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UNIVERSITY OF TURKU

GEOMETRY AND TOPOLOGY OF MULTISCALE FRACTURE NETWORKS

Methodology and characterization

Nikolas Ovaskainen

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University of Turku

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

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Photo taken from the rocky beaches of Geta in Åland. Photo taken by Nicklas Nordbäck on August 10th, 2020.

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ABSTRACT

The study of bedrock fracture networks is essential for applications such as modelling fluid flow, predicting radionuclide and geothermal heat transfer as well as overcoming bedrock engineering challenges since the fractures affect a number of physical characteristics of the bedrock. However, the multiscale nature of these fracture networks poses challenges in observation and analysis as fractures occur at all scales from centimeter-scale features on outcrops to kilometer-scale tectonic margins. To overcome this challenge, this doctoral thesis focuses on the geometry and topology of two-dimensional multiscale fracture networks and presents methods for their multiscale investigation – both existing, from the literature, but also novel methods developed under the course of this work. Scale-independent methods are introduced and employed, allowing for the direct comparison of data collected at different scales. Geometric fracture network properties encompass fracture lengths, orientations, and intensity i.e. the spatial distribution of fractures. Furthermore, the analysis of topological properties focuses on the connectivity and fracture relationships, offering valuable information about the flow potential within the fracture network and potential age relations between fractures, respectively.

This thesis comprises three articles that both address a specific research question in fracture studies while presenting novel methods for these purposes. Research issues include the identification of faults, their damage zones and fracturing that is kinematically unrelated, determination of the data requirements for accurate fracture network characterization and prediction of fracture properties, such as length, for scales of observation, where data collection is challenging. As a result of applying the presented methods, it was found how pre-existing faults affect later fracturing and how through subsampling of fracture trace data the accuracy of fracture data can be assessed. Furthermore, the thesis comprised fracture data collection in length ranges that had previously lacking data and provided estimations on predicting fracture lengths within crystalline rocks.

KEYWORDS: fracture, lineament, fracture network, geostatistics, structural geology

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TIIVISTELMÄ

Kallioperän rakoverkostojen tutkiminen on välttämätöntä nesteiden virtauksen mallintamiseen, radionuklidien ja geotermisen lämmön kulkeutumisen ennustamiseen sekä kallioperärakentamisen suunnitteluun liittyvien haasteiden ratkaisemisessa, koska raot vaikuttavat useisiin kallioperän fysikaalisiin ominaisuuksiin. Rakoverkostojen mittakaavaton luonne kuitenkin asettaa haasteita esimerkiksi niiden havainnointiin ja analyysiin, sillä rakoja esiintyy kaikissa mittakaavoissa. Rakojen koko voi vaihdella senttimetreistä aina kilometrien kokoisiin tektonisiin rajavyöhykkeisiin. Tämän haasteen ratkaisemiseksi tässä väitöskirjassa keskitytään kaksiulotteisten moniulotteisten rakoverkostojen geometrian ja topologian tutkimusmenetelmien hyödyntämiseen ja jatkokehitykseen. Työssä hyödynnetään sekä olemassa olevia että uusia menetelmiä, jotka on kehitetty tämän työn aikana. Väitöskirjassa esitellään ja käytetään mittakaavariippumattomia menetelmiä, jotka mahdollistavat eri mittakaavoissa kerättyjen tietojen suoran vertailun. Geometriset rakoverkostojen ominaisuudet käsittävät rakojen pituudet, suunnat ja rakojen alueellisen jakautumisen. Topologisten ominaisuuksien analysoinnissa keskitytään verkottuneisuuden ja rakojen välisiin leikkaussuhteisiin. Verkottuneisuus antaa arvokasta tietoa rakoverkon virtauspotentiaalista kun taas leikkaussuhteet antavat mahdollisesti tietoa rakojen ikäsuhteista.

Tämä väitöskirja koostuu kolmesta artikkelista, jotka sekä vastaavat tutkimuskysymyksiin rakoverkoista että esittelevät samalla uusia menetelmiä näiden tutkimuksia varten. Ensimmäisessä artikkelissa tärkeänä tutkimuskysymyksenä on siirrosten, niiden vauriovyöhykkeiden ja kinemaattisesti siirroksiin liittymättömen rakojen tunnistaminen. Toisessa artikkelissa määritetään, kuinka paljon rakodataa pitää kerätä rakoverkostojen tarkkaa analysointia varten. Kolmannessa artikkelissa tutkitaan, miten rakojen ominaisuuksia, kuten pituuksia, pystytään ennustamaan sellaisissa mittakaavoissa, joissa niiden empiirinen havainnointi on vaikeaa tai mahdotonta. Tuloksina menetelmien soveltamisessa havaittiin, miten jo olemassa olevat raot ja siirrokset vaikuttavat myöhempien rakojen kehittymiseen ja miten rakohavaintojen osittaisnäytteenoton avulla rakoverkkoanalyysien tarkkuutta voidaan arvioida. Lisäksi työn tuloksena rakodataa kerättiin mittakaavassa, jossa on aikaisemmin tehty vähän rakotutkimuksia, ja annetaan uusia arvioita rakopituuksien ennustettavuudesta kiteisessä kallioperässä.

ASIASANAT: rako, lineamentti, rakoverkko, geostatistiikka, rakennegeologia

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3.5.2024
Nikolas Ovaskainen

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Abbreviations

DFN	Discrete Fracture Network
GIS	Geographic Information System
2D	Two-dimensional
3D	Three-dimensional
Ga	Billion years
ANOVA	Analysis of variance
CCM	Complementary cumulative number
ANCCM	Area-normalized complementary cumulative number
PDF	Probability density function
LiDAR	Light detection and ranging
DEM	Digital elevation model
MSLE	Mean squared logarithmic error

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 Pietari Skyttä, Nikolas Ovaskainen, Nicklas Nordbäck, Jon Engström, Jussi Mattila. Fault-induced mechanical anisotropy and its effects on fracture patterns in crystalline rocks. Journal of Structural Geology, 2021; 146: 19.
- II Nikolas Ovaskainen, Nicklas Nordbäck, Pietari Skyttä, Jon Engström. A new subsampling methodology to optimize the characterization of two-dimensional bedrock fracture networks. Journal of Structural Geology, 2022; 155: 17.
- III Nikolas Ovaskainen, Pietari Skyttä, Nicklas Nordbäck, Jon Engström. Detailed investigation of multi-scale fracture networks in glacially abraded crystalline bedrock at Åland Islands, Finland. Solid Earth, 2023; 14(6): 22.

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N. Ovaskainen's main contribution to the papers was as follows:

Paper I: Co-author of the paper; structural mapping of the field and remote data; all analysis of fracture data; writing most parts of methodology along with major contribution to all other parts.

Paper II: Main author of original draft and revision; conceptualization of the methods; all analysis; writing most parts of the paper.

Paper III: Main author of original draft and revision; conceptualization of the methods; all analysis; writing most parts of the paper.

1 Introduction

Fracture networks of the bedrock play a crucial role in fluid flow, radionuclide transport, geothermal heat transport and bedrock engineering applications [1; 2; 3]. However, studying these fracture networks is challenging due to their multiscale nature, which requires observing them at different scales using diverse but still comparable methods [4]. For these purposes, scale-independent methods are preferred in multiscale fracture network studies to get comparable data from centimeter to meter scale outcrop fractures to hundreds of kilometers scale lineament maps [5]. The study of multiscale fracture networks usually involves investigating their geometric and topological properties. Geometric properties include fracture lengths, orientations, and spatial distributions. On the other hand, topological properties focus on the connectivity and networking properties of individual fractures and fracture sets, which reveal the flow potential within the fracture network.

This doctoral thesis and the accompanying articles collectively contribute towards advancing the methodology for studying these fracture networks with focus on the geometry and topology of two-dimensional multiscale fracture networks. The methods employed in this thesis include orientation, length, topological and intensity analysis, which are used to study the characteristics of fractures at different scales. Each paper delves into specific aspects of fracture network analysis and presents novel methods that have applicability to different scientific problems, ranging from identifying faults and structural domains to understanding the quantity of data needed to accurately characterize fracture networks. In Paper I, two-dimensional characterization was used to find discrete faults, define their damage zones and provide age constraint estimations between fracture sets for the purposes of understanding both how faults and syn-fault fractures form in isotropic conditions and how these affect the formation of later fractures. Paper II presents a new subsampling method for fracture trace data that can be used to answer the question of how much fracture data is required for statistically accurate and precise analysis of characteristics such as fracture length. Paper III presents new data and results from analysis of fracture and lineament trace lengths of 100 to 500 m that have previously been lacking in studies and characterizes multiscale fracture and lineament data for the purposes of improving how fracture properties across different scales of observation are predicted in a crystalline rock exposed by glacial activity.

In other studies, the two-dimensional fracture network characterization methods, which are presented in this thesis, have been previously applied to a variety of issues such as for orientation analysis and length distribution modelling in geothermal investigations [e.g. 6; 7] and hydrocarbon exploration [e.g. 8]. Topological characterization of fracture networks has been applied in generating more realistic DFN model generation by applying a modelling algorithm that stops growth when a growing fracture reaches another [9; 10; 11] with a defined statistical certainty. Furthermore, the topological characteristics of fracture networks have an implication upon the percolation threshold [12] and permeability of fractures as only connected networks enable flow, when excluding the matrix [2; 13].

2 Data

2.1 Fractures

The most important characteristics of remotely digitized fracture trace data are geometry and topology. Additional attribute data includes e.g. fracture filling and kinematic character, based on which the fractures could be classified as e.g. veins, if the filling is significant, or as faults, if movement can be observed from the kinematic character. However, as these attributes are not available when digitizing fractures remotely, the general term fracture is used to refer to all types. The image source for fracture digitization can vary from satellites to drones to hand-held cameras. These sources vary most importantly in the resolution of the output images. The resolution is the most important factor in determining the scale of observation of the digitized fracture data and depending on the research interest the scale must be chosen accordingly. Digitization can be done manually or by using automatic methods [14; 15].

Fracture data used in this work consist of structural measurements, taken in-situ and digitized two-dimensional traces. In terms of data type, the structural measurements usually consist of point data with attributes of the measured fractures including dip, dip direction, kinematics and possible filling. The traces are two-dimensional polylines, i.e. a list of XY coordinate points in order. The focus of this research is on the digitized two-dimensional fracture traces. The structural measurement and fracture trace data have been collected from seashore outcrops of Orrengrund, Loviisa (Paper I) and Geta, Åland Islands (Papers II and III).

Fracture trace data of this Thesis are manually digitized in Geographic Information System (GIS) software using drone images of bedrock outcrops (Figure 1a). Digitization in GIS software results in accurately georeferenced data (Figure 1b). The digitized fracture trace data is delineated by a target area, within which the trace data is then analyzed.

2.2 Lineaments

Lineaments are sublinear features observable on the surface of the Earth. The observation can be done from a variety of surface data sources but primarily from satellite images and topographical and geophysical maps [16; 17; 18, Figure 2]. Lineaments can be identified in the source maps based on various factors, such as their alignment, length, and distinctive patterns visible in the data sources. Using multiple sources for

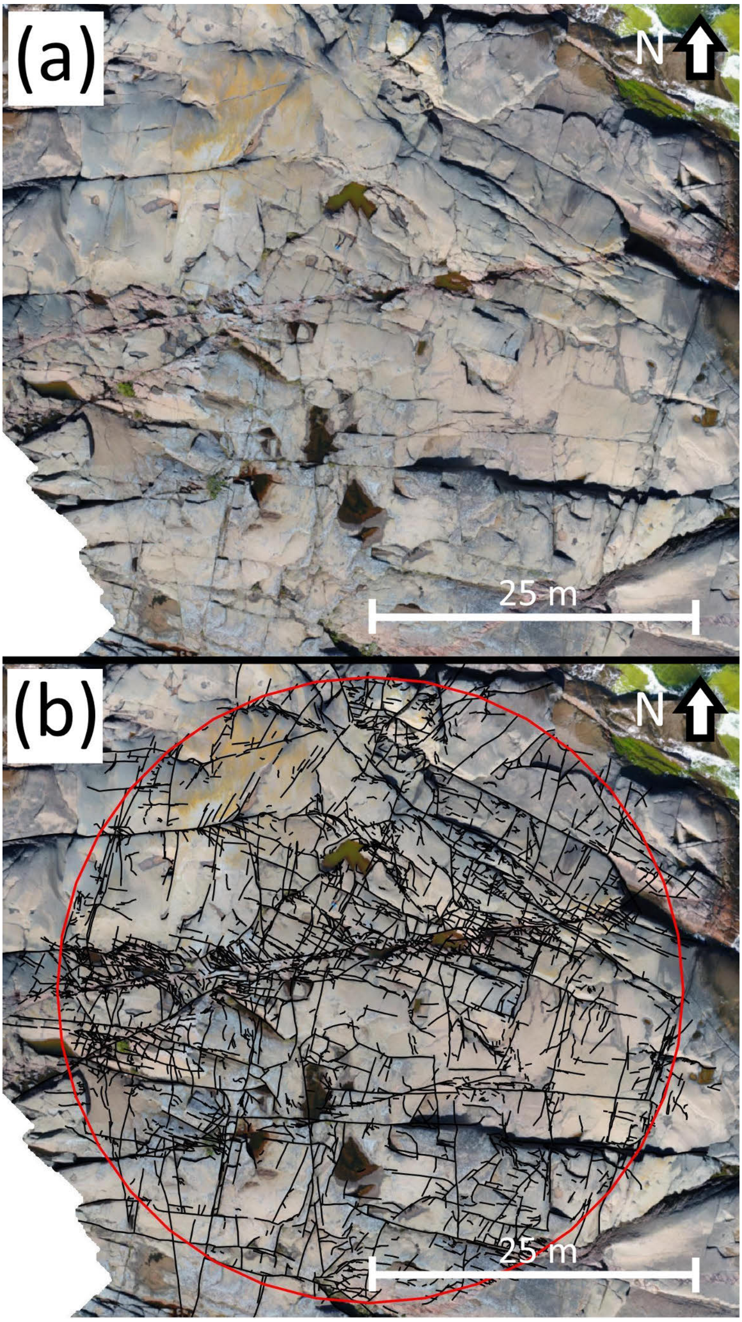

Figure 1. (a) An orthomosaic of bedrock outcrop, Getaberget, Åland Islands, Finland (Paper II). (b) The orthomosaic with digitized traces overlaid on top.

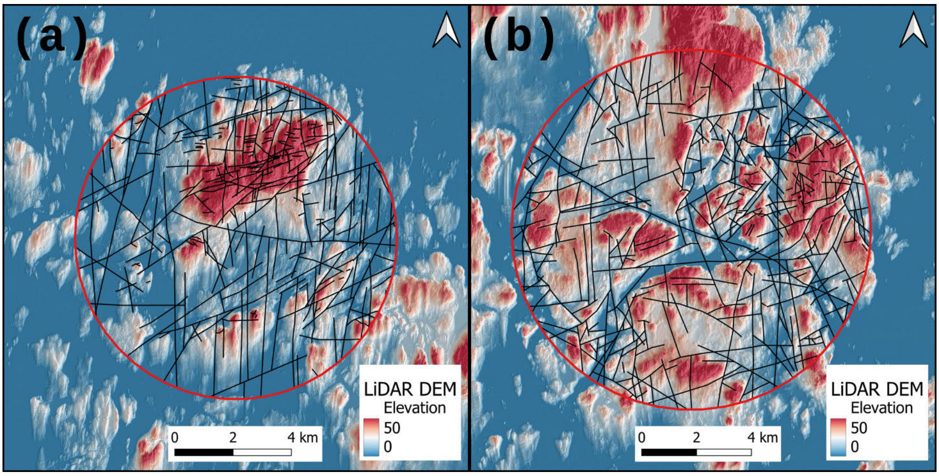

Figure 2. Lineaments interpreted from two areas of Åland Islands: (a) Geta municipality and (b) Sund municipality. Interpretation was done from a light detection and ranging (LiDAR) -based digital elevation model (DEM). The resolution of the DEM is 5.0 $\frac{m}{pixel}$ which corresponds roughly to a scale of observation of 1:20 000. Figure from Paper III.

the interpretation allows the comparison of the source or scale-specific lineaments, and the further integration of source-specific lineaments into a more reliable integrated dataset. Integration involves merging of lineaments from different sources that match or overlap [19].

Lineament data presented in this Thesis were interpreted using the same technical methods as the fractures (Section 2.1). Lineament data were interpreted from magnetic, electromagnetic and digital elevation model raster maps for the purposes of Paper III. The resulting data from three sources was then integrated to create an integrated lineament trace dataset that is used in e.g. orientation and length distribution analysis.

3 Methods and application

A fracture network can be defined as a collection of (interconnected) fractures or lineaments in an area (2D) or volume (3D). The fracture network can be considered to be composed of fracture sets which are collections of fractures grouped based on some attribute. Typical attributes for grouping include orientation and length. When using orientation for grouping, the sets can be referred to as azimuth sets (Paper III). These sets are the result of one or several tectonic events, which are generally defined as geological processes that deform the crust of the Earth. The tectonic events consist of the generation of new faults and reactivation of old ones, which both cause earthquakes and the formation of new fractures. These new fractures are formed in response to the tectonic forces, where for example extensional fractures form in a right angle to the minimum principal stress. Consequently, fractures formed as a result of certain tectonic event often have similar orientations and can thus be grouped into respective azimuth sets [20; 21, Figure 3].

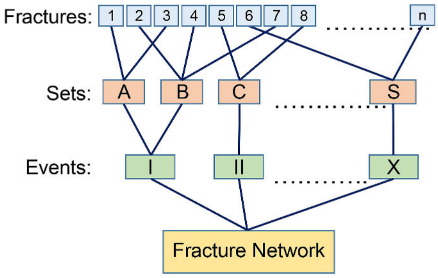

Figure 3. A conceptual model of a fracture network, where individual fractures belong to specific sets that may have been generated as response to an individual (tectonic) event or several events. Figure from Peacock et al. [20].

Individual fractures or lineaments in a fracture network have their own properties, but collectively the fracture network has properties of its own, such as the connectivity between the individual fractures. Characterization of fracture networks consist of both analysis of the collective and individual properties of the fractures. For the purposes of simplification, I refer to both networks of fractures and lineaments as fracture networks and note that all further text related to geometric and topological properties referring to fractures is applicable to lineaments as well. The main methods used within all three Papers for geometric and topological characterization are introduced and summarized in the following sections.

3.1 Orientation

Orientation analysis of lineaments and fractures usually consists of calculating the orientation for each line and plotting the results on rose plots. The calculation of the orientation can be done with a few different methods, but commonly the calculation is simplified to calculating the orientation of a straight line from the start point to the end point of the line which is the method used in all Papers. A rose plot for the purpose of fracture orientation visualization is a histogram, where the orientation frequencies are plotted. The frequencies are weighted by the lengths of the individual fractures. Furthermore, it is recommended to use the area of the individual bars in the plot to describe the magnitude rather than the bar length [22].

The applicability of the rose plots comes in the form of e.g. understanding the potential anisotropy of a fracture network [23; 24; 25; 26]. The rose plots can be used to find preferred orientation groupings of fractures i.e. fracture (or azimuth) sets (Figure 4). These sets can be used as the basis for the brittle structural interpretation of a locality by identifying faults and tectonic events (Paper I) or lineaments which are related more to glacial events rather than the composition and structure of the bedrock (Paper III). Furthermore, the concept of hierarchical organization in the fracture network refers to the presence of different sets of fractures that cause variations in scaling laws between different scales of observation [27, Paper III]. By identifying variations in fracture sets between scales of observation, a hierarchical organization of the fracture network can be identified. This organization might be related to e.g. the thickness of the hosting geological units (e.g. strata or lithological domain) in which the fractures have developed as e.g. the fracture length in a certain orientation might be controlled by the unit boundaries [28]. However, the variations in fracture sets might also be related to differences in the methods used for fracture, or especially lineament interpretation (Paper III).

3.2 Length distributions

Lengths of lineaments and fractures can be in a range from micrometers to hundreds of kilometers. Due to the wide range, their lengths can only be mapped to a certain lower and upper limit [29; 4]. For example, in a microscopy study of a rock sample, the maximum and minimum lengths are constrained by the sample size and the magnification of the microscope, respectively. By contrast, the resolution of the map from which lineaments are interpreted from constrains the range within a lineament study. However, even if the sampling range of an individual study is limited, the lengths of

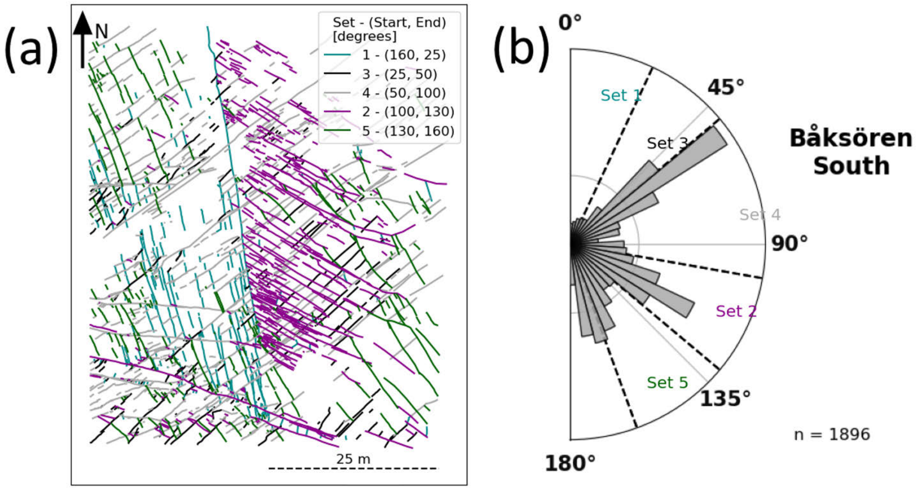

Figure 4. (a) Digitized traces from the Båksören Island, Loviisa, Finland (Paper I). Colors are based on determined fracture sets. Based on structural interpretation of the whole Orrengrund and Båksören fracture network, in this image, set 1 represents faults and sets 3 and 2 represent mostly secondary fractures that are related to the set 1 fractures. Set 4 represents ”regional” fractures, i.e. fractures that are diffusely scattered around the islands. (b) Length-weighted equal-area rose plot of the traces in (a).

fractures and lineaments have been demonstrated to follow scale-independent statistical models, such as the power-law [4; 30]. These models allow predicting lengths across the scale of observations within which the individual studies are conducted. A distribution $n(l)$ of trace or branch lengths l can be described with a power-law exponent a and a constant A [30; 4, Equation 3.2].

$$n(l) = A \times l^a$$

Investigation of the statistical models of fracture lengths increases the reliability of subsequently developed fracture network models, such as Discrete Fracture Network (DFN) models in which three-dimensional fractures are stochastically generated. For the generation of DFNs, constraints based on empirical evidence of the sizes of the fractures should be available [31]. If the generated fractures of the DFN display lengths that are outside the range of any study in a site, the lengths must be predicted using a statistical model such as the power-law (Figure 5). This kind of investigation requires collecting representative fracture data in multiple scales, which might be especially difficult in areas of heterogeneous bedrock (Paper II).

Length distribution modelling was applied in a study for the purpose of distinguishing between faults, syn-fault fractures and other fractures on the Orrengrund island, south of Loviisa, Finland (Paper I). Power-law exponents of the five investigated fracture sets showed a trend, where one fracture set containing faults and

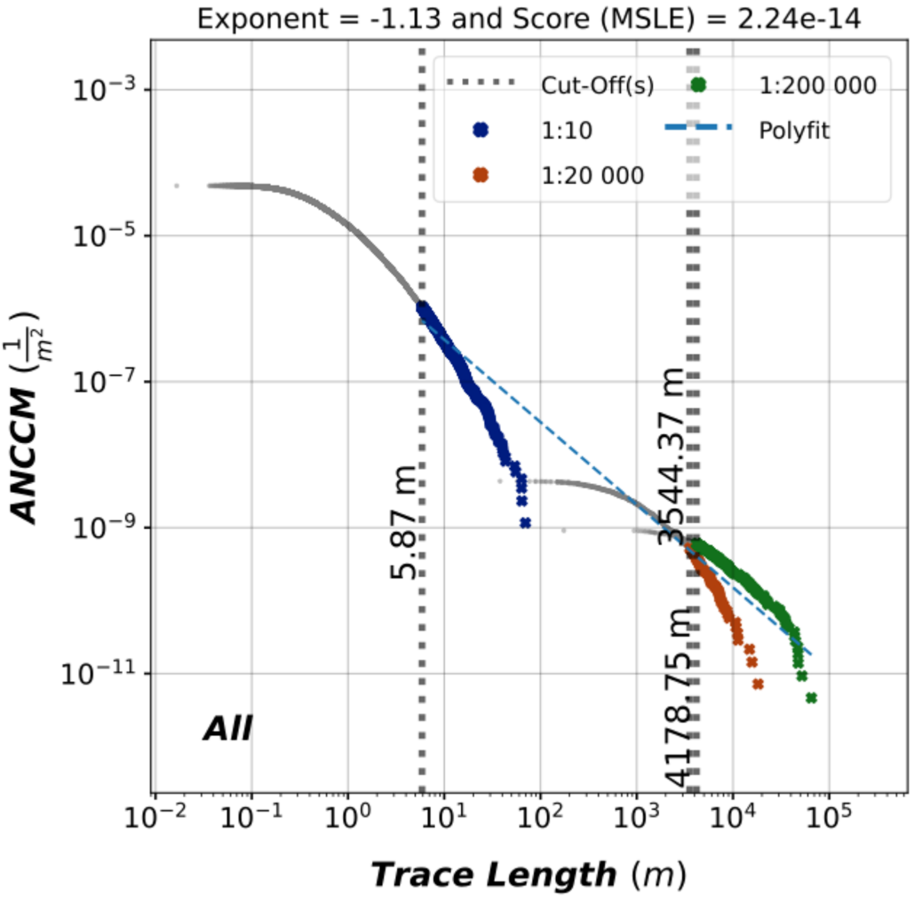

Figure 5. Multiscale length distribution of fractures and lineaments from Åland Islands. In the legend, 1:10 scale represents fracture trace data while 1:20 000 and 1:200 000 represent lineament data. The exponent for the multiscale power-law fit is -1.13 with a goodness-of-fit score, determined with mean squared logarithmic error (MSLE), of 2.24e-14. Figure from Paper III. *ANCCM = area-normalized complementary cumulative number*

another containing syn-fault fractures had higher exponents than fractures kinematically unrelated to any nearby fault. Length distribution modeling was also used to qualitatively estimate the geological significance of lineaments and fractures in different scales of observation by discriminating by the fracture set and providing models for each set individually (Paper III). The results of set-wise length distribution modelling could be used to investigate potential factors affecting the characterization results. For example, the probable effect of glacial erosion on lineament intensity could be identified and subsequently the variance in the geological representativeness of lineaments in different orientations was assessed in Paper III.

3.3 Topology

The topology of a fracture network can be investigated through those properties of the network that do not change if the rock mass hosting the fracture network is subjected to ductile deformation. In the topological view, a fracture network is a graph of branches (=edges) and nodes (=vertices) where, based on interactions between fractures, the branches and nodes can be categorized [26; 5; 32, Figure 6].

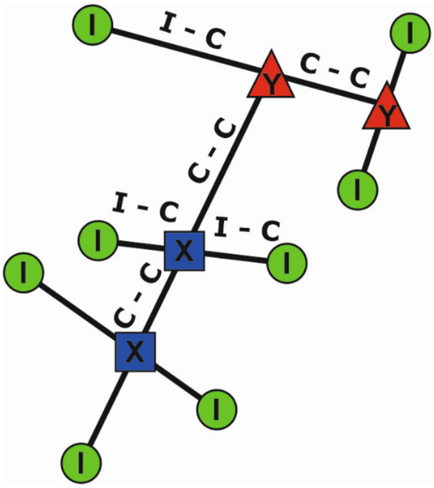

Figure 6. Definition of topological branches and nodes. Nodes are either points of intersection (X-node), abutment (Y-node) or endings in isolation (I-node) of fractures. Branches are the segments of the fracture traces, which extents are defined by the bounding nodes. The branches can be characterized by the types of the two bounding nodes, where X- and Y-nodes are defined as connected (C) and I-nodes as isolated (I).

The Connections per Branch parameter, C_B, is used to quantify the level of connectivity within the fracture network using the counts of Y-nodes, N_Y, X-nodes, N_X, and the count of branches, N_b (Equation 1).

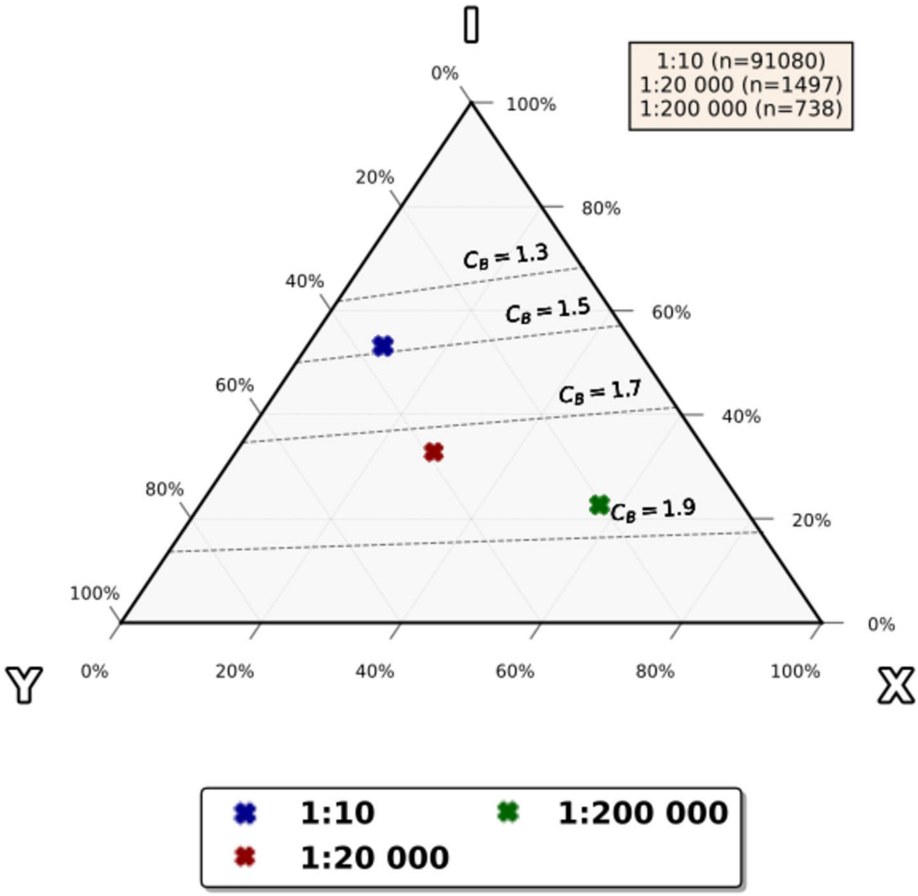

Figure 7. Proportions of X, Y and I nodes visualized in a ternary plot from multiple scales on Åland Islands. Figure from Paper III.

$$C_B = \frac{3N_Y + 4N_X}{N_b} \tag{1}$$

Connections per Branch along with ternary plots of nodes and branches (Figure 7) can be used to investigate the connectivity of a fracture network as X and Y nodes represent connections whereas I nodes represent disconnections in the network [5].

Spatial variation in the values of Connections per Branch was used to discriminate fracture domains, similarly to intensity of fracturing (See Section 3.4, Paper I). Furthermore, by integrating the investigation of fracture sets (Section 3.1) into topological analysis, it is possible to investigate age relations between the fracture sets and subsequently discriminate between tectonic events (Paper I). This is done by quantifying the abutments of a set against another set of fractures and is based on the logic that a new fracture can abut against an older fracture while the opposite is much less likely and only possible with reactivation and new growth.

3.4 Intensity

The fracture intensity (P_{21}) of lineaments and fractures in an area is the total length of lines $\sum L$ divided by the area A [5, Equation 2]. Alternative intensities for two-dimensional fracture networks can be calculated by applying a normalization, where P_{21} is multiplied by the mean length of traces, L_C (Equation 3). Furthermore, topology can be integrated to the intensity calculation by using the topologically determined branches (Section 3.3) instead of the full traces in intensity calculation of branch intensity parameters of B_{21} and B_{22} [5, Paper II]. Furthermore, node counts can be used instead of counting the lines (traces or branches) as a proxy for the quantity of fractures in a area [Figure 6, 33; 5, Papers II and III].

$$P_{21} = \frac{\sum L}{A} \tag{2}$$

$$P_{22} = \frac{\sum L}{A} \times L_C \tag{3}$$

The intensity usually varies spatially due to fracture generation being often heterogeneous and anisotropic. For example, the intensity increases systematically towards the E-W trending major fault and the NW-SW trending subsidiary faults within the upper half of Figure 8, while the intensity outside the faults is significantly lower. Consequently, the variations in intensity can be used to discriminate fracture domains in which intensity is of similar magnitude. These domains might be separated due to variations of intensity on either side of a fault structure (Paper I).

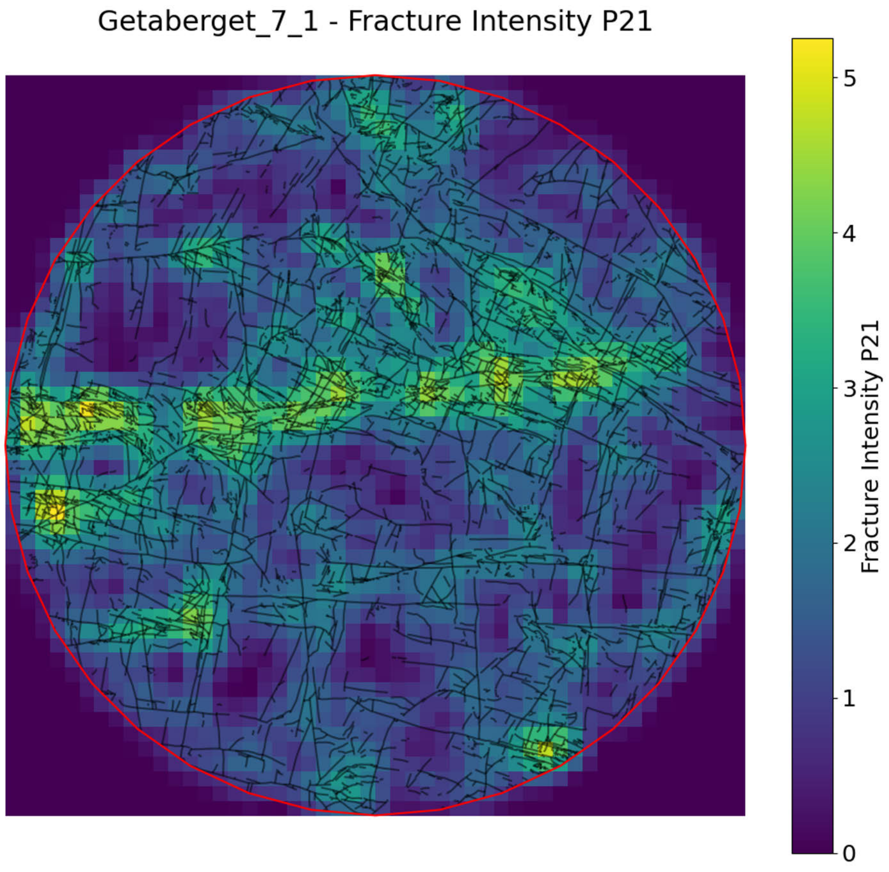

Figure 8. Fracture Intensity P_{21} visualized for the traces of Figure 1. Unit of Fracture Intensity P_{21} is $\frac{m}{m^2}$.

4 Review of the original publications

4.1 Paper I

In Paper I, the focus is on the study of fault-induced mechanical anisotropy and its impact on fracture patterns in crystalline rocks on the island of Orrengrund, Loviisa, Finland. The study area represents mesoscopically isotropic rapakivi granite rock with no apparent ductile deformation, which allows better control on identifying the controlling effect of bedrock stress upon the fracture formation.

A set of approximately north-south trending, sinistral sub-vertical strike-slip faults were found to crosscut the ca. 1.65 Ga rapakivi granites. Properties of these faults include well-developed damage zones and offsets less than 20 cm along the faults, both indicative of the preservation of structures related to the early stages of faulting. In combination with structural field work, both the faults and the associated damage zones were identified using two-dimensional analysis of orientation, length and fracture intensity. Orientation analysis of the faults and fractures of the study area showed orientation maxima which could be attributed to the faults, to syn-fault fracturing or to the more diffuse regional fracturing. Based on field observations and statistical topological crosscutting and abutting relationships between these fracture sets, the faults were found to pre-date the more pervasive regional fractures i.e. fractures kinematically seemingly unrelated to the faults. The evolution of the faults was interpreted to influence the subsequent generation of the regional fractures due to pre-existing structural anisotropy introduced during the faulting stage combined with stress release along the faults. The fractures could be classified based on fracture intensity and topological connectivity characterization into discrete fracture domains, that are specific areas bounded by the faults. The characteristics of the domains were influenced by the pre-existing faults and therefore had varying connectivity and fracture intensity. Furthermore, the syn-fault damage zones could be further classified into ”normal” and ”wide” damage zones, where the wide damage zones are located between faults and have therefore grown larger due to interference between the fault damage zones. Some of these wider damage zones are associated with 100-meter-scale step-overs of the sinistral faults, identified in the fracture trace maps and intensity analysis.

4.2 Paper II

In Paper II, statistical inspection of the amount of data needed for representative characterization of fracture networks is studied. Without information on how much fracture data are needed for accurate calculation of fracture network parameters, there is a chance for both inaccurate characterization of a network due to insufficient amount of data and for expenditure of extra time due to gathering too much data. Therefore, the paper introduces new subsampling methods for fracture network data and the methods are tested at Getaberget, Åland Islands, Finland. Similar to Paper I, the study area consists of isotropic and homogeneous rapakivi granite. The extensive and well-exposed outcrops allow for fracture data gathering with high enough sample counts (n=42499) to test the subsampling methods.

The paper introduces fractopo, which is an open-source Python package designed for the analysis of two-dimensional fracture and lineament trace maps. Furthermore, fractopo is supplemented with scripts for the purposes of subsampling. Results include, besides the subsampling method development, noted differences between the characterization methods, where e.g. the topology through Connections per Branch can be accurately modelled from smaller amounts of data than modelling the power-law exponent of the length distributions of fractures. The study results include methods for the preliminary optimization of areal fracture network sampling coverage in crystalline rocks. For example, when sampling outcrop fracture networks, with trace lengths ranging from 1 cm to 35 m, surveyed using drone orthomosaics with a ground sampling distance of 0.55 $\frac{cm}{pixel}$, the authors recommend a total sampling area of 8000 m^2 with 8 or more circular sampling circles with radii of approximately 18 m. This sampling setup ensures an accurate and precise determination of e.g. the fracture trace power-law exponent. The released subsampling methods are furthermore applicable for the purposes of analysis of variance (ANOVA) tests in any target site, where fracture trace data is collected.

4.3 Paper III

In Paper III, fracture data from Paper II were supplemented with lineament data to expand the fracture network study of Åland Islands, Finland to multiple scales. The inclusion of lineament data in studies of fractures allows investigating the properties of fracture networks across scales and can possibly be used to predict fracture properties of all lengths. Multiscale studies of fracture networks have previously focused on sedimentary rocks, whereas this study produces novel data and results in a crystalline bedrock setting. A special focus was placed on gathering data from fractures of intermediary length range of 100 to 500 m. Fractures of this length range are e.g. of safety significance for disposal of nuclear waste, but are typically difficult or impossible to sample in a statistically consistent way. Furthermore, the effect of glaciations on the lineament data were investigated for the purposes of assessing the uncertainty caused by the preferential erosion in glacial flow direction.

This study reveals a dominant fracture pattern that spans the Åland Islands with WNW-ESE and N-S oriented lineaments. The WNW-ESE lineaments are likely large brittle bedrock structures, while at least some of the N-S lineaments are more likely glacial features which have formed due to preferential erosion in the dominant glacial flow direction (N-S). This interpretation is based on the lack of geophysical lineaments in the N-S direction, whereas N-S oriented topographical lineaments were pronounced in quantity and length.

The length distribution results showed that length data from the intermediary range (100 - 500 m) did not fit the same length distribution model as the fractures. Further method development in this area on length distribution analysis was suggested to more accurately assess the prediction capability across the intermediary length range. Specifically, investigation of possible censoring of long traces suggests that fractures at the 1:10 scale and lineaments at the 1:20 000 scale may be better modeled with a power law when combining a censoring cut-off with a truncation cut-off. In terms of multiscale topological analysis, a trend is observed, where the values of connections per branch and degree of X-nodes decrease as the scale decreases i.e. lineaments (1:200 000 and 1:20 000) have higher values than fractures (1:10). This trend, which contradicts the expectation of scale independence, should be considered in future studies, as it may be related to specific digitization methods or data rather than natural phenomena. The method developments for multiscale fracture network characterization, displayed in this paper, are freely available as part of the open-source fractopo package.

5 Discussion

When applying the introduced two-dimensional fracture network characterization methods, some potential shortcomings exist which fortunately can be avoided by acknowledging the issues and using software, such as fractopo, where these issues, when related to analysis, are already taken into account [34]. For example, fracture intensity is often correlated with the proximity to faults which makes it a good indicator of nearby faults (Paper I) but also prone to high local variation which might cause uncertainty to the results when sampling area or sites are limited (Paper II). Another possible issue in fracture intensity determination is that it usually calculated using the number of lines (traces or branches) within a certain area. However, using the number of lines is influenced by sampling issues related to the boundary of the area. This issue is minimized when using topological node counts as a proxy for the amount of fracturing [5; 35; 33, Paper II].

Issues regarding the collection of two-dimensional fracture trace data from nadir images of outcrops include the lack of horizontal fractures for in e.g. connectivity analysis (Paper II). To minimize this and similar issues, remotely digitized data should always be augmented with at least some structural field measurements to investigate the three-dimensional character and interactions between the fractures (Papers I and II). Furthermore, a representative quantity of remote fracture data should be collected that adequately captures the likely (spatial) variation in fractures. To investigate the required quantity of data, statistical subsampling and ANOVA tests should be conducted [36, Paper II].

An issue in the determination of fracture sets is that the determination is often based on orientation maxima found on rose plots. However, the orientations might vary spatially due to e.g. proximity to faults [37, Paper I]. Consequently, the fracture set determination should be done after the variation in fracture orientations in the whole study area has been characterized remotely, and, if possible, in-situ. Faults in a study area can be identified both remotely and in-situ through damage zone recognition and kinematic indicators, respectively (Papers I and II).

Although the crosscutting and abutting relationships are useful in investigating age relationships between fractures or fracture sets, the relationships can not be used to absolutely constrain the ages of the participating fractures as fracture reactivation and local variations in fracture orientations cause high uncertainty in the results (Paper I). However, through the use of fault dating using e.g. K-Ar methods [38] the topological relations can be possibly constrained to absolute ages, augmenting both the interpretation of the dating results and the age relationship analysis due to the topological age relationship data being much easier to gather from e.g. remote digitization.

In multiscale studies, lineaments might not represent brittle bedrock structures, and are instead e.g. glacial structures, whereas fracture data are not associated with such uncertainty (Paper III). As it is not possible to verify the lineaments, their representativeness should instead be investigated using cross-referencing of lineament data between multiple methods and scales together with fracture data. This cross-referencing can include comparing orientations, length distributions and fracture intensities. A special interest is in determining if a power-law can model multiscale lineament and fracture lengths as it offers predictive capabilities to length ranges that can not typically be sampled [39; 4, Paper III] such as the 100 to 500 m gap [40; 31]. Furthermore, in multiscale length distribution analysis of lineaments and fractures the lower and upper bounds of the length data must be taken into account as both the resolution and target area extent limit the collected data [4; 30, Paper III]. Although the lower bound is usually taken into account in (power-law) modelling of length distributions using cut-offs (e.g. Figure 5), the effect of the upper bound should also be taken into account in a statistically reproducible way (Paper III). Development of length distribution modelling tools that automatically take into account both bounds in all data should be continued to increase the reproducibility of length distribution studies. Furthermore, use of the probability density function (PDF) in place of the complementary cumulative number (CCM) is recommended for more statistically representative modelling of multiscale data [41, Paper III].

6 Conclusions

The presented methods of two-dimensional fracture network characterization augment any study of the brittle bedrock by providing opportunities for detailed description of lineaments and fractures and for cross-referencing between scales of observation, as the methods are not restricted to any single scale for the data. Within this thesis, data based on outcrops, digital elevation models and geophysical maps have been used, and the presented methods have been shown to reveal significant details in all data. The use of orientation, length and fracture intensity analysis can reveal patterns and relationships between faults and fractures, as demonstrated at the Orrengrund study site, where structural anisotropy caused by strike-slip faults were found to affect the formation of later, kinematically unrelated, fractures. Furthermore, combination of orientation and length analysis revealed the likely effect of glacial erosion on lineament interpretation on the Åland Islands. Methods developed within this thesis include a method to analyze and plot the crosscutting and abutting relationships between fracture sets. The statistic analysis of crosscutting and abutting relationships successfully revealed age relationships between the faults and fractures at the Orrengrund study site. Furthermore, the developed subsampling methods for optimizing fracture data collection enable the optimization of two-dimensional fracture sampling by revealing how the sampling area and sample quantity affect different fracture network characteristics. Furthermore, even though method development is still recommended for better analysis of multiscale length distributions, it is evident that there exists trends between the lengths of lineaments and fractures in the study area of Åland Islands.

The implemented methods for fracture network characterization are made freely available as part of the open-source fractopo package [34]. Recommendations for further studies include development of algorithms for automatic cut-off optimization and the continued inclusion of topological network characteristics in multiscale studies. Future contributions and discussions related to the open-source package and methodology are encouraged.

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