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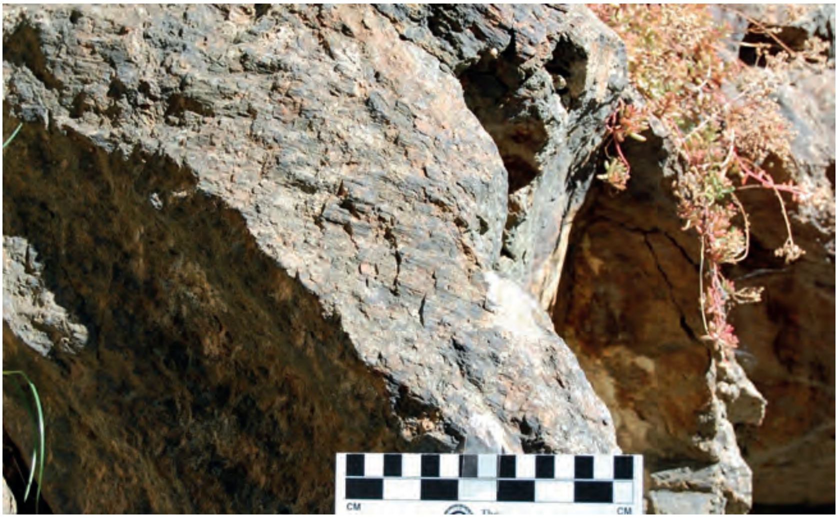

STUDY ON CORRELATIONS BETWEEN ROCK STRESSES AND MAJOR FAULT ZONES

Ann Bäckström
Yanting Chang

BeFo Report 174

Cover photo:
Figure 21. An example of a fault surfaces from site Nockeby (02) surface no. 002a) indicated as 02-002a in Table 1.

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STUDY ON CORRELATIONS BETWEEN ROCK STRESSES AND MAJOR FAULT ZONES

Förstudie av korrelation mellan spänningsregioner och stora förkastningar

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BeFo Report174
Stockholm 2020
ISSN 1104 – 1773
ISRN BEFO-R—174—SE

PREFACE

The stress field is an important issue in design and construction of underground structures. A number of tunnel and other underground infrastructure projects are in the planning phase or under construction in Sweden. Stress measurements have been performed in the Stockholm area and the measurement results have provided basis for planning and design of the underground projects within the region. In Perman and Sjöberg's report (2007), the stress fields in the central parts of Stockholm are divided into different domains, based on engineering assessments of the measurement data (Perman & Sjöberg, 2007). The domains are bounded by the major fault zones in the area.

The rock stress measurements show however relatively large variations, which leads to uncertainties in the applications of the measured data in design of the underground projects. The main aim of this study is to provide complementary information on rock stresses by studying the movements of major fault zones. A method called "stress inversion" has been tested in this study. This method has been previously used for tectonic studies worldwide. In the Nordic region a number of tectonic analyzes were performed at locations including Forsmark, Laxemar-Simpevarp and Olkiluoto, where they have been able to identify different stress fields in the geological history (Sanitot et al., Viola et al., 2009, Viola et al., 2011, Mattila Et al., 2014).

As a complementary study, a simplified numerical modelling has been performed in this study, aiming to connect the rock stresses to the geological features, namely the movements of the major fault zones. This opens up to an interesting research field, where the geological knowledge is combined with rock mechanics. This combination is believed to be able to improve the knowledge on rock stress distributions and orientations.

The results of this study indicate that the major principal stress in Stockholm area is likely oriented in the E-W direction, which has the best correlation to the movements of the fault zones. The variations of the stress orientation are insignificant, even the fault zones have local impacts on the stress orientations.

The working group for this study is consisted of Ann Bäckström, former Pöyry Sweden AB and Yanting Chang, Geton Consulting AB.
The reference group contributed with valuable suggestions, background data and review and consisted of: Curt Wishmann, Raymond Munier, Giulio Viola, Carl-Olof Söder, Ulf Andersson, Daniel Ask and Per Tengborg (from BeFo). In addition, a number of people have shown interest and been involved in appreciated discussions. These are Lars Maersk Hansen, Susanne Grigull, Carl-Henric Wahlgren and Frano Cetinic.

The project was funded by Rock Engeneering Research Foundation - BeFo and through in-kind by the working group's organizations.

Stockholm, 2020
Per Tengborg

FÖRORD

Spänningsfältet är en viktig fråga i underjordiska anläggningsprojekt. Ett flertal tunnel- och bergrumsprojekt är under projektering eller byggande i Sverige. Spänningsmätningar har utförts och mätresultaten ligger till grund för planeringar och projektering av underjordsprojekt som pågår i Storstockholmsområdet. I Perman och Sjöbergs rapport har domänindelningen av spänningsfälten i de centrala delarna baserats på en ingenjörsmässig bedömning av mätdata (Perman & Sjöberg, 2007) där domänerna avgränsas av de större förkastningszonerna i området.

Spänningsmätningarna visar dock på relativt stor spridning, vilket leder till viss osäkerhet i användningen av spänningsdata till exempel i projekteringsarbete. Huvudsyftet med denna studie är genom att analysera främst rörelse-indikatorerna runt förkastningszoner kunna bedöma spänningsfördelning inom Stockholmsområdet. En metod som kallas ”stress inversion” har testats i denna studie. Den här metoden har använts för tektoniska analyser i världen, inklusive i Norden, bl. a. i Forsmark, Laxemar-Simpevarp och Olkiluoto, där man har kunnat identifiera olika spänningsfält i olika geologiska tidsperioder (Sanitot et al. 2011, Viola et al. 2009, Viola et al. 2011, Mattila et al., 2014).

Som komplement har också en förenklad numerisk modellering utförts som ett försök att koppla bergspänningar till geologiska företeelser, nämligen rörelser av större förkastningszoner. Detta öppnar ett intressant forskningsområde, där geologiska kunskaper kombineras med bergmekaniska metoder. Denna kombination anses kunna fördjupa kunskaper, bl. a. om bergspänningsfördelning och -orientering.

Resultat av denna studie indikerar att huvudbergspänningsorientering inom Stockholms-området ligger huvudsakligen i E-W-riktning. Variationer av spänningsorienteringen är små, även de större förkastningszonerna har lokal påverkan på bergspänningsorienteringen.

Arbetsgruppen för denna studie består av Ann Bäckström, f.d. Pöyry Sweden AB och Yanting Chang, Geton Consulting AB.

Referensgruppen bidrog med råd och granskning och bestod av: Curt Wishmann, Raymond Munier, Giulio Viola, Carl-Olof Söder, Ulf Andersson, Daniel Ask och Per Tengborg (BeFo). Dessutom har ett flertal personer visat intresse och diskuterat projektet med arbetsgruppen, bl. a. Lars Maersk Hansen, Susanne Grigull, Carl-Henric Wahlgren och Frano Cetinic.

Projektet finansierades av Stiftelsen Bergteknisk Forskning – BeFo och genom viss in-kind av arbetsgruppens organisationer.

Stockholm, 2020
Per Tengborg

SUMMARY

This report presents a pilot study in which the relative movements of major rejections in the Stockholm area have been investigated. Then, rock stress directions are estimated by analyzing the movement data using a theory called "stress inversion" as well as numerical modeling.

Methods based on the theory of stress inversion have previously been used in Forsmark, Laxemar-Simpevarp and Olkiluoto (Sanitot et al., 2011, Viola et al., 2009, Viola et al., 2011), where different stress fields could be identified in different geological periods.

In the framework of this project, mapping of fractures with movement indicators has been performed in 6 different locations in the Stockholm area. The relative movements are identified from striations on fracture surfaces as well as displacement of intersecting structures, such as dykes. Totally, data on 46 fracture surfaces have been obtained.

The movement data can then be analyzed and the rock stress directions obtained by using the computer program "Tensor". The "stress inversion" theory is used in the computer program. An important assumption for the "stress inversion" theory is that the direction of the movement on a fracture is parallel with the largest shear stress on the fracture surface.

An effort has also been made in inventory of geological investigations from the infrastructure projects in Stockholm, for example, Citybanan, Forbifart Stockholm, City Link and Metro extensions. Data from core boreholes, reports, displacement measurements, etc. have been analyzed and compiled. Based on these materials, relative movements in the major fault zones can be identified. The results indicate that the Stockholm area has been subjected to a tectonic movement in the E-W direction, where the rock mass has deformed under brittle conditions (i.e. about 0-15 km deep in the crust).

A simplified 2D numerical model with different displacement boundary conditions has been performed. By comparing the calculated movements in the fault zones with the identified as mentioned above, a likely regional stress field for the Stockholm area can be obtained. The result indicates that major principal stress in the Stockholm area is likely oriented in the E-W direction. The result does not suggest a clear stress domain division as described by Perman and Sjöberg (2007).

KEYWORDS:

Rock stress, stress domain, regional stress field, fault zone, movement indicator, striations, tectonic movement, stress inversion, numerical modelling.

SAMMANFATTNING
Denna rapport redovisar en pilotstudie där de relativa rörelserna av större förkastningar inom Stockholmsområdet har undersökts. Sedan uppskattas spänningsriktningar genom att analysera rörelsedata med hjälp av en teori som kallas ”stress inversion” samt numerisk modellering.

Metoder baserat på ”stress inversion”-teorin har tidigare använts i Forsmark, Laxemar-Simpevarp och Olkiluoto (Sanitot et al., 2011, Viola et al., 2009, Viola et al., 2011), där man har kunnat identifiera olika spänningsfält i olika geologiska tidsperioder.

Inom ramen för detta projekt har kartering av sprickor med rörelseindikatorer utförts på 6 olika platser i Stockholmsområdet. De relativa rörelserna identifierades från strieringar på förkastningsytor och som deformation av korsande strukturer som gångar och dylikt. Sammanlagt har data på 46 st. förkastningsytor samlats.

Med hjälp av dataprogrammet ”Tensor” kan rörelsedata analyseras och bergspänningsriktningar beräknas baserat på ”stress inversion”-teorin. Ett viktigt antagande för ”stress inversion”-teorin är att rörelseriktning på en spricka sammanfaller med den största skjuvspänningen på sprickytan.

En insats har också gjorts i att inventera undersökningsmaterial från infrastrukturprojekt inom Stockholm, t. ex. Citybanan, Förbifart Stockholm, City Link och tunnelbaneutbyggnad. Data från kärnborrhål, rapporter, mätningar m.m. har analyserats och sammanställts. Baserat på dessa material kan relativa rörelserna i de större förkastningszonerna identifieras. Resultaten indikerar att området har utsatts för en tektonisk rörelse i E-W-riktningen när bergmassan deformerats under spröda förhållanden (dvs ca 0-15 km djup i skorpan).

En förenklad 2D numerisk modell med olika ”displacement boundary conditions” har utförts. Genom att jämföra de beräknade rörelserna i förkastningszonerna med de identifierade som nämns ovan, erhålls ett troligt regionalspänningsfält för Stockholmsområdet. Resultatet indikerar att huvudbergspänningsorienteringen inom Stockholmsområdet ligger huvudsakligen i E-W-riktning. Resultatet visar inte på en tydlig spänningsdomänindelning som beskrivs av Perman och Sjöberg (2007).

NYCKELORD:
Bergspänning, spänningsdomän, regionalspänningsfält, förkastningszon, striering, rörelseindikator, tektonisk rörelse, stress inversion, numerisk modellering

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1. INTRODUCTION

For design and construction of underground structures, information of stress fields is an important base. There are a number of tunnel and underground infrastructure projects, which are under construction or planning in Sweden. Within the Stockholm area, stress measurements have been performed and the results have provided basis for planning and design of the underground projects within the region. According to Perman and Sjöberg's report (2007), the stress fields in the central parts of Stockholm are divided into different domains. The domains are bounded by major fault zones.

The rock stress measurements show however relatively large variations, which leads to uncertainties in the applications of the measured data in design of underground projects. The study presented in this report is an attempt to extract information on rock stresses by studying geological features, namely the movements of major fault zones. It is hoped that the study results could provide complementary information of rock stresses for engineering purposes.

The framework of this study consists of the following elements.

- Mapping of fractures with movement indicators: The mapping has been performed in 6 different locations in the Stockholm area. The relative movements will be identified from striations on fracture surfaces as well as displacement of intersecting structures, such as dykes.

- Data analysis: By using the theory of “stress inversion”, rock stress directions will be obtained by analyzing the movement data. The base for the "stress inversion" theory is that the direction of the movement on a fracture is parallel with the largest shear stress on the fracture surface. The data analysis will be performed by means of the computer program "Tensor".

- Inventory of the existing geological investigations: An effort will be made to collect and analyze the geological investigations from the infrastructure projects in Stockholm, for example, Citybanan, Forbifart Stockholm, City Link and Metro extensions. The aim is to identify the tectonic movements of the fault zones.

- Numerical modelling: A simplified 2D numerical model with different displacement boundary conditions will be performed. By comparing the calculated movements in the fault zones with the identified as mentioned above, a likely regional stress field for the Stockholm area can be obtained.

The report consists of the following chapters:

Chapter 1: Introduction

Chapter 2: Regional geological settings, including the results of the performed rock stress measurements.

Chapter 3: Investigation of major geological structures, where the locations and performance of the filed mappings are described, as well as the collected geological data are presented.

Chapter 4: Reconstruction of the stresses by using the theory of “stress inversion”.

Chapter 5: Numerical modelling, where the model, boundary conditions and results are presented.

Chapter 6: Discussions and conclusions.

2. REGIONAL GEOLOGICAL SETTING

The Stockholm area is geologically located within the Bergslagen province which formed during the Svecofennian orogeny (1750-2600 Ma) (Stephansson, 1979). It is thus included in the Svecofennian domain which comprises a sequence of supracrustal and intrusive rocks extending from Finnish Lapland and northernmost Sweden to Västervik (Lindström et al., 2000) formed between 1.75-2.0 Ga (Gáal and Gorbachev, 1987). The Svecofennian orogeny formed much of the continental crust of the present day Sweden and Finland as well as some minor parts of Russia. It is a part of the Baltic shield (also referred to as the Fennoscandian shield) and comprises the exposed Precambrian northwest segment of the East European craton (Buchan et al., 2000).

The Bergslagen province is included in the southern Svecofennian domain and is currently characterized by a thrust regime with a predominant NW-SE orientation.

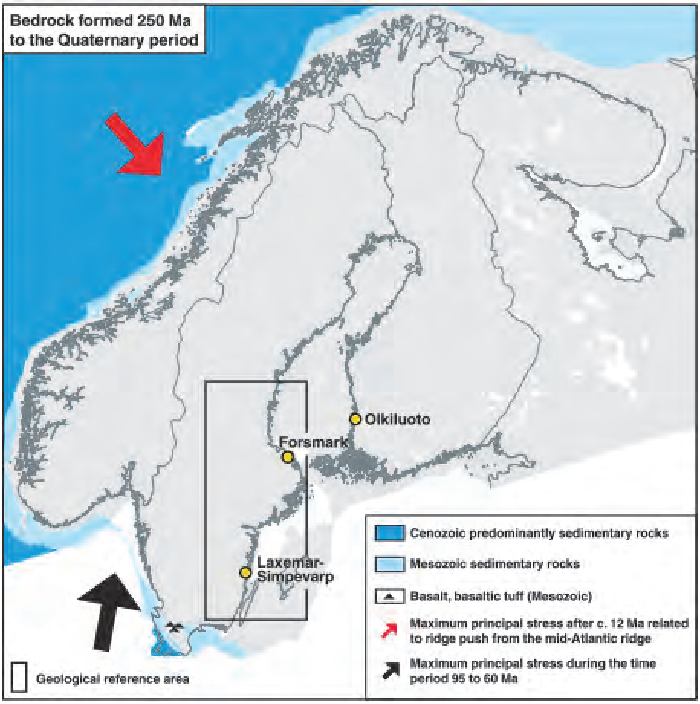


Figure 1. Already at about 250 Ma most of the rock in Fennoscandia was formed (shown in grey). The principal stresses dominating since then are shown as large arrows. The figure is based on the database that accompanies the geological map of the Fennoscandian shield (from Söderbäck, 2008).

2.1. Regional stress state

The stress fields occurred over geological time have caused the deformational features, which are evident in the Stockholm bedrock. The stress field acting on this region today is believed to be the tectonic forces from the Mid Atlantic Ridge push and to a much lesser extent the formation of the Alps which has been acting since 250 Ma (Figure 1) (Söderbäck, 2008). They have been active during different times. The tectonic forces from the Alps had their major events during 95 to 60 Ma, whereas the ridge push from the Mid Atlantic ridge started at about 12 Ma and is now probably the most dominant force.

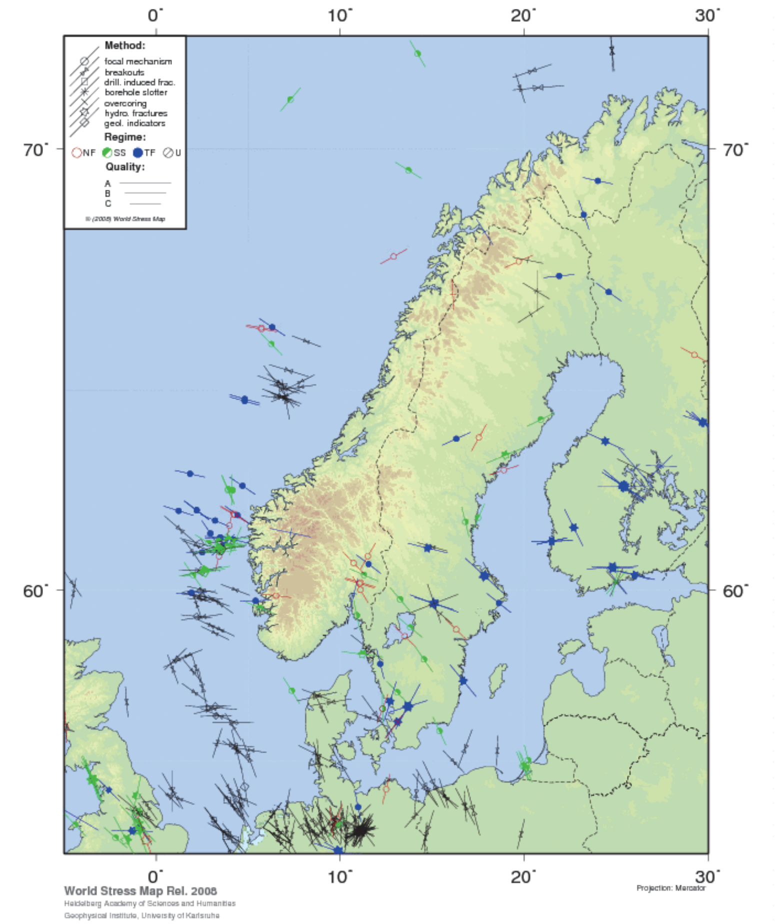


Figure 2. The current stress map over Scandinavia from the project World stress map, Heidbach et al. (2008).

A compilation of stress measurements in the world can be downloaded from the world-stress map at http://dc-app3-14.gfz-potsdam.de/pub/stress_data/stress_data_frame.html and the current one over Scandinavia is reproduced here (Figure 2). The in-situ stress measurements presented in the map are from areas juxtaposed to Stockholm, indicating a current compressional stress field with a NW-SE maximum horizontal stress that is inferred to result from mid-Atlantic ridge push (Martin, 2007; Glamheden et al., 2007). The vertical stress is mainly controlled by the weight of the overburden.

In later chapters, it will be shown that the dominant fracture orientation is NW-SE, but first we need to begin at the beginning with the formation of the crust in this region.

2.2. Main aspects of the regional structural framework

The rock mass region in which Stockholm is situated is known as the Bergslagen region. Our study area is situated along the eastern margin of the Bergslagen area. In the Stockholm part of Bergslagen the bedrock with its supracrustal and igneous rocks are mainly formed between 1960-1840 Ma. (Persson et al. 2001). To get an overview of the possible events that might have lead up to what we see today we have listed the largest known events found from earlier studies in and around Bergslagen. This order looks very clean chronologically but should be read with care and the knowledge that these events can affect each other to a varying degree and many of them are long term events. Also the event itself can be divided into several stages affecting different areas at different times. Thus, this is a list that looks "clean" but must be read as a major events list with many local effects ranging in time.

The following events have affected the bedrock in the area to a varying degree:

- The formation of the Bergslagen sequence starts during the Svecofennian orogeny; the dominating part of the rock types formed between 1.96-1.84 Ga. (Persson et al. 2001).

- The ductile deformation and metamorphism took place between 1.9-1.8 Ga (Koistinen et al., 2001).

- Gáal and Gorbachev (1987) suggested that the supracrustal and intrusive rocks were formed in a somewhat larger time span, i.e., between 2.0-1.75 Ga.

- A ductile shortening at 1.7–1.6 Ga with a NE-SW orientation is established in an area approximately 350 km northwest of the Stockholm area, where post-

Svecofennian rocks were formed which are dated to 1.7 Ga (Bergman et al., 2006).

- The Gothian orogeny occurred in the vicinity of the Stockholm area, it occurred in western Fennoscandian shield between 1750 and 1500 Ma and is now overprinted by the Sveconorwegian orogeny.

- The occurrence of Mesoproterozoic extensional events in southeastern Sweden is indicated by the intrusion of different generations of dolerite dyke swarms. Dykes that formed around 1.6 Ga and trend WNW-ESE are present approximately 120 km west of Stockholm (Stephens et al., 2009).

- Wickman et al. (1983) reports of Rb-Sr ages of veinlets and veins from 1600-1500 Ma and 1250-1100 Ma indicate growth of epidote during the early part of the Mesoproterozoic in the area north and NE of Lake Mälaren. This coincides with a known tensional movement in the region.

- In the Lake Mälaren and on the shore of the lake, Jotnian sandstones (>1260 Ma) (Gorbatchev and Kint, 1961) are preserved in deep trenches, indicating faulting before or at this time period.

- Söderlund et al. (2005) identified dolerites in the Protogine Zone with U-Pb ages of 1,215 - 1,221 Ma, The Central Scandinavian Dolerite Group 1,264 - 1,271 Ma, the Tuna dikes and age equivalents in Dalarna with ages of 1,461 - 1,462 Ma as well as Värmland dolerites with ages of 1,568 Ma and Breven-Hällefors dolerites with ages of 1,595 Ma. The favoured tectonic model for these dykes implies that the majority of these suites were related to active margin processes somewhere west (and possibly south) of the Fennoscandian shield. Dolerite intrusions are interpreted to reflect discrete events of back-arc extension as the arc retreated oceanward (Söderlund et al. 2005).

- SvN, Sveconorwegian orogeny (1140–960 Ma) (Andersson et al., 2008). The forming of the Neoproteozoic Sveconorwegian orogeny to the southwest of the Svecofennian domain occurred with a series of compressional and extensional orogenic phases.

- Neoproterozoic extensional events are indicated by dykes that formed at 0.98–0.95 Ga with orientations trending NNW-SSE. The dated dolerites occur to the west of the Stockholm area (Söderlund et al., 2005) and are called the Blekinge-Dalarna dolerites. They have been dated to 0.946 – 0.978 Ma (Söderlund et al., 2005). The favoured tectonic model implies that the majority of these suites were related to active margin processes somewhere west (and possibly south) of the Fennoscandian shield during the later stages of the Sveconorwegian orogeny. Dolerite intrusions are interpreted to reflect discrete events of back-arc extension as the arc retreated oceanward (Söderlund et al. 2005).

- The Palaeozoic Caledonian orogeny (approximately: 490–390 Ma).

According to Stephansson (1979), the Bergslagen region includes the Leptite seismo-tectonic zone. This is one of eleven zones in Fennoscandia derived from association of seismic events (between the historic years 1497-1975) along zones of crustal weakness. The Leptite Zone is described as a circular structure surrounding the Vdala-Upland and the Dala batholites. From the seismic events the conclusion that earthquakes are distributed around the granitic core of the Vdala-Upland and Dala batholite can be drawn (Stephansson, 1979). According to Stephansson (1977) the Vdala-Uppland batholith is the largest and most characteristic in form of the batholiths in central Sweden. It has an almost circular outcrop within a belt of synorogenic granites and foliated granitic gneisses which concentrically surround a core of less deformed quartz diorites and granodiorites.

2.3. The local brittle structural framework

In a seismo-tectonic study of the Fennoscandian shield area (Stephansson, 1979) the preservation of the Jotnian sandstones (>1260 Ma) (Gorbatchev and Kint, 1961) in down-faulted basins and the juxtaposed diabase clearly indicates post-Svecofennian faulting within the Leptite Zone. The post-Svecofennian tensional regime and normal faulting is corroborated by the emplacement of the dolerite dyke swarms in the age interval 1.57-0.95 Ma in Bergslagen and adjacent areas (Söderlund et al., 2005). There are several identified dolerite dykes in the study area that have orientations similar to the radio-dated Bergslagen dykes, thus, it is likely that they are of a similar age.

From studies made in an area to the NE of Stockholm, it is found that the area has repeated been subjected to brittle deformation between the ages 1750-250 Ma and later (Figure 3) (Stephens et al, 2009).

Several of the large fault zones of the area such as Lambardfjärden, Söderströms and Stocksund fault zone were affected by brittle deformation during this time (Figure 4).

2.4. Lambardfjärden fault zone

The Lambard fjärden fault zone is probably a ductile shear zone that has been subjected to brittle geological events at a later stage.

In Stålhös (1968) and Persson et al. (2001) the Lambardfjärden fault zone is indicated but no characterization or evidence was produced to verify the existence of the zone on these maps. It has been interpreted as a normal fault dipping approximately 70-80° towards the southwest (Stålhös, 1968; Persson et al., 2001; Trafikverket, 2010).

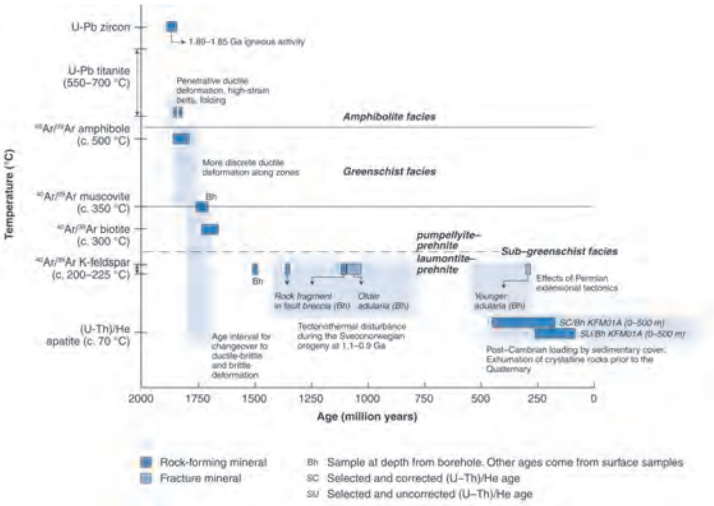


Figure 3. Summary of radiometric age data and the bedrock geological evolution in the Formark area in the NE part of the Bergslagen region (Stephens et al., 2009).

Figure 4. Part of map of fault and fracture zones in the Stockholm area from Stålhös (1969) with the fault names along the structures. The thick black lines are dolerite dykes (indicating possible extensional phase) crossing the area, the thin dashed lines are fracture zones according to Stålhös (1969).

Figure 5. Results from the investigation by Vass, 2012. The coloured lines are the tunnels for the project Förbifarten, where the colours denotes the expected rock quality. The bore holes are indicated in red.

During the pre-feasibility study of the Stockholm Bypass (Förbifart Stockholm, *in Swedish*) project several investigations of this fault zone were produced. Data from surface mapping, drillings and various geophysical studies were compiled in a Master of Science thesis by Vass (2012). Here evidence is presented for the existence and the characteristics of this fault zone, as well as a structural model of it. An approximately 160 m wide diffuse shear zone has been found from the drilling of Lambardfjärden. The core of which can be described as a NW-striking brittle-ductile shear zone with steep dip and it is observed in the drill core 08F351K, 08F532K and parts of 10F535K. In the core 08F532K two breccias occur with a NW and NE orientation with moderate dip. A breccia striking NW with a moderate dip is found in the core 10F535K (Figure 5).

The most frequent (cementing) mineral fillings in the 08F351K core are calcite, chlorite and clay minerals. Minor components of mineral fill are also red feldspar, hematite, and quartz, whereas silty sand occurs as fracture filling (Vass, 2012).

According to Vass the Lambardfjärden zone is a part of a conjugate system where the NW-striking Lambardfjärden fault has a right-lateral sense of shear together with a NNE-striking segment can be considered as a separate fault with a left-lateral sense of shear.

2.5. Stocksund fault zone

Stålhös, 1969 suggests a fault zone from Norrviken in the north to Stockholm Kungshamn (Nacka) in the south (ending at the Söderströms fault zone) (Figure 4). He suggests a fault zone oriented NW-SE with a dip towards SW. during the City Link project (a tunnelling project for Svenska kraftnät) the water passage at Stocksund was drilled with three cored drill holes, 13VEC02K, 13VEC10K, in the northern part of Stocksund and 13VEC14K, to the northwest of the two others. The orientation of the dominant fracture set in drill core 13VEC10K is in the direction of the fault zone previously identified in the SGU map, about 295-300°/70-80°.

From the oriented core 13VEC02K 5 measurements have been made by a student at Uppsala university, unfortunately the results are not published yet. The location of the 13VEC10K core can be seen in Figure 6. The core yielded two surfaces with slickensides in the area of the core with two zones of clay and two instances of core loss (0,75 m and 0,5 m), this area is not possible to orient for obvious reasons (no core). A photo of the clay alteration at 76 m core, just below the area of core loss can be seen in Figure 7.

Figure 6. Location of the bore hole 13VEC10K in Stocksundet, crossing the fault zone.

Figure 7. Fault gouge in core 13VEC10K. OBS the upper photo is of fault gouge at about 76 m and the lower is at about core length 72,9 m.

Figure 8. Location of drill hole 13VEC14K in Stocksundet.

No slickensides were identified in the drill core 13VEC14K located further to the north Figure 8. The fractures in this drill hole are not as persistent in one direction but the two dominant fracture sets display one fairly steep dipping SW-NE striking and a sub-horizontal set striking SE-N by NW.

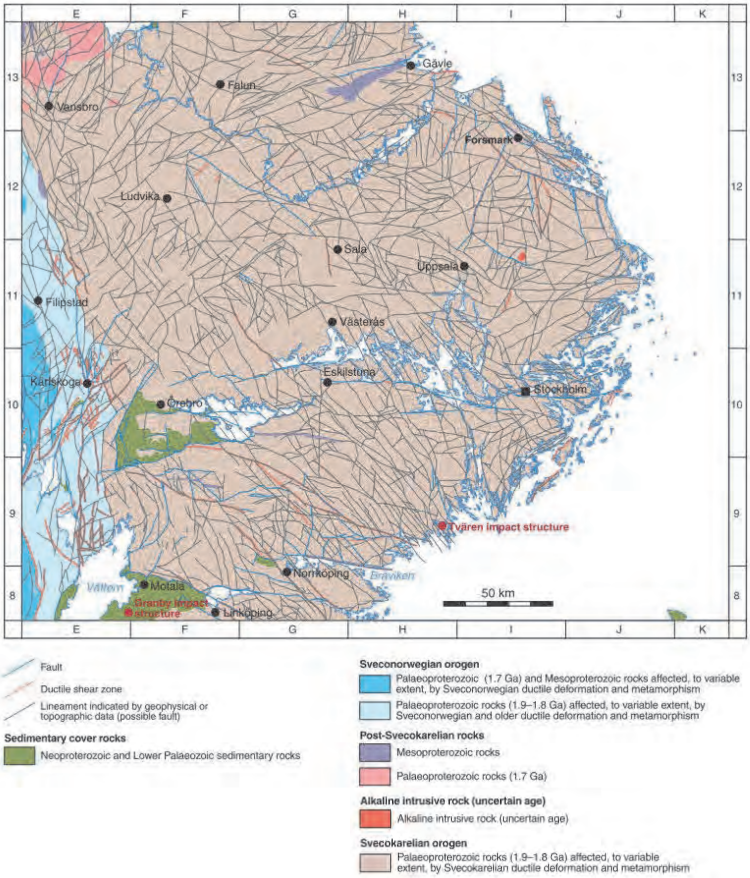
2.6. Söderströms fault zone (a k a Söder Mälarstrands fault zone)

This is a regional fault zone and a part of the northern limit of what is referred to as the Sörmland horst which is a raised morphological feature stretching in E-W direction along the southern margin of the lake Mälaren all the way to Kilsbergen in Närke (Stålhös, 1968; Stephens et al., 2009). The Sörmland horst is suggested to be about 220 km long, E-W striking zone with a width of 110 km containing about 5 minor zones identified in the topography (Henkel and Roslund, 1994). As it is such a distinct morphological feature it is suggested by Henkel and Roslund (1994) to be a result of recent activity with a date of less than 10Ma. The Söderströms fault zone follows the northern shore of the Södermalm Island.

The fault zone is suggested to be included in a fault system defining one of the first order deformation zones in Sweden (Henkel and Roslund, 1994). The first order steep fault zones is defined in the report by Henkel and Roslund as "an area characterized by deformation concentrations due to horizontal-differential movements of lithospheric blocks with an individual distance of these features depending on the thickness of the included layers in the lithosphere". For the Fennoscandian shield that is about 250 km, this is the general thickness of the lithosphere under the central parts of the shield (Henkel and Roslund, 1994).

Further to the west this system is involved in faulting of N-S striking dykes with an E-W displacement (Figure 9).

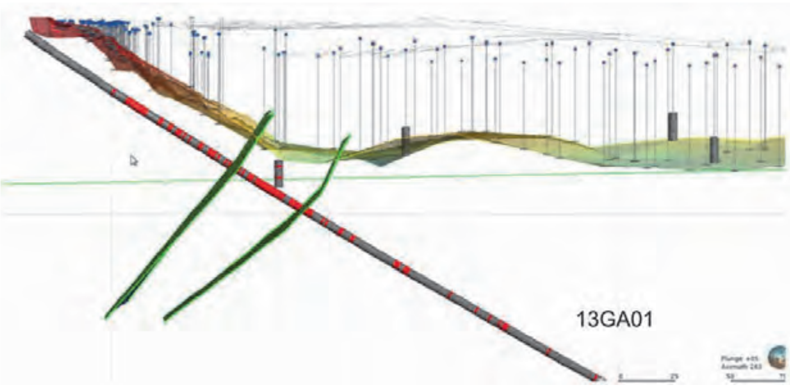
As the name Sörmland horst implies the rock mass to the south of the fault zone has been displace upwards at some point in time, probably several hundred of meters from which now only a few tens of meters are displayed due to erosion. This fault has thus been acting as a reverse fault with possible displacements of several hundreds of meters, now eroded down to a few tens of meters This displacement down faulted the Jotnian Mälaren sandstone (about 1.2 Ga) further to the west for more than 500 m and this has been drilled and reported in Olsson, 2003 and Henkel et al., 2004 amongst others. It has likely been active between the ages 1750-250 Ma and later (Stephens et al, 2009). The fact that it has been active after the Cambro-Silurian times (about 600-400 Ma) can be seen at the plains of Närke (near Ösrebro) where the fault system is involved in down faulting of Lower Paleozoic sediments.



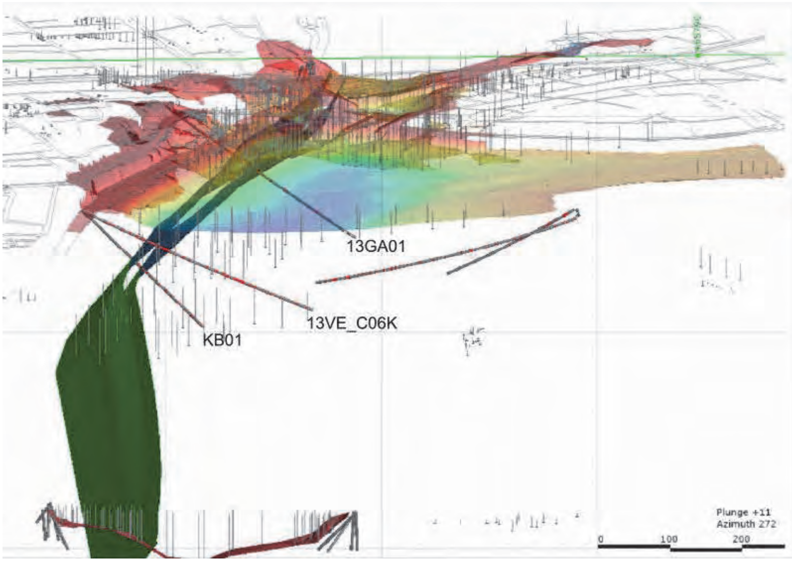
a.

b.

Figure 9. a) Lineaments and faults, and their relationship to ductile shear zones and the major tectonic units at the ground surface in the Bergslagen region, after Stephenson et al. 2009. b) Detailed view of the involvement of the fault system that Söderströms fault is a member in the down-faulting of the Lower Paelozoic rocks near Örebro (Stephens et al., 2009). For legend see Fig. a.



a.



b.

Figure 10. a) 3D-model of the interpreted Söderströms fault from ENE towards Slussen and b) detailed view of the fault when it cuts the bore-hole 13GA01 (Olsson et al., 2014).

It is crossed by drill holes: 13GA01 (for project: Slussenprojektet), KB01 (for project: CityLink), 13VEC06K, 13VEC07K and 13VEC09K (all three for project: CityLink).

According to a 3D-Geomodel based on these drillings, amongst other information, of the fault at Strömmen in Stockholm (Olsson et al., 2014) the fault has an orientation of ~70-90°/~ 70°, and is described as a duplex structure. As it is described as a duplex structure the width varies strongly.

In the 3D-model, the central part of the fault is described as a zone of a few tens of meters limited to the north with a zone of oxidized rock of fairly good quality rock, and to the south with an oxidized zone with fractured rock (Olsson et al., 2014), (Figure 10).

Today, it is likely a strike-slip fault with right-lateral movement where the northern shore is moving east and the southern westwards (Stålhös, 1968; and Stephens et al. 2009). According to a study by Golder, Sweco and the department of geophysics at the University of Uppsala, made for Citybanan about 2005, this movement is possibly continuing with a few mm today (Hansen and Vestgård, 2015). The study of displacements, using high resolution GPS, were made 1997-2002, with additional measurement in 2014-2015.

In this work the assumption is made that this fault zone continues to the SW and is here referred to as the SW extent of this fault zone. This does not have to be the case, it can also continue further to the W-NW along the southern shores of Kungsholmen and then continuing onto land in Nockeby/Hässelby area.

The south western extent of this fault zone passes between Sätra and Kungshatt (Figure 11). The kinematics of this part of the zone has been investigated in the Stockholm bypass project (Figure 12) in three bore holes (08F152K, 08F153K and 10F156K) and on outcrops in the area. According to Ignea, 2015 this "kinematic investigations the majority of the fracture zones can be assumed to have a right-lateral horizontal shear component. The orientation of the zones of crushed rock shows that the dominating orientations range from ENE-WSW to NNE-SSW" From the fracture infilling a weak connection could be found between dip-slip faulting and chlorite infilling and between strike-slip faulting and graphite infilling (Ignea, 2015), indicating that these are two different generation of kinematics.

The borehole 10F156K displays several areas with crushed rock but there are two main areas which can be identified as fracture zones. One is in the area close to the southern shore of Mälaren with a dip to the SE and the dominant fracture minerals are chlorite and clay.

From the investigations of the bore holes, strike-slip with a right-lateral movement along the fault zone is indicated. Ignea interpreted the area to be characterized by either a conjugate fracture system or by Riedel shear fractures, formed by WNW-ENE oriented stress field from the Atlantic ridge push forces (Figure 12). The suggested orientation of the stress field has been plotted in Win tensor and presented in Figure 13.

Figure 11. Location of the bore holes in Fiskarfjärden (Ignea, 2015).

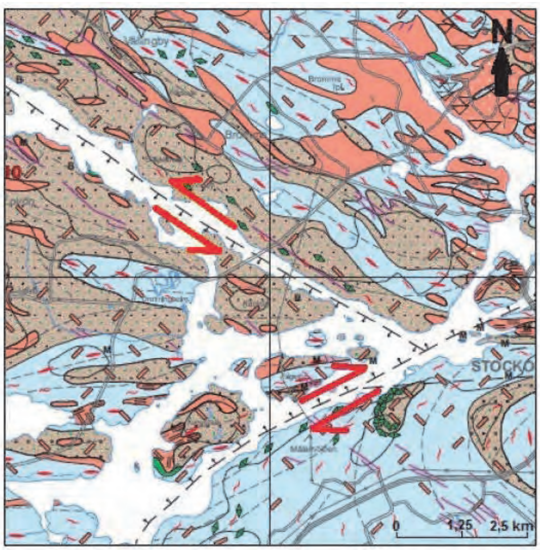


Figure 12. Suggested model for the kinematic indicators found in the core from Fiskarfjärden. Here both the fault in Fiskarfjärden and Lambardfjärden fault zone is involved in the event as they form conjugate faults.

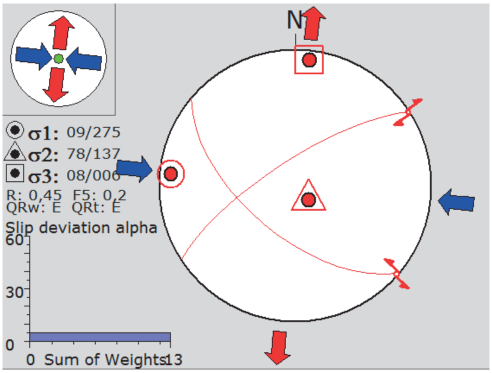


Figure 13. The suggested orientation of the stress field plotted in Win tensor for the Fiskarfjärden results.

Generally, in investigations of drill cores for infrastructural projects the kinematic indicators are not included in the parameters identified. There is a way to back calculate the existence of these features. In the classification system for rock masses with respect to stability of underground openings (the Q-system) the existence of slickensides are included in the Joint Roughness (Jr) parameter (being set to 0.5 when slickensides are observed). However, the crucial information of the orientation of the kinematic indicators needs to be measured separately. This demands that the drill core is revisited and the orientation of these features are measured. This was done by Vass (2012) on the drill cores for Lambardfjärden fault and by Ignea (2015) for the possible SW continuation of the Söderströmsfault at Fiskarfjärden (close to Sätra).

2.7. Smaller fault zones in the area

Smaller fault zones have been identified in infrastructural projects such as the City line. In the northern part of the City line (Citybanan *in Swedish*) Andersson and Swindell (2008) identified 14 **weakness** zones along the route of the City line; the most prominent crossing the City line at Kungsgatan and södra Riddarholmen; its strike is WNW-ESE.

In investigations from a water tunnel in the northern part of Stockholm city, 15 smaller fracture zones (referred to as crushed rock zones in Hildebrant, 2001) are found. Six of them have a strike of NW-SE to NNW-SSE and five have a strike of NNE-SSW to NE-SW. The zones with a NW-SE to NNW-SSE orientation are the dominant. These orientations are also found on the surface in this area thus the trends found on 30-40 m depth are reflections of the trends found from surface mapping (Hildebrant, 2001).

2.8. Dominating fracture sets

Persson (1998) identifies three major fracture sets: NW-WNW (NW-SE according to Stålhös, 1968), ENE-NE (NE-SW according to Stålhös, 1968), and N-S (Figure 14). They do not include the additional fourth set of E-W which Stålhös describes as the strike of several weakness zones in the area. Andersson and Swindell (2008) also identify three sets of dominant fractures in the northern stretch of the City line project (north of Torsgatan (which is one of our sites) to Riddarholmen in the south (just north of the Söderströms fault zone)). They investigated 70 drillcores with a total length of c. 3000 m, 1850 m of existing tunnels, and 1000 m of rock outcrops for the City line project. They found that (1) the most common fracture set is subhorizontal, then (2) steep fractures striking NE, and finally (3) NW-WNW-striking fractures with variable dips to the NE. The first two dominate the northern and southern, mostly granitoid parts of the City Line area, while the NW-striking fractures are most prominent in the central, gneiss-dominated area. They also find that in both cases the direction of the brittle fractures appears to be largely controlled by the foliation in the gneiss and they conclude that a significant part of the subhorizontal fractures may be related to unloading after isostatic rebound.

In Stephens et al. (2009) the study of an area to the NE of Stockholm identifies these gently dipping zones, which are at a high angle to σ_3 in the current stress regime, as most susceptible to dilatational strain and reactivation and, thereby, most susceptible to bear groundwater at the present time.

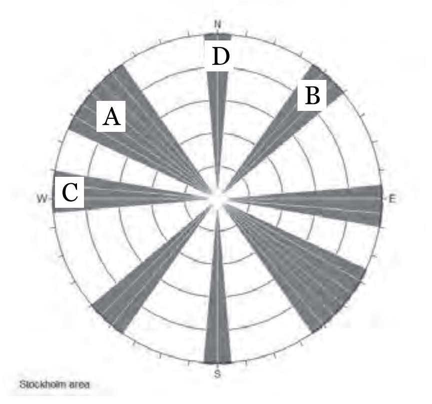


Figure 14. Rose diagram of the dominant fractures in the Stockholm area according to Andersson and Swindell (2008), where group A strike NW-SE, group B NE-SW, group C E-W and group D N-S.

2.9. Mineralogy in fractures

As Stockholm has a long history and we see a deep erosional level the minerals in the fractures are very diverse, but some notes can be made.

According to Andersson and Swindell, (2008) the most common minerals in the fractures in their study area (the northern part of the City Line) are calcite and minor chlorite. Clay and graphite (only in the gneiss) occur as infill materials locally.

During the investigation of the area around Fiskarfjärden the fracture infilling show that a weak connection could be found between dip-slip faulting and chlorite infilling and between strike-slip faulting and graphite infilling (Ignea, 2015), indicating that these are two different generation of kinematics.

In the bore holes in Lambardfjärden (Vass, 2012) the most frequent mineral-fillings are calcite, chlorite, laumontite, prehnite and clay minerals. Many surfaces display no mineral fillings at all, whereas the less frequent minerals were red feldspar, pyrite, zeolite, hematite, quartz, biotite, epidote, talc, dull and oxidized surfaces, and silty-sandy fracture surfaces.

Many of the surfaces investigated in this study displayed no mineral fill, but quartz, heamatit, calcite and some dull and oxidized surfaces were identified.

2.10. Exisiting in-situ stress measurements

The In-situ stress measurements used in this study are the ones presented in Perman & Sjöberg (2007). They made a compilation of the existing stress measurements in the Stockholm region for the infrastructure project Citybanan. About 80 measurements were presented although 5 were excluded for various reasons (Figure 15).

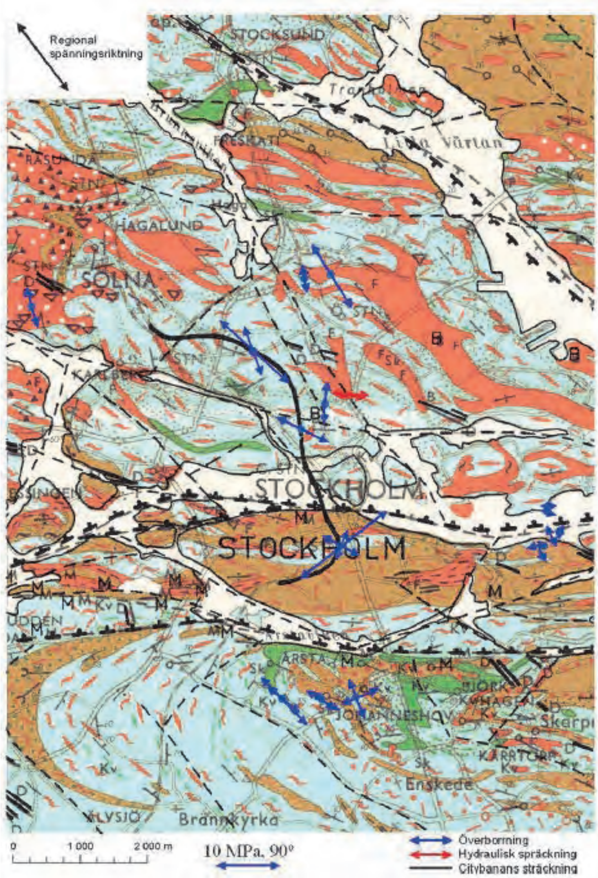
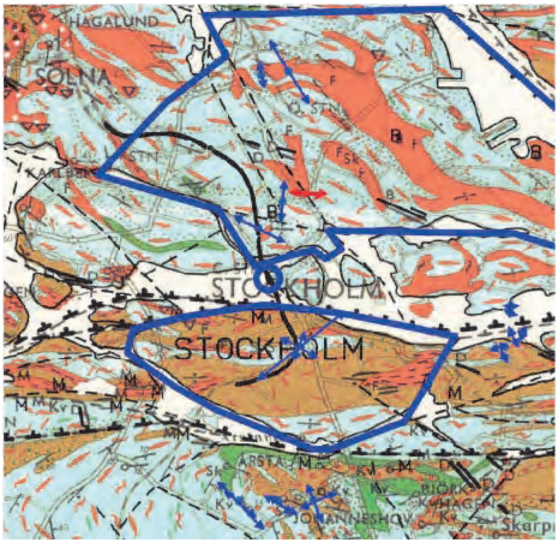


Figure 15. Geology and structures as well as direction and average value for the maximum horizontal stress axis for in-situ stresses in the Stockholm area. The regional stress direction is presented in the upper left corner. The figure is a combination of several maps and is thus an estimate. From Perman & Sjöberg, 2007, the geological map is from Stålhös (1969).



Från Perman och Sjöberg, 2007

Figure 16. Stress domains according to Perman and Sjöberg, 2007.

They identified three s.k. "stress domains" along the project Citybanan (Södermalm, Riddarholmen and Norrmalm), where the in-situ stresses had different orientations. Perman and Sjöberg (2007) identified that the fault zones were natural borders between these stress domains and that was what triggered the present investigation (Figure 16).

3. MAPPING OF GEOLOGICAL STRUCTURES

Faults have different tectonic histories and effects of movements during this history are seen as slip along faulted fractures.

In this project, we identified fractures with kinematic indicators such as the cross-cutting relationships of the fractures and veins, sealed fractures or partially opened fractures and striated slicken-sides (Figure 17).

The most common indicators are the slicken-sides, thus they are generally the features identified in this study, although at some locations relative identifiers have been found such as faulted dykes (in Lidingö). Only the features with clear indicators are used thus the small amount of data points. The slicken-sides where it could be suspected that they were parallel to the foliation, and thus rather was an artefact of the foliation, were not measured.

It was found that the weathering from the glaciations of the area has removed these features in many areas, thus they could mainly be found on over-hangs and on fresh surfaces in road outcrops.

The relative movement was established as we were looking at the feature as well as other information relevant for the analysis, thus the sense of movement (slip-direction), rock type, fracture orientation, as well as other features were collected at the site.

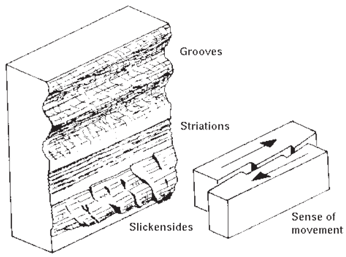


Figure 17. Examples of slip indications on fracture surfaces and the sense of movement indicated.

3.1. Mapped outcrops and road cuts

The following six locations have been visited (Figure 18).

1. Hässelby
2. Nockeby
3. Sätra
4. Lidingö
5. Kungsträdgården
6. Torsgatan.

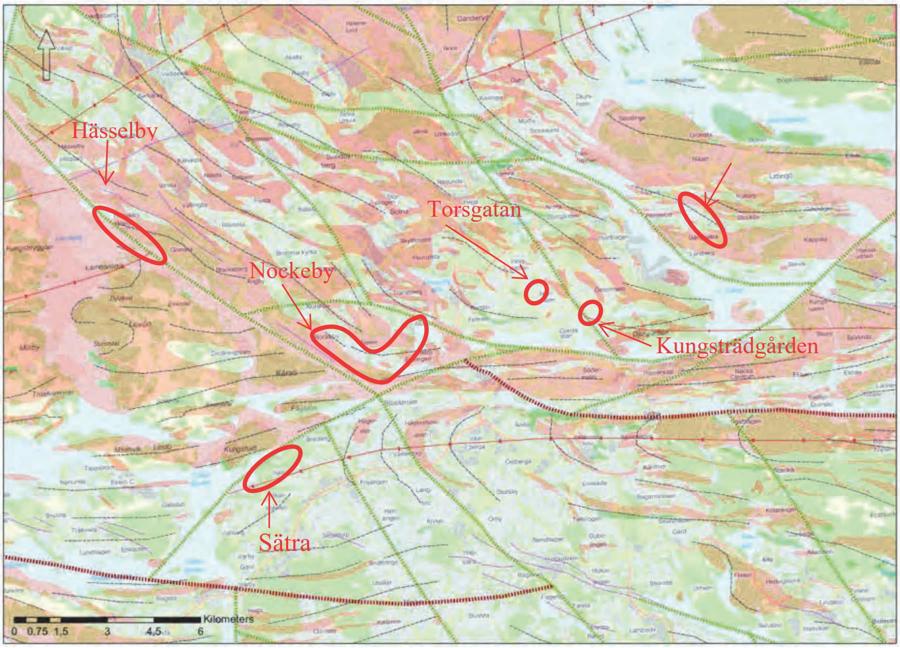


Figure 18. The areas of investigation shown on a map of deformation zones and fault zones as well as a simplified geological map from SGU, 2009.

3.1.1. Hässelby strand

First visit was paid to Hässelby where the outcrops along the shore of Lambardfjärden were mapped. Their smooth erosional surfaces did not convey many kinematic indicators (about three points). These points did not yield any directional data but they indicated that there had been movements in the area. Figure 19 shows zones indicated shear with formation of duplex.

Figure 19. Fractures from data point 2 at location Hässelby. Shear are indicated by rudimentary indication of duplex formation.

3.1.2. Nockeby

In Nockeby the northern shore of the junction of the Söderströms fault and Lambardfjärden fault was investigated, here more road-cuts and other areas where the fractures had been exposed from scaling were examined which yielded more data (8 indicators).

Figure 20. An example of a rock wall from the Nockeby area where the fault surfaces were exposed (site Nockeby (02) surface no. 005) indicated as 02-005 in Table 1.

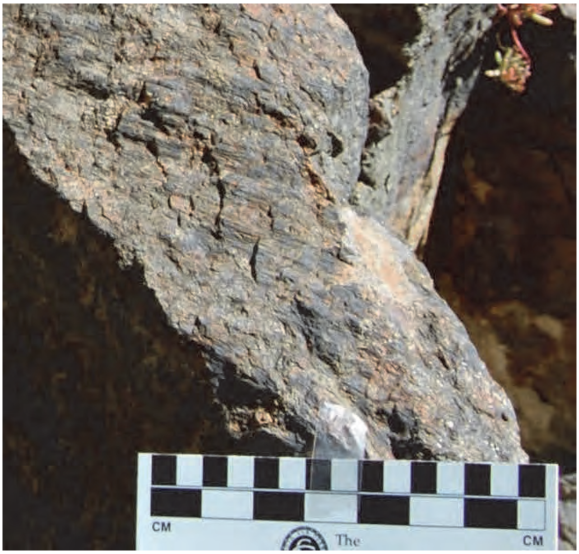


Figure 21. An example of a fault surfaces from site Nockeby (02) surface no. 002a) indicated as 02-002a in Table 1.

3.1.3. Sätra

In Sätra the exposed rock along the shore were again investigated as well as some faulted surfaces on outcrops in the forested area just south of the shore yielded a few data points (7 points).

Figure 22. An example of a rock wall from the Sätra area where the fault surfaces were exposed (site Sätra (03) surface no. 002) indicated as 03-002 in Table 1.

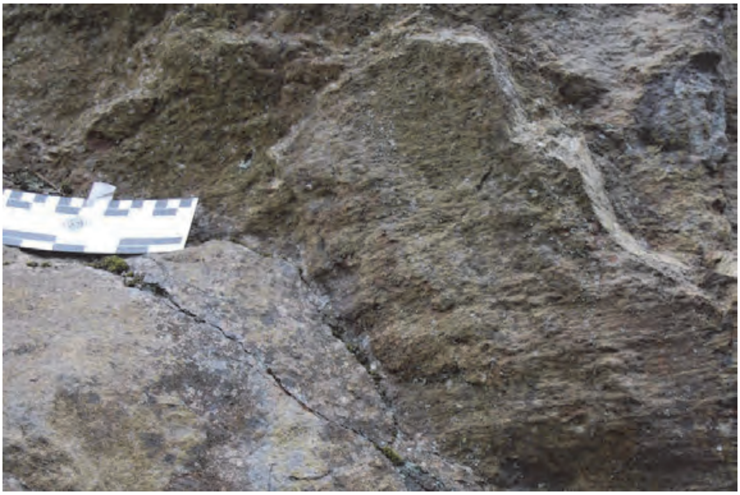


Figure 23. An example of a fault surfaces from site Sätra (03) surface no. 002) indicated as 03-002 in Table 1.

3.1.4. Lidingö

For Lidingö a distance mapping of the rock wall for the local train was investigated and accessed at the stations when this could be done safely. This location yielded only four data points.

Figure 24. An example of a rock wall from Lidingö where the relative movement were exposed as normal faulting of pre-existing fractures (site Lidingö (07) surface no. 002) indicated as 07-002 in Table 1.

Figure 25. An example of normal faulting of pre-existing fractures from Lidingö (07) surface no. 002, indicated as 07-002 in Table 1.

3.1.5. Kungsträdgården

The underground station Kungsträdgården close to the junction between the Söderströms fault and one smaller fault zone yielded 13 data points.

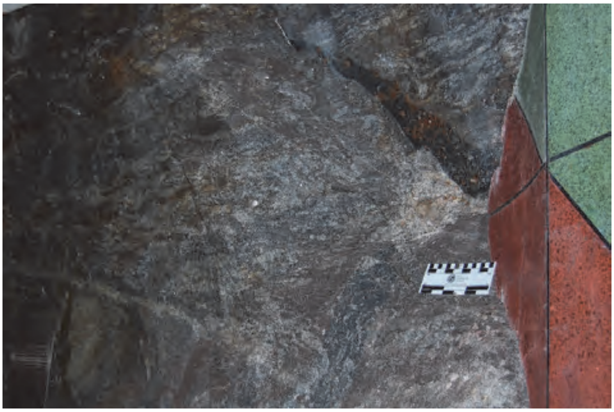


Figure 26. An example of a rock wall from Kungsträdgården platform where the fault surfaces were exposed (site Kungsträdgården (09) surface no. 005) indicated as 09-005 in Table 1.

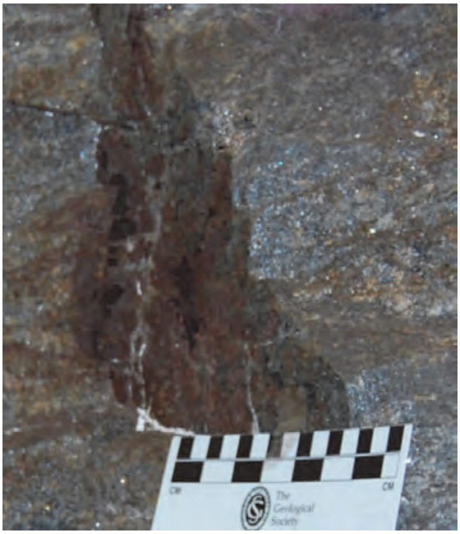


Figure 27. An example of a fault surfaces from the subway station Kungsträdgården (09) surface no. 009) indicated as 09-009 in Table 1.

3.1.6. Torsgatan

At the final location of Torsgatan, a long road cut was examined and yielded 12 data points.

Figure 28. The rock wall at Trosgatan where the fault surfaces were exposed (site Torsgatan (10).

Figure 29. An example of a fault surfaces from Torsgatan (10) surface no. 008) indicated as 10-008 in Table 1.

3.2. Summary of mapping data

The measured kinematic data is 46 points around Stockholm, these are listed in Table 1. There are two ways of measuring the orientation of the surface striation and it is either giving the values in rake or as azimuth and plunge. Rake is described as the angle between the line and the strike line of the plane in which it is found, measured on the plane. Generally:

- left-lateral strike slip: rake near 0°
- right-lateral strike slip: rake near 180°
- normal: rake near −90°
- reverse/thrust: rake near +90°

as shown in Figure 30.

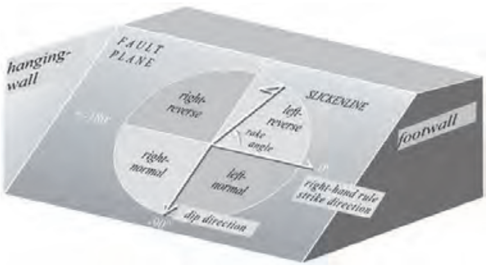


Figure 30. The figure shows the Aki and Richards (1980) convention for rake angle (from homepage malg.eu) used in this study.

A few orientations of surface striations are measured using the Azimuth and plunge convention, commonly because it was difficult to measure rake on those surfaces for various reasons.

The results from the investigation is presented in Table 1.

Table 1. Summary of all measured values from this study. The conventions used are noted in the table or described in the text above.

		Orientation plane		Orientation surface striation				Certainty
Data point	Location	Strike	Dip	Rake or slip (+/-0-360^0)	Azimuth	plunge	Type of movement	X-unknown S-supposed P-probable C-certain
01-001	Hässelby	35	90	-	215	56	Unknown	X
01-002	Hässelby	220	60	-	40	2	Unknown	X
01-003	Hässelby	94	35	-12			Normal/Left-lateral	S
02-001	Nockeby	320	80	105			Revers/Right-lateral	P
02-002a	Nockeby	102	60	160			Revers/Right-lateral	P
02-002b	Nockeby	112	75	5			Revers/Left-lateral	P
02-003	Nockeby	96	60	60			Revers/Left-lateral	P
02-004	Nockeby	300	15	-50			Normal/Left-lateral	P
02-005	Nockeby	320	75	40			Revers/Left-lateral	P
02-006	Nockeby	330	70	1			Revers/Left-lateral	P
02-007	Nockeby	345	70	45			Revers/Left-lateral	S
3001	Sätra	60	70	-20			Normal/Left-lateral	P
3002	Sätra	80	70	-5			Normal/Left-lateral	P
3003	Sätra	80	80	-100			Normal/Right-lateral	P
3004	Sätra	45	75	120			Revers/Right-lateral	P
3006	Sätra	50	89	179			Revers/Right-lateral	P
3007	Sätra	260	80	-45			Normal/Left-lateral	P
7001	Lidingö	272	40	175			Revers/Right-lateral	S
7002	Lidingö	0	40	90			Revers	S
7003	Lidingö	0	59	-90			Normal	S
7004	Lidingö	20	30	90			Revers	S
09-001	Kungsträdgården	22	70	1			Revers/Left-lateral	S
09-002	Kungsträdgården	290	60	-	84	36	Normal/Right-lateral	S
09-003	Kungsträdgården	0	70	1			Revers/Left-lateral	C
09-004	Kungsträdgården	320	55	5			Revers/Left-lateral	S
09-005	Kungsträdgården	310	55	-30			Normal/Left-lateral	P
09-006	Kungsträdgården	350	25	-	101	24	Normal/Right-lateral	S
09-007	Kungsträdgården	290	70	1			Revers/Left-lateral	S
09-008	Kungsträdgården	270	70	1			Revers/Left-lateral	P
09-009	Kungsträdgården	320	70	1			Revers/Left-lateral	P
09-010	Kungsträdgården	120	24	-105			Normal/Right-lateral	P
09-011	Kungsträdgården	280	75	-10			Normal/Left-lateral	P
09-012	Kungsträdgården	15	90	-	25	90	Unknown	X
09-013	Kungsträdgården	100	60	1			Revers/Left-lateral	S
10-001	Torsgatan	210	70	-40			Normal/Left-lateral	S
10-002	Torsgatan	270	60	-50			Normal/Left-lateral	P
10-003	Torsgatan	181	70	120			Revers/Right-lateral	P
10-004	Torsgatan	92	80	170			Revers/Right-lateral	P
10-005	Torsgatan	310	70	15			Revers/Left-lateral	P
10-006	Torsgatan	120	80	-165			Normal/Right-lateral	P
10-007	Torsgatan	272	72	45			Revers/Left-lateral	S
10-008	Torsgatan	325	70	45			Revers/Left-lateral	P
10-009	Torsgatan	110	89	-130			Normal/Right-lateral	S
10-011	Torsgatan	85	70	165			Revers/Right-lateral	S
10-012	Torsgatan	295	60	45			Revers/Left-lateral	P
10-013	Torsgatan	85	70	165			Revers/Right-lateral	P

4. STRESS RECONSTRUCTION

Faults have different tectonic histories and effects of movements during this history are seen as slip along faulted fractures. The stress fields causing these slips can be reconstructed using the theory of “stress inversion”. Based on this theory, the computer program TENSOR (Delvaux & Sperner, 2003) is constructed and is used for this study.

4.1. Method description

The theory of “stress inversion” is based on the Wallace-Bott hypothesis: slip on a fracture plane should be parallel to, and in the same sense, as the maximum shear stress on the plane. This means that the slip direction depends on the shape of the stress ellipsoid. Nonetheless, the stress magnitudes will not be obtained by this theory. The theoretical details for extracting stress orientations based on observed slips of fracture surfaces are described by Angelier, 1994.

Step one is always to identify the sense of movement in the field. During the analysis the first step is to identify the different fractures with similar sense of movement, similar minerology and other distinguishing features. Then the evaluation of which fractures fits the same stress field is identified.

Analysis were made using the Win Tensor software which calculates the most likely stress state for the investigated structures. The error bar shows how well the result fits the data. The suggested stress orientations are presented in a stereonet with the data as well as in numbers to the side of the stereonet. The the fracture slips that fits with the stress solutions suggested are found as pink slip-symbols on the data-fractures (Figure 31). The arrows on the faults show the direction of the movement, single arrows show dip slip (such as normal and revers faulting) and double arrows show strike-slip (such as left lateral (sinistral) and right-lateral (dextral). It is necessary to point out that the results from this analysis are orientations of the stresses, not the magnitudes.

The software is a share-ware developed at Royal Museum for Central Africa, Earth Sciences, Geodynamics and mineral resources by Delvaux and is presented by Delvaux and Sperner (2003) and further developed by Delvaux.

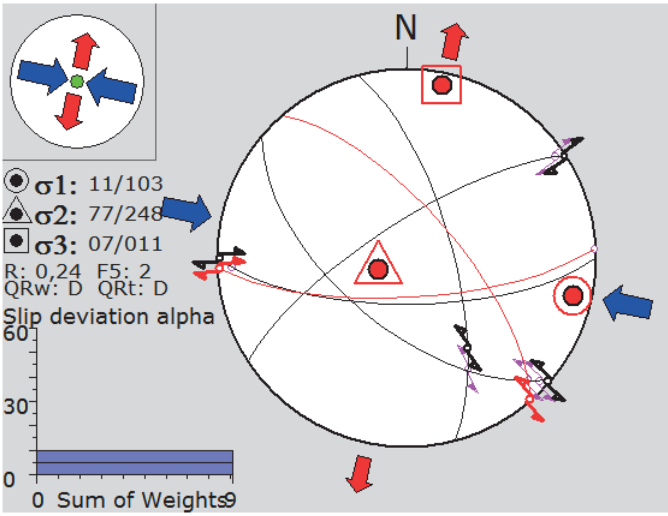


Figure 31. Example of evaluation by using the win tensor program. The error bar shows how well the result fits the data (lilac bars in lower left corner).

4.2. Data analysis

The local results are first presented for their mapping locations. The combination of the data from all the sources is then presented.

4.2.1. Local results

Different areas yielded different amount of data due to local conditions, such as erosional level of outcrops (general rule: strongly glacially eroded surfaces (up-ice side) are terrible for finding kinematic indicators, whereas the glacial lee side of the same outcrop can be useful. Road cuts and exposed tunnel walls were found to be the best sites for finding slip surfaces), amount of outcrops, overgrowth of surfaces and general exposure of the outcrop.

Six locations were sampled from Sätra in the west to Lidingö in the east.

Sätra is located on the southern shores of Mälaren where the SW continuation of the Söderströms fault zone is located in Fiskar fjärden. The bore holes investigated by Ignea (2015) are located just north of this area. Here seven data points are found along the shore and in the forest hills to the south.

The Hässelby area is located on the eastern shore of Lambardfjärden further to the north of Sätra, here the hills are rather strongly glacially eroded and does not yield many datapoints. Only three data-points were found over a rather large area (Figure 32).

In Nockeby, to the south of Hässelby, a larger number of road-cuts in the search area yielded more data. Here we have eight data-points (Figure 32).

These three sample locations are in the western part of the area, whereas Torsgatan, Kungsträdgården and Lidingö are more in the eastern part of the Stockholm region (Figure 32).

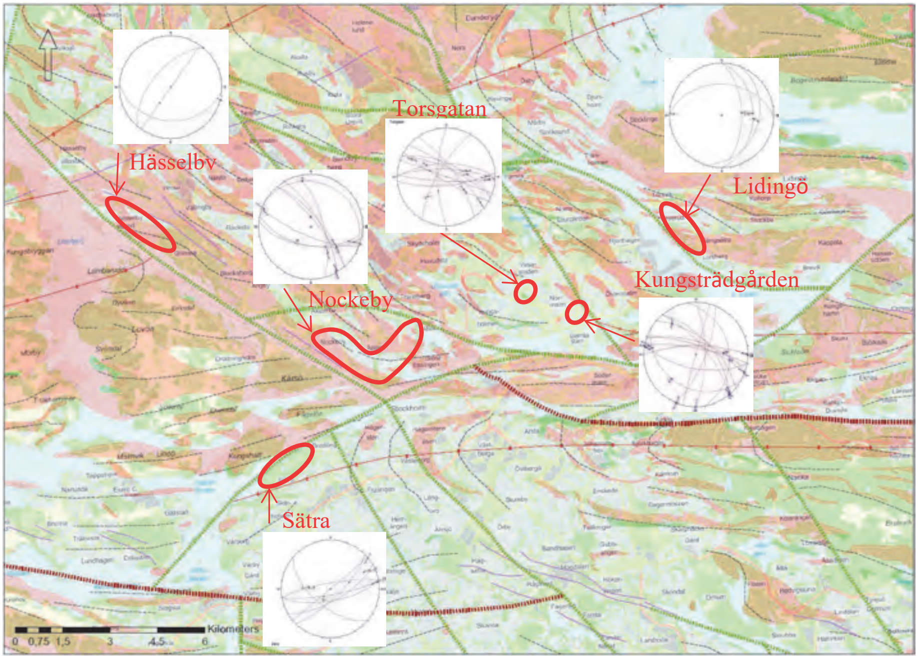


Figure 32. Map of results and their locations.

The Nockeby and Hässelby area is to the north of the Söderström fault whereas Sätra is to the south of the fault. The closest Fault to the Hässelby and Nockeby area is the Lambardfjärden fault (Figure 33).

When comparing the results it can be seen that results from Sätra show a fracture orientation parallel to the nearest fault whereas the Nockeby data set show correlation with the dominant fracture set in the area (NV-SE) as well as the E-W striking set (Figure 34). As seen in Figure 35 the results show an inclination to the E-W striking Söderström fault zone and the Stocksund fault zone further to the east, although this can be the fact that they follow the same fracture groups, E-W and NV-SE respectively. The Nockeby area is close to a junction between two faults and thus two distinct fault directions are identified in this data set.

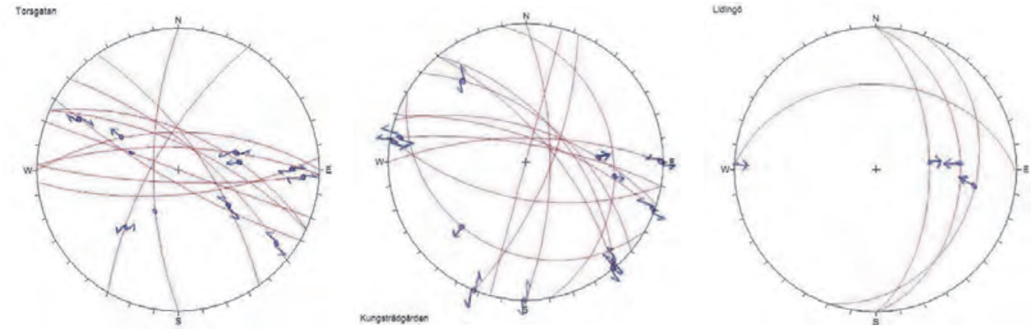


Figure 33. Lower hemisphere stereoplot with faults shown as large circles. Results from Sätra (to the left), Hässelby (middle) and Nockeby (to the right). The arrows on the faults show the direction of the movement, single arrows show dip slip (such as normal and revers faulting) and double arrows show strike-slip (such as left lateral (sinistral) and right-lateral (dextral)).

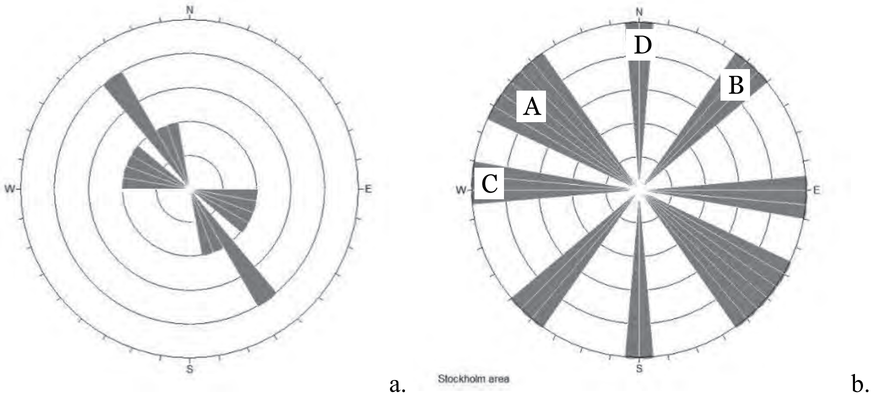


Figure 34. a) Rose diagram of the data from Nockeby, b) dominant fracture groups from Andersson & Swindell, 2008 for comparison.

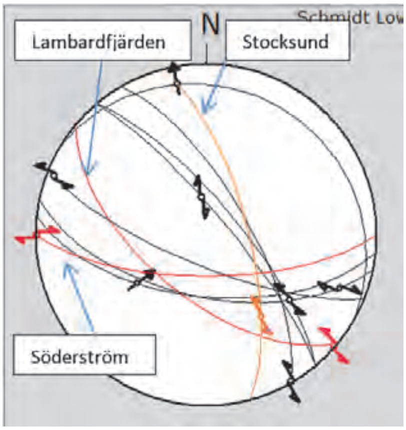


Figure 35. Solution in win tensor with the data from Nockeby as black fractures and the faults in the area shown as colored faults.

Further to the east we find the Torsgatan site as well as the Kungssträdgården site and finally furthest to the east is the Lidingö site (Figure 32, Figure 36).

The Torsgatan site show many directions for fractures with slip, although the dominant direction for these fractures are NW-SE and E-W striking sets, similar to Nockeby (Figure 37).

Kungsträdgården site is the mapping of the underground subway station with the same name. The dominant fracture direction is rather to the WNW-ESE, where the dip is rather steeply towards north (e.g. $280^0/75^0$) and the less dominant fracture direction is in line with the NW-SE fracture set that dominates the general area (Figure 36; Figure 38).

The site furthers to the east is the Lidingö site. Here only four data points were collected. They differ from the others by being dominated by N-S striking fractures with mainly vertical slip (Figure 36; Figure 39).

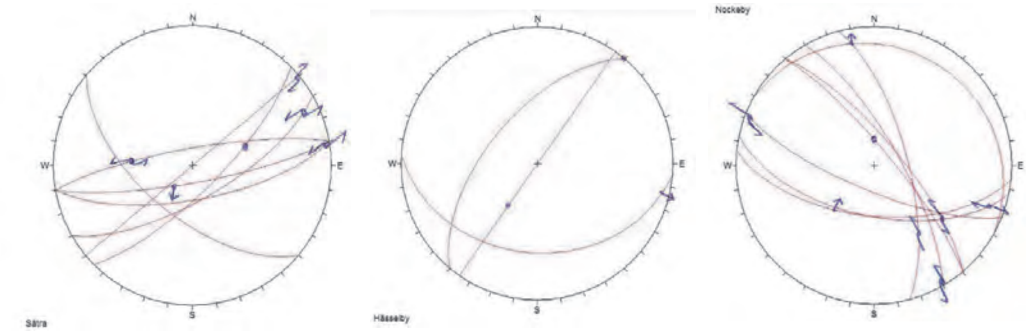


Figure 36. Lower hemisphere stereoplot with faults shown as large circles. Results from Torsgatan (to the left), Kungsträdgården (middle) and Lidingö (to the right). The arrows on the faults show the direction of the movement, single arrows show dip slip (such as normal and revers faulting) and double arrows show strike-slip (such as left lateral (sinistral) and right-lateral (dextral)).

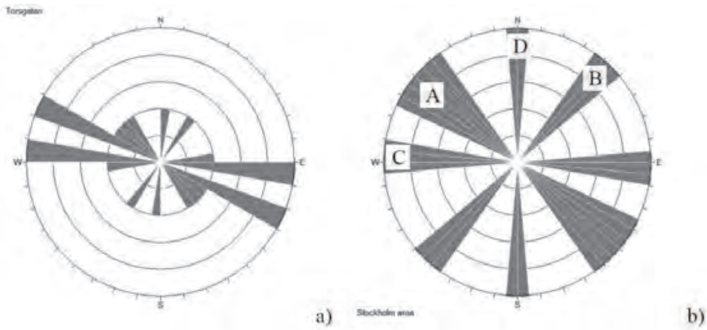


Figure 37. a) Rose diagram of the data from Torsgatan, b) dominant fracture groups from Andersson & Swindell, 2008 for comparison.

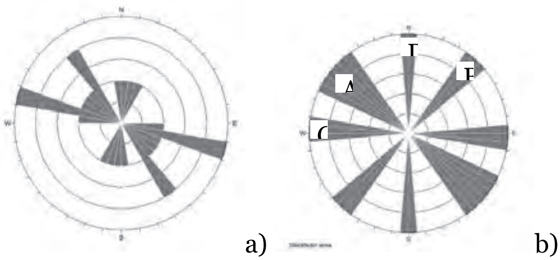


Figure 38. a) Rose diagram of the data from Kungsträdgården, b) dominant fracture groups from Andersson & Swindell, 2008 for comparison.

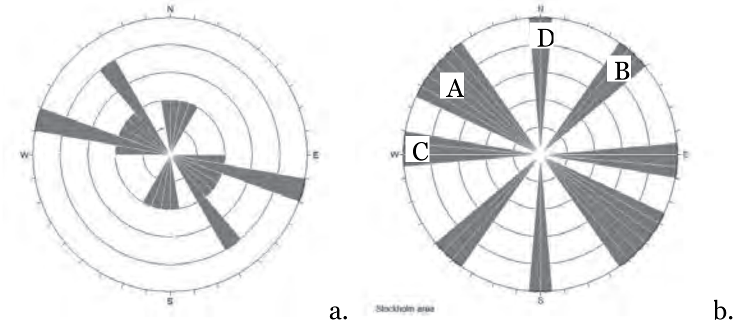


Figure 39. a) Rose diagram of the data from Lidingö, b) dominant fracture groups from Andersson & Swindell, 2008 for comparison.

4.3. General results

When combining all the sites the different slip types were divided into groups (Figure 40). Left-lateral fractures can be found on sites: Nockeby (3), Sätra (3), Kungsträdgården (9) and Torsgatan (4), mainly at Kungsträdgården (Figure 41). Many of these fractures (7/19; 36%) fall within the dominating fracture group of the area, the NW-SE group (Figure 39b).

Right-lateral fractures are found in Nockeby (2), Sätra (2) and Torsgatan (6) (Figure 42). Of the ten fractures, three show correlations with the E-W direction and are all found at Torsgatan (Figure 39).

Normal faults can be found at all the locations and any preferred orientation cannot be discerned (Figure 40;Figure 43) but contrary to this revers faults are rather rare and identified in Nockeby (1), Lidingö (3) and Torsgatan (1) Figure 44. The amount of results does not allow for any identification of preferred orientation.

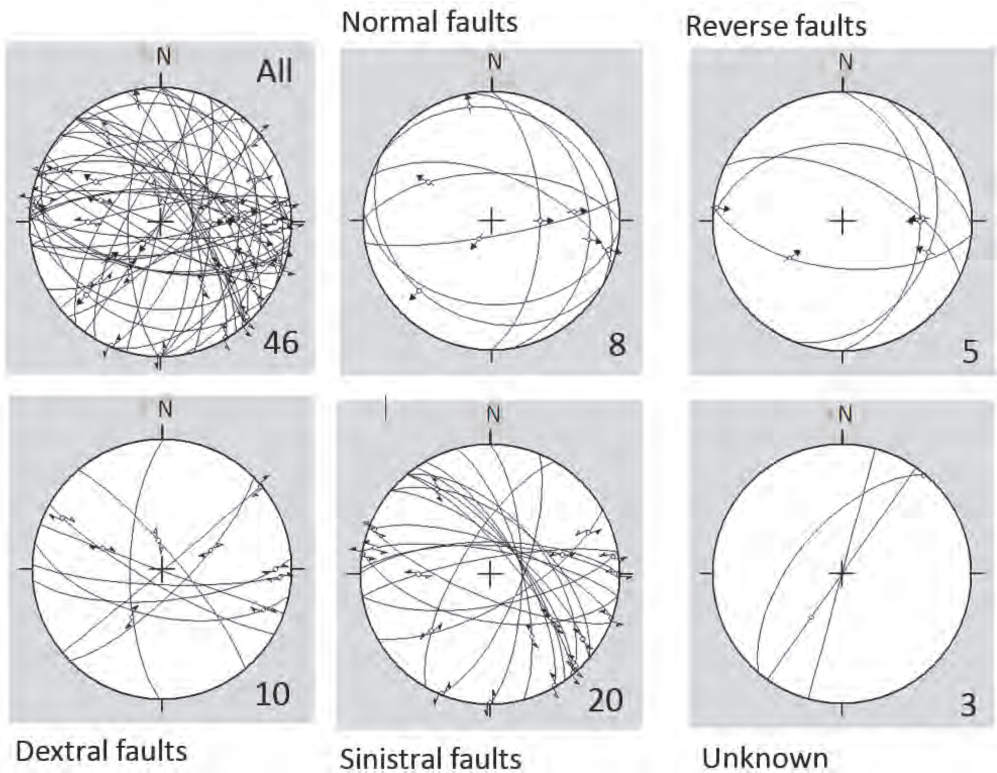


Figure 40. All the results divided into groups depending on type of slip. The arrows on the faults show the direction of the movement, single arrows show dip slip (such as normal and revers faulting) and double arrows show strike-slip (such as left lateral (sinistral) and right-lateral (dextral)).

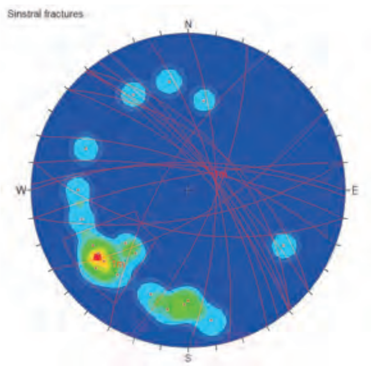


Figure 41. Contour plot of faults with left-lateral movement.

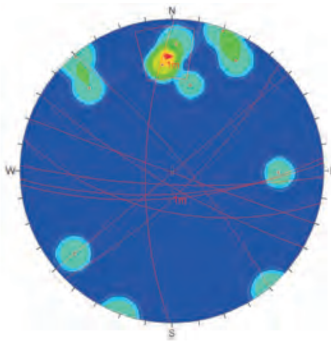


Figure 42. Contour plot of faults with right-lateral movement.

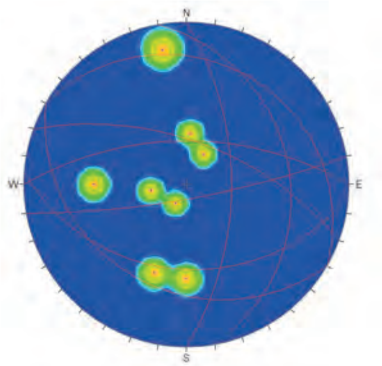


Figure 43. Contour plot of faults with normal movement.

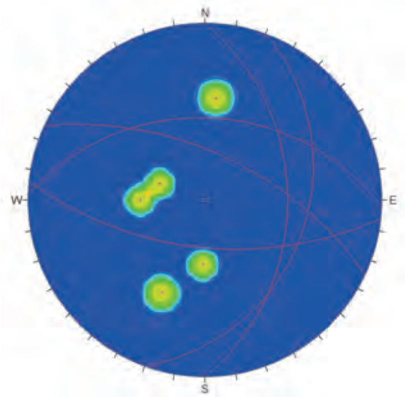
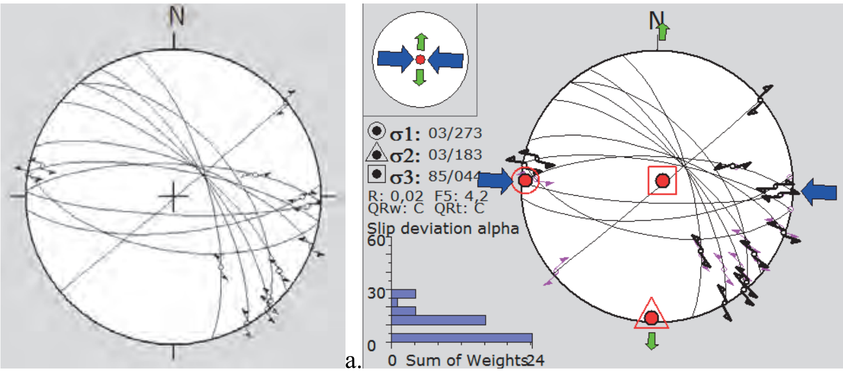


Figure 44. Contour plot of faults with revers movement.



a. b.

Figure 45. a) Faults from strike-slip data representing a conjugate set where the right-lateral NW-SE fractures and the left-lateral W-E fractures are combined. b) The solutions in win tensor.

The small amount of data does not allow for local stable solutions, thus the data has been combined across the entire area and then stable solutions have been identified.

One rather stable solution is the strike-slip data representing a conjugate set where the right-lateral NW-SE fractures and the left-lateral W-E fractures are combined (Figure 45). The data is collected from all locations except Lidingö, are represented by 13 data-points. The stress field suggested is oriented with the major stress axis in the subhorisontal E-W orientation, and a vertical minor stress axis (Figure 45b.). This solution is presented as a conceptual model presented over the Stockholm area in Figure 46 and the movement of the Söderström and Lambardfjärden fault is presented as as a block model of conjugated fractures in Figure 47.

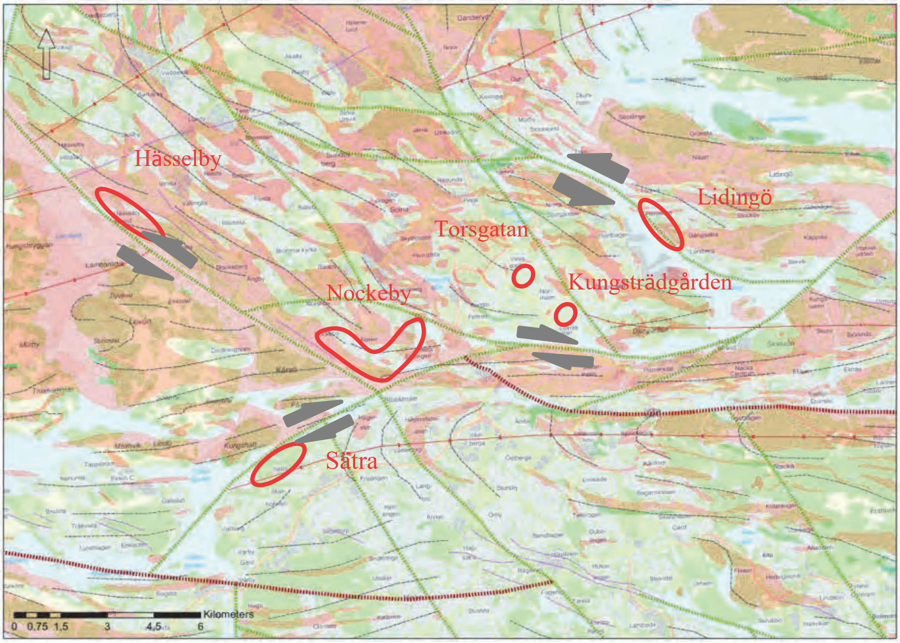


Figure 46. Suggested slip along faults in the Stockholm area from 65% of the results in this study and the investigation of Ignea (2015).

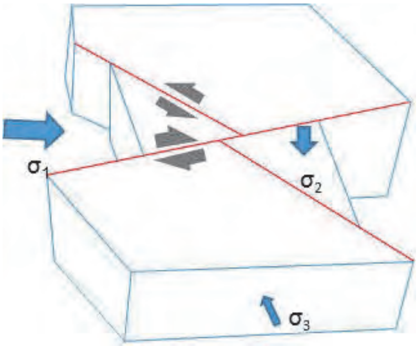


Figure 47. Block model of conjugated fractures here representing the faults Söderström fault and Lambardfjärden fault.

5. NUMERICAL SIMULATIONS

The geological mapping conducted in this study and other geological investigations provide information of local movements of the major fault zones within the area of Stockholm. To study the associations between the local movements in a geological domain, numerical modelling could be a useful tool. Within this project, an attempt has been made using a simplified 2D numerical model. The software used for the modelling is UDEC.

The starting point of the numerical modelling is to simulate the shear movements of the major deformation zones, which is a different approach from commonly performed stress-based modelling. The basic principle of the modelling is described as follows.

- A conception model with major deformation zones in the Stockholm area is set up. The major deformation zones are those, for instance, Lambardfjärden, Söderströms and Stocksund. The conception model used in this study is shown in Figure 48.

- Different cases with various displacement boundary conditions are performed. To minimise the boundary impact on the deformations and stresses in the area of interest, so called "relaxation zones" are implemented around the conception model.

- The shear movements of the deformation zones modelled from the different cases are extracted and then compared with the mapped movements of the zones. By finding the best fit between the modelled and mapped zone movements, the best case could be identified. Theoretically, the best fit can be found by mathematical regression analysis. One such example by using the least squares method is given by Chang, 2005. In this study, the best fit is identified by judgement.

- The stresses modelled in the best case can then be further studied and conclusions be made by e.g. comparing the measured rock stresses.

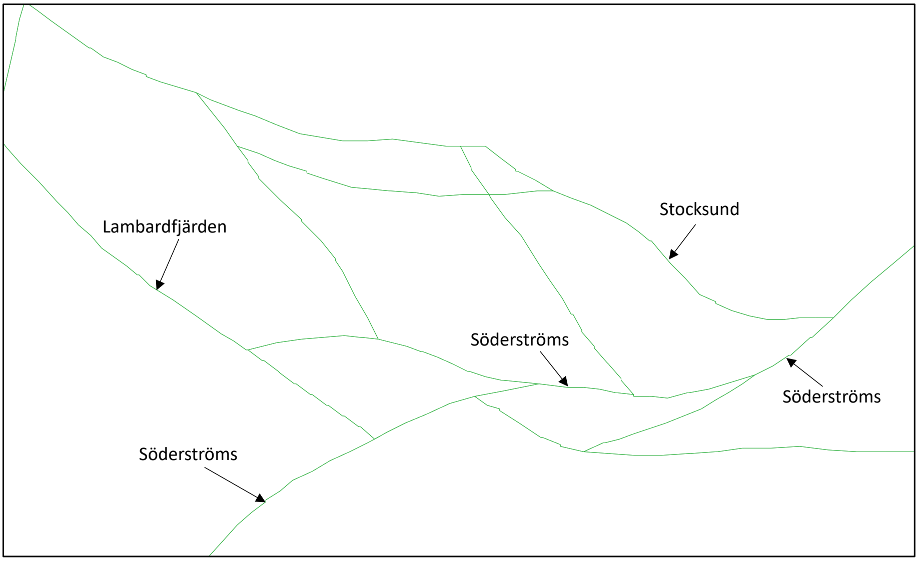


Figure 48. Conception model with the modelled deformation zones.

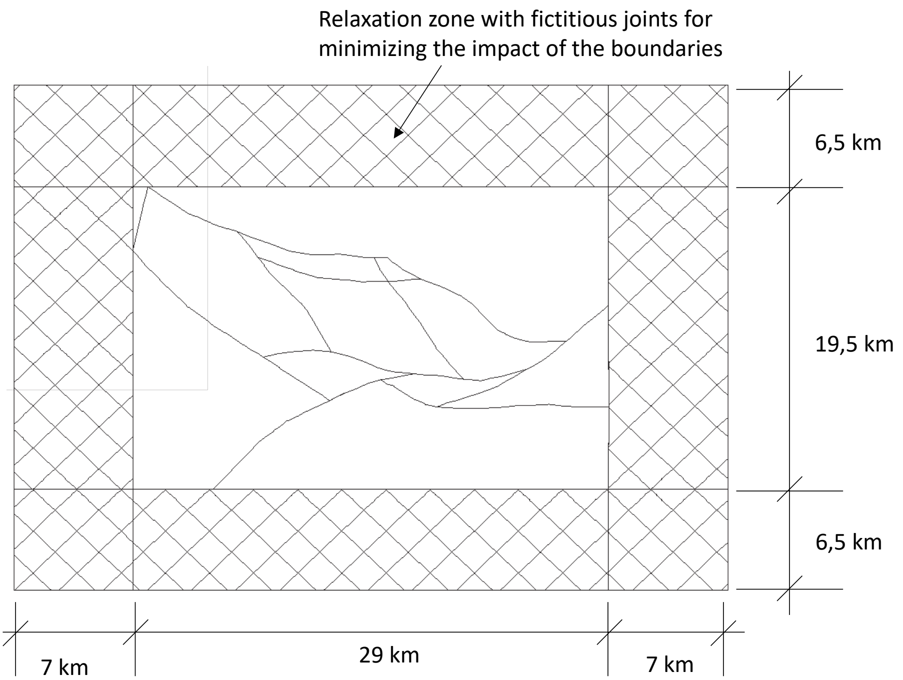


Figure 49. The model used in the numerical simulations.

It should be, however, pointed out that the approach done in this project is an attempt to model geological features by numerical means. It is believed that more efforts are needed for enhancing applications of rock mechanics tools in study of geological structures.

The model used in this study is shown in Figure 49. After experimenting with different modelling alternatives, the cases with different boundary conditions as shown in Figure 50 are chosen.

The rock mass is modelled as elastic medium, which is of course a simplification of the actual rock masses. The deformation zones are modelled as Mohr-Coulomb model, which means that the sides of the zones can slip when the shear strength of the zones is reached. The material parameters for the rock mass and the deformations zones are given in Table 2 and Table 3. The rock quality is equivalent to good rock with a Qbas value of 4. The cohesion of the zones is set to zero, to model the zones having in fact poor and crashed core zones.

Table 2. Material properties for rock mass.

Material	E_m [GPa]	μ_m
Rock mass	25	0,25

Table 3. Material properties for deformations zones.

c_j [MPa]	ϕ_j [°]	ks [MPa/m]	kn [MPa/m]
0	15	250	500

The cases are run with the following procedures:

1. Setting up boundary conditions: The boundary conditions are displacement based, which means that displacement velocities are prescribed in the UDEC-model. The moving displacement boundaries are assigned with displacement velocity δ_v = 2,5e-5 m/s. The low value of displacement velocity is chosen in order to avoid chocking in the model.

2. Stepping: 1 414 000 steps are assigned for stepping to achieve 1 m displacement on each moving boundary. The run time has been 4-5 hours.

3. Equilibrium: The unbalanced forces are reduced to less than 500 by issuing "solve" command, in order to achieve better accuracy of the modelling.

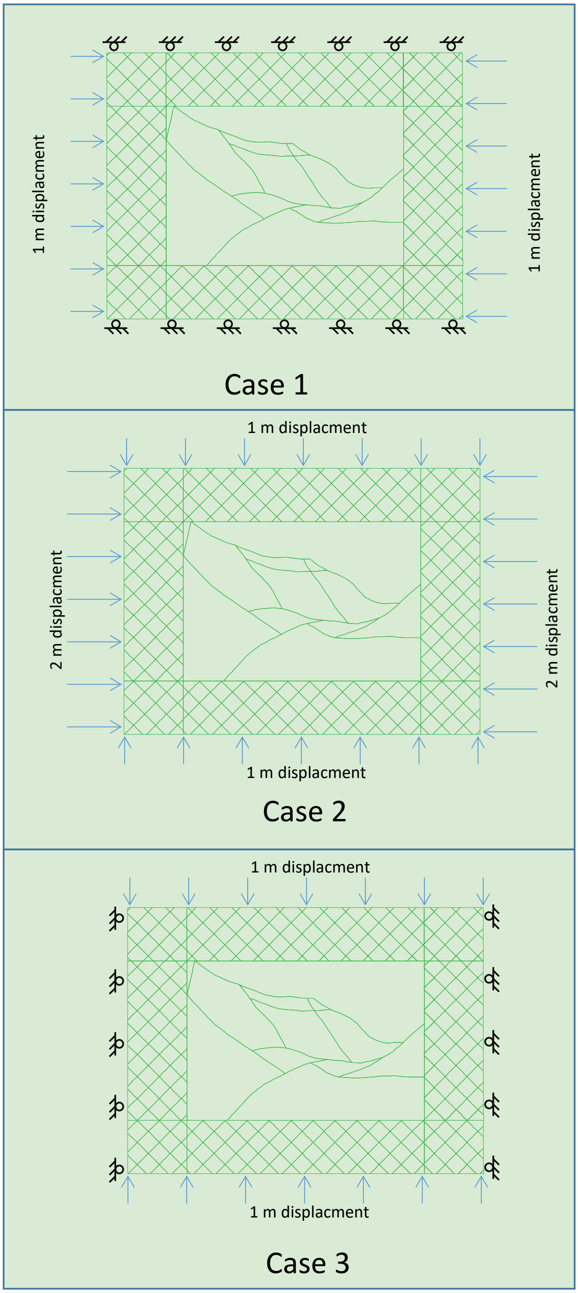


Figure 50. Performed cases with different displacement boundary condition.

The modelled relative shear movements along the major deformation zones for the cases are presented in Figure 51, Figure 52 and Figure 53. It can be seen that the Case 1 shown in Figure 51 gives the best fit to the relative shear movements as described in Figure 46. The results of Case 1 indicate that the predominated east-west tectonic movements originated the observed shear movements of the deformations zones. This modelling result is believed in a reasonable agreement with the interpretations of the geological events, for instance, the mid-Atlantic ridge push.

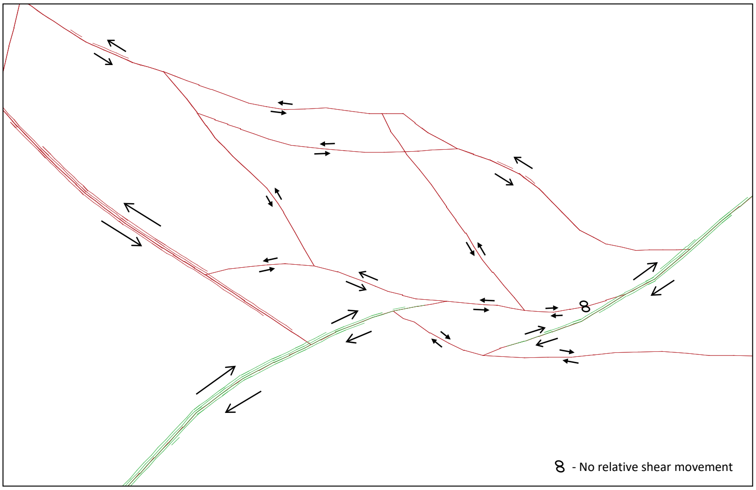


Figure 51. Shear movements of the deformation zones, Case 1.

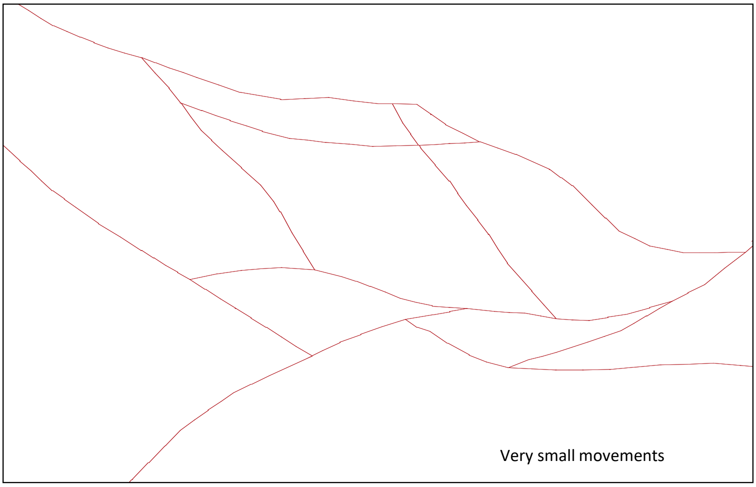


Figure 52. Shear movements of the deformation zones, Case 2.

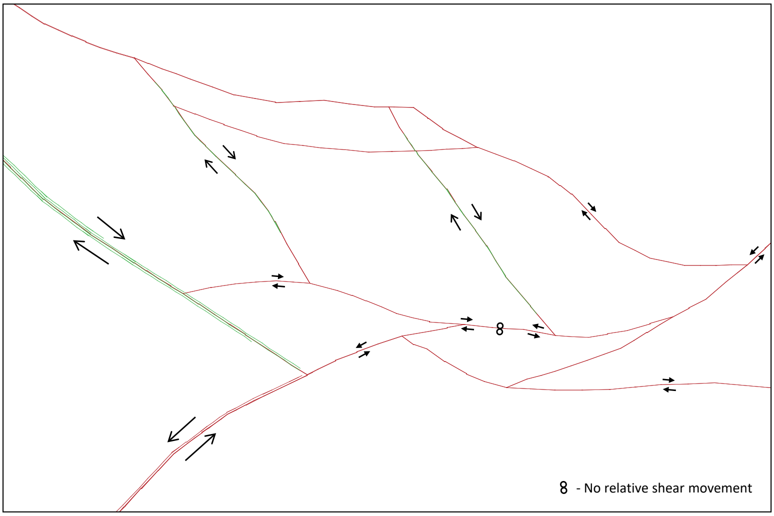


Figure 53. Shear movements of the deformation zones, Case 3.

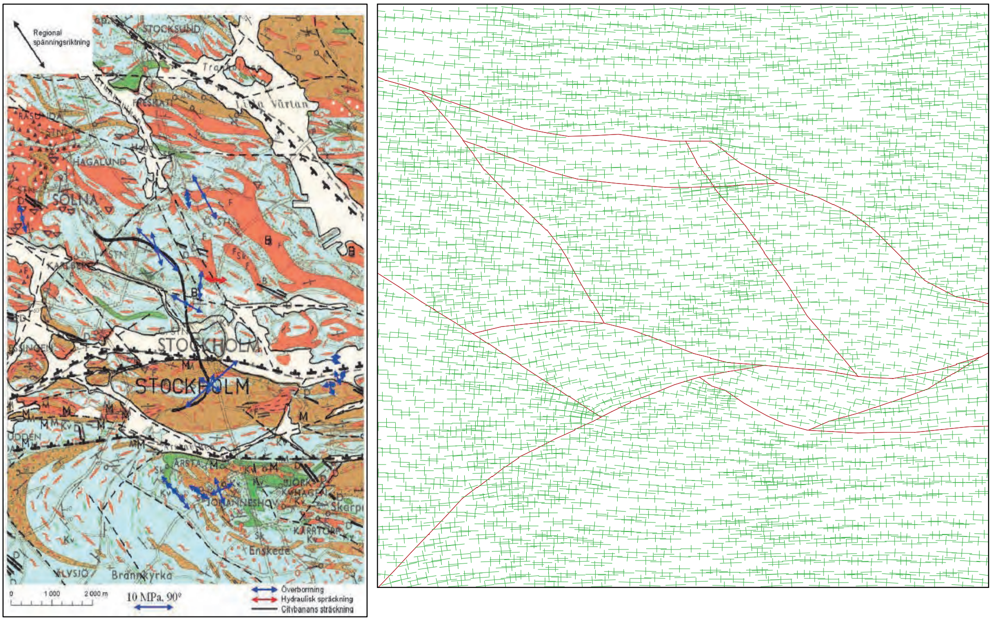


Figure 54. Stress directions obtained from Case 1 compared with rock stress measurements.

Figure 54 presents a comparison between the stress directions obtained from Case 1 and the rock stress measurements. The results from Case 1 show that the predominating direction of the major principal stress (σ_H) is oriented East-West, because of the driving movements in the same direction from the surrounding regions. The directions of the major principal stress (σ_H) is, however, slightly rotated in the vicinity of the zones. The explanation of the stress rotation is that the zones have limited ability to transfer shear stresses from one side to the other.

The stress directions from the stress measurements show somewhat larger variations. It could be explained by the facts that the stress measurements by over coring are performed by measuring strains in the scale of 3-5 cm. Local geological features of this scale, such as crystal sizes in the rock, could have significant influences on the results of rock stress measurements.

Because the movement magnitudes of fault zones are unknown, the stress magnitudes will not be possible to be modelled. It is, however, interesting to look into the relative stress levels. Figure 55 shows the results of relative stress levels of σ_H obtained from Case 1. It shows that the stress levels in the vicinity of faults Söderström and Lambardfjärden are relatively low. There are also some limited areas with stress concentrations. The differences in the stress levels are however insignificant from the engineering point of view.

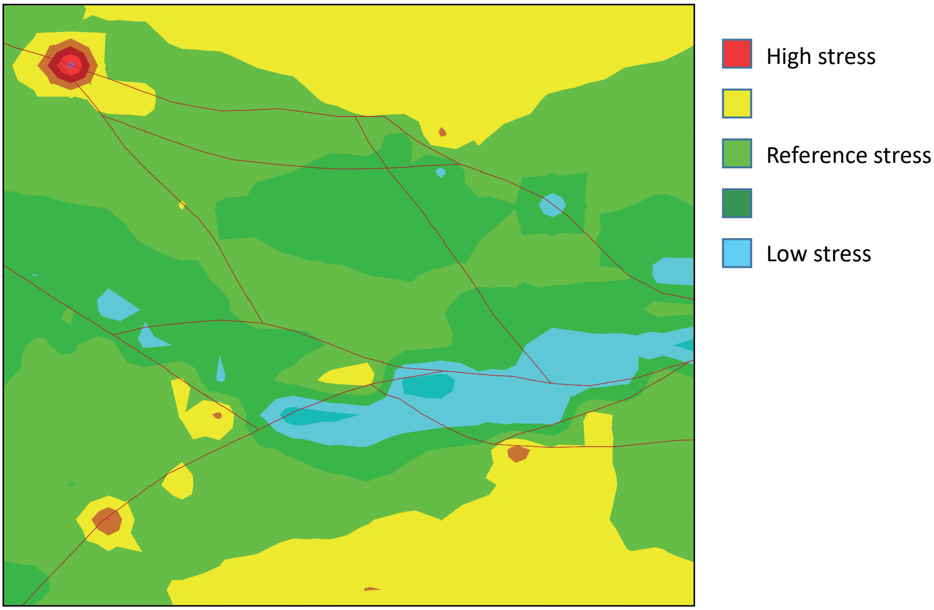


Figure 55. Relative stress levels (major principal stress) obtained from Case 1.

The following lessons have been learned from this simplified numerical modelling.

- This 2D model with some major deformation zones demonstrates that the numerical tools could have great potential in analysing geological structures. Applying rock mechanics in geological studies would be an interesting field of research. With the modern numerical tools and computer power, it is feasible to perform 3D models with complex geological features.
- It has been discovered in this simple model that applying boundary conditions for modelling geological events could be a difficult task. For simulating geological movements as done in this project, applying displacement boundary conditions is believed being more advantageous. Displacement boundary conditions can be, for instance, easier related to geological events.
- The available numerical discontinuity models are developed for modelling rock joints/fractures, the surfaces often having contacts. Major geological zones, however, have complex structures, often having transition zones and core zones. The opposite sides of such a zones have no contacts. Therefore, the existing numerical discontinuity models might over-estimate the shear resistance of the major geological zones. The properties to be used in such modelling shall be carefully evaluated.

6. DISCUSSIONS AND CONCLUSIONS

Generally speaking, rock stresses and fault movements were originated by tectonic events. There must be close relationships between movements of fault zones and rock stresses. The study presented in this report is an attempt to correlate rock stresses in the Stockholm areas with the movements of the major fault zones. The results of the study could provide complementary information of rock stresses for engineering purposes.

Dating of when the fault movements occurred in the geological history is not, however, included in this study.

The findings from the fracture slips mapped in the fields are compared with material from the geological investigations for the different major infrastructure projects. The comparison made between the conjugate solution and the results from earlier studies such as the bore hole study by Ignea (2015) indicates that the major stress tensor is sub-horizontal in the E-W direction (Figure 13 and Figure 45).

The investigations of kinematic indicators in boreholes provide much valuable information on the movements of the fault zones. Such investigations are described in two master thesis of the fault zones in Fiskarfjärden (the SW extent of the Söderströms fault zone) (Ignea, 2015) and the zone in Lambardfjärden (Vass, 2012). The two investigations reach though opposing results regarding movement directions of the Lambardfjärden fault. They do however agree on the slip type for the fault, which is strike-slip. The Lambardfjärden fault can of course have moved in both directions through time and the authors may identified different geological events. This conclusion of strike-slip is, however, consistent with 65% of the fracture slips identified in this study.

For the Söderströms fault, the results from Olsson et al. (2014), Hansen and Vestgård (2015) indicate that the ~70-90°/~ 70° oriented fault is subject to right-lateral strike-slip. The S-W part of the Söderströms fault was also investigated by Ignea (2015). Right-lateral movements were identified for that part of the fault zone.

A stress reconstruction is made based on the movements of the fault zones as well as the two dominant strike-slip fracture groups. Result is presented in Figure 56, indicating that the major principal stress is sub-horizontal and is likely oriented in the WNW-ESE direction.

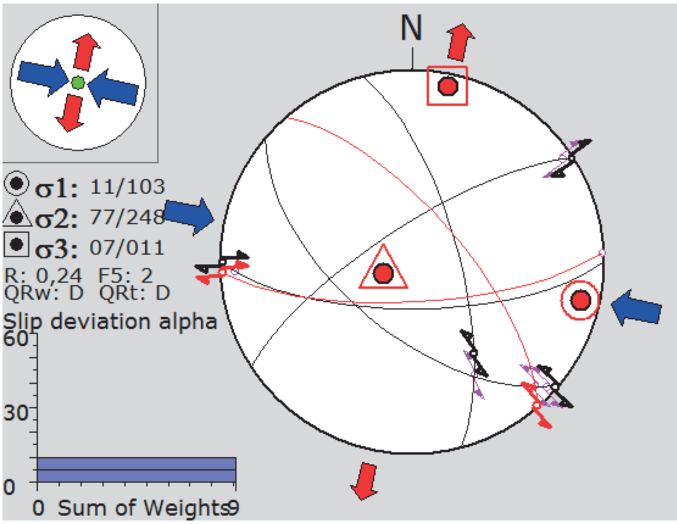


Figure 56. Stress reconstruction based on movements of fault zones as well as two dominant strike-slip fracture groups.

This stress reconstruction suggests that the fracture group with left-lateral slips oriented in NW-SE and fracture group with right-lateral slips in E-W constitutes a conjugate set that could be correlated to the stress field as suggested by Perman and Sjöberg, 2007.

A simplified 2D numerical modelling has been performed with different boundary conditions, using the commercial software UDEC. Case 1 gives the best fit of the deformation patterns of the fault zones as shown Figure 46.

The modelling results indicate that the observed zone movements are originated by the E-W tectonic movements. This modelling result is in a reasonable agreement with the interpretations of the geological events, for instance, the mid-Atlantic ridge push. The stress orientations are likely to be predominately oriented also in E-W directions because of the E-W tectonic movements. Stress rotations occur in the vicinity of the zones, because the zone have limited ability for transferring shear stresses from one side to the other.

The stress levels are relatively lower along the faults fault Söderström and Lambardfjärden. There are some limited areas with stress concentrations. The differences in the stress levels are however insignificant from the engineering point of view.

This simplified 2D model demonstrates that the numerical tools could have great potential in analyzing geological structures. Modern numerical tools and computer power make it feasible for performing 3D models with complex geological features. Applying rock mechanics in geological studies would be an interesting field of research. Boundary conditions for modelling geological events could be a difficult issue. Applying displacement boundary conditions is believed being more advantageous and easier to relate to geological events.

The result of this study could raise another engineering consideration. There are tunnels of infrastructure projects in Stockholm passing through some of the major faults zones. The lifetime of the tunnels is > 100 years. It is believed that it would be necessary to investigate the current movements of these fault zones, because significant movements during the lifetime would result in damages or affect the functionality of the tunnels.

7. EKÄNNANDEN

Ett stort tack riktas till referensgruppen för detta projekt som bestod av: Per Tengborg (BeFo), Curt Wishmann, Raymonds Munier, Giulio Viola, Carl-Olof Söder, Ulf Andersson och Daniel Ask för era bra tips och bakgrundsdata.

Dessutom har ett flertal personer visat intresse och glatt diskuterat projektet med oss, bla. Lars Maersk Hansen, Susanne Grigull, Carl-Henric Wahlgren och Frano Cetinic.

Ett flertal personer (organisationer) har dessutom delat med sig av information om borrhål och mätningar såsom Sorin Ignea, Magnus Leander, Robert Swindell, Rolf Axen och Anja Olsson.

Tack ska också ges för tillgången till open access database for the World Stress Map: Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D., and Müller, B., The World Stress Map database release 2008 doi:10.1594/GFZ.WSM.Rel2008, 2008.

Liksom för att delar av resultaten kunde tas fram genom att använda programmet Win-Tensor, som utvecklats av Dr. Damien Delvaux, Royal Museum for Central Africa, Tervuren, Belgium.

Vi beklagar att alla idéer som föreslagits inte har varit möjliga att utforska i detta projekt, men är imponerade av kunskapen som uppfinningsrikedomen hos dem vi har varit i kontakt med p.g.a. detta projekt.

8. ACKNOWLEDGEMENTS

A great appreciation is directed to the reference group for this project consisting of: Per Tengborg (BeFo), Curt Wishmann, Raymonds Munier, Giulio Viola, Carl-Olof Söder, Ulf Andersson and Daniel Ask for your good suggestions and background data.

In addition, a number of people have shown interest and have been happy to discuss the project with us, bla. Lars Maersk Hansen, Susanne Grigull, Carl-Henric Wahlgren and Frano Cetinic.

A number of individuals (organizations) have also shared information about boreholes and measurements such as Sorin Ignea, Magnus Leander, Robert Swindell, Rolf Axen and Anja Olsson.

We are also grateful for the possibility to collect information from the open access database for the World Stress Map: Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D., and Müller, B., The World Stress Map database release 2008 doi: 10.1594 / GFZ.WSM.Rel2008, 2008.

Parts of the scientific results were obtained using Win-Tensor, a software developed by Dr. Damien Delvaux, Royal Museum for Central Africa, Tervuren, Belgium.

We regret that all the avenues suggested have not been possible to explore in this project but are impressed by the knowledge as ingenuity of the people that we have encountered.

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10. APPENDIX

10.1. Appendix 1. Table of measured kinematic indicators.

See BeFo's home page: https://www.befoonline.org/publikationer

10.2. Appendix 2. Field notes with site-photos.

See BeFo's home page: https://www.befoonline.org/publikationer

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Visiting address: Sturegatan 11, Stockholm
ISSN 1104-1773