulting (Ojala et al., 2018, 2019) seems to have caused merely reactivations of the previously formed brittle structures, it is most likely that any future stress states will cause reactivations of the existing brittle structures rather than the formation of new ones within the already saturated brittle system.

Although the new isotopic data from Olkiluoto and the new structural data from both Olkiluoto and the Åland rapakivi improves the understanding regarding the brittle evolution of the crust within central Fennoscandia, individual faulting stages remain loosely constrained. To validate the existing models and to further constrain the individual faulting stages in time, it is recommended that future studies would concentrate on extending the geochronological database with isotopic dating and detailed structural analysis of brittle structures from within different lithostratigraphic units, such as from the Åland rapakivi batholith.

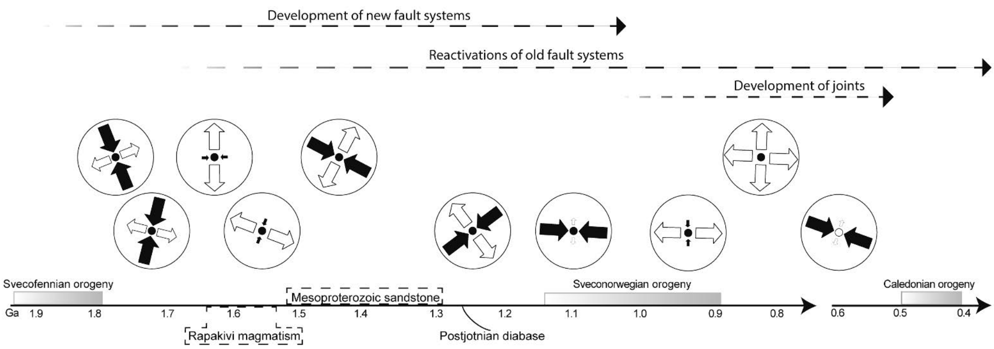

Figure 4. Chronological sequence of paleostress stages responsible for the Precambrian brittle development within southern Finland. The model is based on the results of this thesis and results of Mattila and Viola (2014).

5.2 Scalability of brittle structures

Accurate modelling of fracture networks requires a detailed understanding about the properties of brittle structures, including parameters for fracture length, density, connectivity, aperture, and orientation. Since bedrock volumes contain numerous fractures at all different scales, accurate characterisation and deterministic modelling of all individual brittle structures is impossible and, therefore, Discrete Fracture Network (DFN) modelling methodology, utilising statistical information of fractures, is typically used for modelling the brittle structures in rock volumes. The access to multiscale information on brittle structures is, however, typically restricted due to the absence of large outcrops, resolution of remote sensing data and dimensional restrictions of datasets. Thus, scaling laws (e.g., Bonnet et al., 2001), are needed to interpolate and extrapolate brittle data for the scales that are not present within the available datasets.

The results in Paper II identified limitations associated to the censoring and truncation effects of remote sensing methods and biases related to the multiscale mapping of lineaments and fracture traces. Especially the topological relationships between lineaments were found to be disguised by sedimentary censoring. Furthermore, the impact of glacial erosion was identified as a possible source of bias concerning lineament data, but the extent of this bias remains uncertain. In addition to the methodological uncertainties associated to the multiscale characterisation of brittle structures, the orientation of both joints and fault structures are controlled by the mechanical variations of bedrock due to e.g., varying lithology and the nature of ductile precursors. Thus, the scalability of brittle properties has limitations depending on the representative elementary volume (i.e., the size of the system which follows the same scalability pattern), that may equal e.g., a lithological unit, ductile domain or even the total extent of the brittle crust. As an example, the longest lineaments within the Åland rapakivi (Paper III), which extend beyond the limits of the rapakivi batholith, show different orientations compared to the outcrop scale fault structures.

Concerning length scalability, most datasets had a best fit while modelled with a lognormal distribution. However, the 1:200 000 resolution lineaments and UAV fracture traces (Paper II) were also found to be well represented by power law distributions, although with different exponents of -1.92 and -2.26 respectively. Furthermore, UAV fracture traces of less than 2 m in length only fitted lognormal length distribution. The reason for the differing length distribution for < 2 m fractures can be explained by the "universal fracture model" by Davy et al. (2010), according to which the longer fractures represent a more saturated part of the fracture network where fracture growth is controlled by interactions between fractures. The shortest fractures, on the other hand, represent younger fractures that can propagate more freely. The difference in the length distribution of lineaments and UAV fracture traces can be attributed not only to spatial variations arising from various sampling area sizes, but also to that they represent distinct types and ages of brittle structures. In general, the 1:200 000 scale lineaments represent fault zones that formed between 1.75–1.1 Ga and the UAV fracture traces mainly represent joints that postdate most of the faulting stages. Since joints formed within previously faulted and, consequently, fractured bedrock, the propagation of joints was restricted and influenced by these pre-existing structures. Unlike faults, where specific strain localization occurs, with a few large structures accommodating much of the shear deformation (Sornette et al., 1993; Hardacre and Cowie, 2003), such localization does not happen during jointing. Instead, deformation during jointing is more evenly distributed within the fracture network with joints growing as single fractures, lacking damage and core zones, and often terminating when reaching pre-existing fracture planes. As an example of these restrictions in joint propagation, the maximum joint length that was observed within the outcrops on Geta, Åland Islands, was less than 200 m and usually less than 50 m. Similar results concerning the maximum lengths for individual fractures has also been reported from Olkiluoto (Nordbäck, 2014).

Due to limitations in data availability from the Inkoo area, caused by the lack of large outcrops and resolution of remote sensing datasets, a break in data occurs between 100 m and 1 km. Therefore, the lower limit where power law length distribution remains valid for lineaments and corresponding upper limit for outcrop fracture traces (joints) could not be defined. From this perspective, if outcrop fracture and lineament datasets follow different distributions, extrapolation between the 100 m and 1 km data gap is problematic. Based on the results from Paper II, observations from Olkiluoto (Nordbäck, 2014) and Åland Islands (Paper III) the -1.92 power law exponent for joints in Inkoo could be utilised for between 2–200 m long fractures. The other length intervals of the fracture network would need to be modelled using other length distributions.

6 Conclusions

By involving remote sensing, structural field investigations, and isotopic dating techniques, this thesis contributes towards a time-constrained understanding of the brittle tectonics within central Fennoscandia:

1) The Svecofennian ductile structures have contributed to the generation of specific zones of weakness within the bedrock, at all different scales. These initially ductile zones served as precursors for subsequent brittle structures and were selectively reactivated during the following stages of brittle deformation, depending on the prevailing stress regime.
2) The brittle evolution of the bedrock in southern Finland, initiated due to roughly N–S compression at around 1.75 Ga.
3) Based on the interpretation of large-scale structures within southern Finland, stages of N–S and E–W extension resulted in the nucleation and reactivation of preferably oriented structures during the pre-1.6 Ga and the 1.58 Ga rapakivi magmatism (and sedimentary basin formation), respectively.
4) WNW–ESE to NNW–SSE compression, inferred to 1.55–1.4 Ga, caused the nucleation of dextral E–W trending strike-slip faults. This tectonic stage is possibly also responsible for reactivations of suitably oriented pre-existing brittle structures, such as the Porkkala-Mäntsälä and the Sottunga-Jormua shear zones.
5) NE–SW compression as observed from E–W trending sinistral and N–S trending dextral strike-slip faults, within the Åland rapakivi, is correlated to paleostress results and the isotopically dated fault reactivations in Olkiluoto at around 1.3–1.2 Ga.
6) Based on structural and isotopic data from Olkiluoto, E–W compression during the Sveconorwegian orogeny (1.1–1.0 Ga) caused the nucleation of low-angle faults.

7) The collapse of the Svecofennian orogeny, due to E–W extension, is registered as 0.97–0.87 Ga isotopic reactivation ages within the fault systems of Olkiluoto.
8) The age of jointing is loosely contrained as younger than the strike-slip faulting on Åland and older than the Cambrian sedimentary sequences.

Regarding the scalability of brittle structures, the results of this thesis indicate that confident modelling of bedrock fracture networks requires an understanding of the uncertainties and limitations of source datasets and the geological history and properties of the bedrock volumes:

1) Censoring and truncation can cause limitations for multiscale mapping of lineaments and fracture traces. The exact length of individual brittle structures and topological relationships between different brittle structures are typically disguised by sedimentary features.
2) Scalability of brittle features and the representative elementary volume is affected by the anisotropies of the bedrock, including e.g., lithological, and ductile domains.
3) The 1:200 000 lineaments and >2m UAV fracture traces show a good fit with power law distributions with exponents of -1.92 and -2.26 respectively. UAV fracture traces of less than 2 m in length only fitted lognormal length distribution. Differences in length scalability between different datasets is attributed to different age relationships and modes of deformation between faults and joints.
4) The gap in data between 100 m to 1 km challenges defining power law limits for lineaments and outcrop fractures; extrapolation across this gap is problematic if datasets have different distributions. Based on observations in Olkiluoto and Åland Islands, the -1.92 power law exponent for joints in Kopparnäs could be representative for 2–200 m long joints.

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Nicklas Nordbäck

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