Major Fracture Zones in Fiskarfjärden, Stockholm

Sorin Ignea
Major Fracture Zones in Fiskar fjärden, Stockholm

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Abstract

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This Master thesis is written in connection with the Stockholm Bypass project which is Trafikverkets and Sweden’s largest infrastructure project to date. It will consist of 21 km of motorway running west of Stockholm city linking the southern and the northern parts. Out of the total 21 km of motorway, 17 km will run through rock tunnels and cross beneath the Lake Mälaren at 3 places. One of these places is the water passage Fiskarfjärden, situated between Sätra and the island of Kunghatt which has been carefully studied with geological (drill core mapping, BIPS, Water-loss measurements and outcrop mapping) and geophysical (reflection and refraction seismic) methods. This has been used to produce an engineering geological prognosis over the area which indicates that the rock mass in the water passage is heavily fractured and of poor quality. Due to this, additional investigations of the structural framework and the large-scaled structures in the area have been undertaken. The objectives of this thesis are therefore to analyze and classify available geological data, identify and model the major fracture zones situated in the water passage, investigate the kinematics of the fractures focusing on the relative movement between the blocks, if possible, determine the stress orientation and, predict how these major fracture zones will affect the Stockholm Bypass rock tunnel. The available data provided a good opportunity to examine the area. The drill core mappings showed that the dominating fracture orientation in the water passage is WSW-ENE with deformation structures supporting faulting along these fractures. The additional outcrop mapping and drill core mapping which focused on finding kinematic indicators revealed that fractures in the area have been reactivated both as strike-slip and dip-slip faulting and that dextral strike-slip faulting is dominating in a WSW-ENE orientation and sinistral strike-slip faulting in a NW-SE orientation.

The orientation of these two fault surfaces matches the main faults on the geological map and indicates that the area is composed of a conjugate fracture set with conjugate shearing whereas the combination of the dominating fracture orientations in the drill cores with the kinematic observations and fractures found in the field correlates with Riedel shear fractures in a dextral shearing configuration. The majority of the zones of crushed rock that cut the tunnel show a dominating WSW-ENE orientation. At this angle to the NW-SE oriented horizontal stress field, these fractures are more likely to experience closure since they are oriented approximately normal to the stress field. The zones of crushed rock that are either oriented E-W or NNE-SSW are more likely to reactivate as strike-slip faults. The very few fracture zones that are oriented NW-SE and correlate to fractures with sinistral shearing are likely to reactivate as dip-slip faults as they are oriented parallel to the present day extensional forces or as strike-slip faults if they are located at depth.

Keywords: Stockholm Bypass, structural model, major fracture zones, kinematic indicators

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(Sorin Ignea)


Nyckelord: Förbifart Stockholm, stora strukturer, stora sprickzoner, kinematiska indikatorer

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1. Introduction

The Stockholm Bypass project is Trafikverkets and Sweden’s largest infrastructure project to date. This new route will consist of 21 km of motorway running west of Stockholm city linking the southern and the northern parts, and will go from Kungens Kurva in the south to Häggvik, Sollentuna in the north (Fig. 1). As the population in the Stockholm area is growing the need for a new motorway is increasing. The aim is that this new route is going to help unburden the current high traffic load from Essingeleden (current motorway) and the inner city traffic. Thereby decreasing congestion and shorten travel times for both local traffic and public transportation. Out of the total 21 km of motorway, 17 km will run through rock tunnel (e.g. to decrease the environmental impact from car exhaust). The rock tunnels will run beneath the lake Mälaren at three places and link to 6 interchanges located above ground. The project is estimated to cost around 28 billion SEK and to have a construction time of 8-10 years with construction start planned to begin mid-2015. The design of the Stockholm Bypass project is carried out by several of Sweden’s largest infrastructure companies, where ÅF in consortium with the Scottish company Aecom (former URS) is designing 4 out of the 6 interchanges.

Figure 1. Planned route for the Stockholm Bypass. The study area is marked on the map (www.trafikverket.se).
After working for ÅF Infrastructure with the Stockholm Bypass project I saw the geological engineering obstacles that had to be overcome when working on a project of this scale. In addition to understanding and classifying the rock mass quality, understanding the structural framework is also of great importance. The water passage between Sättra and the island of Kungshatt is one of the places where the Stockholm Bypass will cross beneath the lake Mälaren (Fig. 2) and reaching a maximum depth of 60 m. The area has been carefully studied with geological (drill core mapping, BIPS, Water-loss measurements and outcrop mapping) and geophysical (reflection and refraction seismic) methods. Aerial and satellite photography has also been provided. The data has then been used to produce a geological engineering prognosis over the area. The prognosis which among others bases the prognosis on the rock mass quality classification systems, Q and RMR, shows that the water passage is mainly composed of bedrock interpreted to be rocks of class four and five on the RMR scale where five is the worst (Barton, 1974). Due to this, the need for producing a structural geological model has been requested in order to better understand the structural framework of the large-scale structures and how these will affect the tunnel stability.

This thesis will therefore focus on the water passage between Sättra and Kungshatt with the objectives to (1) analyze and classify available geological data (2) identify and model the major fracture zones situated in the water passage, (3) investigate the kinematics of the fractures focusing on the relative movement between the blocks, (4) if possible, determine the stress orientation and (5), predict how these major fracture zones will affect the Stockholm Bypass rock tunnel.

**Figure 2.** Planned route for the Stockholm Bypass in the study area (www.trafikverket.se)
2. Background

For this MSc thesis a large amount of data was available from both geological and geophysical studies. However, only data from geological studies were examined.

2.1 Outcrop mapping

A number of different outcrop mapping have been performed during the different stages of the Stockholm Bypass project, both initial outcrop mappings along the whole planned tunnel route between the years 1992-1993, and complementary outcrop mappings on selected areas. This study will present two different complementary outcrop mappings, both performed in Sätra and Kungshatt. The first was performed by WSP between 24/3 – 11/7 2010 and the second by ÅF on the 24th of October 2012 (Fig. 3). The outcrops were located using aerial photographs and geological maps and therefore the exact location of the outcrops is not available. The outcrop mapping conducted by WSP includes description of the outcrop lithology, fracture and structure orientation. The outcrop mapping conducted by ÅF includes description of outcrop lithology, fracture – and weakness zone orientations. Larger fracture zones have been identified and measured as well. The structure orientations include both foliation and lineation measurements while the lithology is described in terms of rock type, color and grain size. Overall very few foliation measurements are available. For fractures measurements where the dip values could not be measured accurately due to tight cracks, the description “steep” has been used and the measurement values set to vertical (90°). In total 44 different structure - and 767 fracture measurements were done on Kungshatt and Sätra. Fracture characterizations in terms of e.g. mineral fillings and kinematic indicators have not been mapped.
2.1.1 Lineament interpretation

Interpretation of large scale structures have been conducted through lineament analysis. This has been done by interpreting landforms from a structural geological perspective. Lineaments are defined as linear or slightly bent structures in the terrain which reflects the underlying tectonic features in the bedrock. However linear surface features in the terrain can also be the result of features formed during the last ice age therefore all lineament interpreted features are defined as potential. The mapping of lineaments was conducted through remote sensing which is a technique used to study large scale structures. Together with topographic maps and height data features such as weakness zones could be interpreted. The topography in the area is characterized by topographic highs and soil filled valleys. These valleys have been interpreted as possible weakness zones (Fig. 4). In total 10 different weakness zones have been interpreted in the area. The main orientation is WSW-ENE to NNE-SSW, however, weakness zone 159 shows an E-W orientation.

Figure 3. Outcrops mapped during the complementary outcrop mappings. WSP outcrop mapping (red dots) and AF outcrop mapping (yellow dots).
2.2 Boreholes

Outcrop mapping provides valuable information of the geology (e.g. lithology, structures, and fractures). However, the information is limited to outcrops. In order to gather additional information about the subsurface geology, boreholes were drilled. Several boreholes were drilled in Sätra and the water passage between Sätra and Kungshatt where all drill cores where successfully retrieved (Fig. 5). The locations were selected to the proximity of the planned tunnel route and therefore reflect the geology of the desired area. In total, three boreholes (08F152K, 08F153K and 10F156K) were drilled (two straight and one directional). The cased drilling was done by Zublin and the cored drilling by DrillCon. The drill core diameter in drill core 10F156K, 51 mm and 24 mm, where the smaller diameter was used in intervals where the borehole was directed and not straight. In Table 1, data from the drill cores is summarized and in Figure 6, the location, orientation and extent of the drill cores are presented.
Table 1. General information about the boreholes in the Sätra and Kungshatt area.

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Drill core length (m)</th>
<th>Hole diameter (mm)</th>
<th>Core diameter (mm)</th>
<th>Inclination (degrees)</th>
<th>Bearing (degrees)</th>
<th>BIPS range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08F152K</td>
<td>41</td>
<td>66</td>
<td>51</td>
<td>49.6</td>
<td>345</td>
<td>34.65 – 75.12</td>
</tr>
<tr>
<td>08F153K</td>
<td>55</td>
<td>66</td>
<td>51</td>
<td>50.0</td>
<td>154</td>
<td>-</td>
</tr>
<tr>
<td>10F156K</td>
<td>289</td>
<td>66.33</td>
<td>51.24</td>
<td>45-3.4</td>
<td>326-333</td>
<td>9 - 293</td>
</tr>
</tbody>
</table>

Figure 5. Depth, orientation and extent of drill core 10F156K, 08F152K and 08F153K.
2.2.1 Drill core loggings

The drill core loggings were performed by GeoSigma on the whole length of the drill cores (Table 2), and included a detailed description of the lithology, structures and fracture characterization. The lithological description includes rock type, color, texture, grain size and weathering amount of the rock mass. The weathering classification used (ISRM, 1978) has a graded weathering scale ranging from 1-5, where W1 is (fresh rock), W2 (slightly weathered), W3 (moderately weathered), W4 (highly weathered) and W5 (completely weathered). In the structure description, features such as penetrative fabrics (e.g. foliation) and deformation zones (e.g. mylonitic, cataclastic and gouge), as well as zones with crushed rock are documented. At places along the drill core where core loss has occurred, the depth and extent has been documented. The fracture description includes fracture density, orientation (strike and dip), mineral infillings, alteration, roughness and shape of fracture planes, fracture width, aperture, and alpha angle. Furthermore, all fractures have been classified through the parameters used in the Q and RMR rock mass classification systems.

Two of the parameters have been set to a constant value, the orientation of the discontinuities to 0 and the groundwater conditions to 15. Despite the detailed description of the drill cores some information is lacking. This includes e.g. conjugate fractures, orientation of healed fractures and, possible kinematic indicators (e.g. striations).
### Table 2. Mapping range for each drill core.

<table>
<thead>
<tr>
<th>Drill core</th>
<th>Mapping range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08F152K</td>
<td>34.65 – 75.12</td>
</tr>
<tr>
<td>08F153K</td>
<td>29.24 – 84.40</td>
</tr>
<tr>
<td>10F156K</td>
<td>9 - 298</td>
</tr>
</tbody>
</table>

#### 2.2.2 BIPS (Borehole Imaging Processing System)

BIPS is used to produce high resolution images of features present inside the surrounding borehole wall. It consists of a circular and elongated shaped instrument that continuously records the borehole wall with precise azimuth and orientation as it is inserted into the borehole. It acts as a supplement to the traditional drill core mapping and gives detailed information about the features of the borehole. The method has many different applications e.g. fracture identification (both natural and induced as an effect of drilling.

The generated images can be presented in different ways, both in 2D and 3D. The most common way of presenting the data is through an “unrolled” flat 2D image. Due to unrolling of the image, features such as bedding, fault and fractures that intersect the cylindrical borehole at an angle appear as sinusoidal lines (the amplitude of the curve is a function of the dip angle), while features that cut the borehole at a straight angle remain straight (Williamson et al., 1999).

For this project Malå GeoScience conducted the BIPS study in order to complement the drill core mapping and to provide information in sections that were not logged during the mapping. The exact orientation of the different features of the borehole was defined and information about the character of the crushed areas (often coinciding with fault or fracture zones) of the drill core could be obtained. The BIPS-logging provided both position and orientation of the crushed areas. Measurements were taken every millimeter generating a high quality image. The raw data was processed with the software BoreMap. The image was unrolled and assigned color to every measurement point to produce the final image, on which quantitative and qualitative analysis then could be carried out.

#### 2.2.3 Water-loss measurements

Water-loss measurement is mainly used to provide information about fracture network and permeability of the rock mass. By introducing water into a borehole under a known time interval with known pressure and flow speed, changes in these parameters can be evaluated to provide information about e.g. hydraulic conductivity and the presence of fracture networks (Woodward, 2005).

The water-loss measurements where performed by DrillCon for drill core 08F152K and 08F153K and by Geosigma for drill core 10F156K. For the two former, the measurements were divided into different depth intervals with a constant pressure of 0.2 MPa. For each interval a measurement time of 1 minute was used. For intervals where no water-loss was detected the measurement time was increased to 5 minutes. The final result is presented as the amount of water-loss.
(liters) per minute at a specific depth interval. For drill core 10F156K the results are presented as hydraulic conductivity, which is the rate of flow through a unit medium and was calculated for each 3 m interval. Along drill core 10F156K several sections (52.00 - 54.50 m, 62.65 - 63.20m, 77.60 - 78.60m, 89.10 - 91.70m, 147.80 - 151.50 m and 194.00 - 206.00 m) had to be stabilized with cement, therefore the recorded water-loss at these sites is potentially lower than the natural state.

3. Geological setting

3.1 Regional – Svecofennium

The area of focus for this thesis is located within the Bergslagens Province which was formed during the Svecofennian orogen. The rocks in the Svecofennian domain were formed between 2.0 and 1.75 Ga and consist mainly of crystalline rocks, both of supracrustal – and intrusive origin (Gaál and Gorbatschev, 1987; Stålhös, 1969). The Svecofennian orogen comprises a large portion of the Fennoscandian Shield and covers the main part of the bedrock in Sweden and western Finland. It borders to three major orogenic belts, the Archean domain in the north, Sveconorwegian orogen (1.10 - 0.92 Ga) in the southwest and the Caledonian orogen (0.5- 0.4 Ga) in the northwest. The Svecofennian domain hosts both supracrustal – and plutonic rocks formed between 1.93 and 1.84 Ga (Gaál and Gorbatschev, 1987), with the peak of crustal growth occurring between 1.9 and 1.8 Ga (Weihe et al., 2005). Island arc-type volcanic rocks and coeval calc-alkaline granitoids formed between 1.9-1.87 Ga dominate the domain whereas 1.8-1.78 Ga plutonic rocks represent the product of the youngest magmatic event (Weihe et al., 2005). Deformation is visible in different volumes throughout the domain, and peak metamorphism occurred between 1.85-1.80 Ga. Crustal deformation in a brittle manner commenced around 1.8-1.7 Ga (Viola et al., 2009, Saintot et al., 2011).

Several different models attributed to the evolution of the Svecofennian orogeny have been presented. The models such as Lahtinen (2005), proposed a model where the evolution of the shield involved amalgamation of several microcontinents and island arcs and defined by five different orogenic stages.

3.1.2 Local – Bergslagen province

The northern and the western parts of Bergslagen are dominated by metavolcanic rocks, while metasedimentary rocks are found in the SE (e.g. Stålhös, 1991; Allen et al. 1996). Overall, the prevailing rock type is synvolcanic plutonic rock. The metasupracrustal rocks in the region are dominated by 1.9-1.89 Ga felsic metavolcanic rocks which reach a total thickness of 8 km (Lundqvist, 1979; Allen et al., 1996; Lundström et al., 1998). The volcanic rocks are attributed to be derived from shallow, submarine, pyroclastic volcanoes (Allen et al., 1996). Hence, the area has been interpreted as a continental extensional basin (Allen et al., 1996) and the sedimentary successions in the SE being
interpreted as an accretionary prism (Korja & Heikkinen, 2005). According to Hermansson et al (2008) and Gaál and Gorbatschev (1987) the evolution of the province involved several stages of magmatism, thermal doming and subsidence, deformation and metamorphism and tectonic switching. Large differences in metamorphic grade occur throughout the province ranging from greenschist – to granulite facies. Throughout the province, steeply dipping, WNW-ESE-striking ductile shear zones are found. The most significant shear zone is the Singö Shear Zone which is located in the northernmost part of the province. Metamorphism in the area has been attributed to at least two metamorphic events, penetrative ductile deformation during the Svecokarelian orogen and low grade localized deformation in the west during the Sveconorwegian orogen (Hermansson et al., 2008).

The Bergslagen bedrock is generally characterized by series of N-S oriented open to tight fold arcs, that vary in size from a few kilometers to over 20 km. Ståhlös (1969) defined two different fold phases in the Bergslagen province, F1 and F2, attributed to two different compression directions. The older deformation phase responsible for the F1 folds, interpreted to have been formed by E-W oriented compression, resulted in tight to isoclinal folds which are overturned to the west and with N-S oriented, east dipping and shallowly plunging fold axes. The later F2 folds where developed by N-S oriented compression and deformed the F1 folds. The fold axes have an E-W orientation and are parallel to a strong stretching lineation and foliation within the rocks.

3.1.3 Sätra – Kungshatt

The study area is comprised of metaigneous and metasedimentary rocks (Fig. 7). The metaigneous rocks include granites, granodiorites and tonalites whereas the metasedimentary rocks include metagreywackes and micaschists. Both show local occurrences of migmatization resulting in veined gneisses, and are often found together with younger intrusions of granite, aplite and pegmatite (Persson et al., 2001). These younger intrusions occur as thin strings and show a general ENE-NE to WNW orientation. Throughout the Stockholm area, the grey – to red colored, fine – to medium grained, 1.8 Ga, Stockholm granite is a common element. It is predominately found as lenses and covers large parts of Kungshatt. Even younger 1.25 Ga dolerite dykes ranging between 1 – 50 m in width, intersect the metaigneous rocks predominately with a WNW to NW orientation (Morfeldt, 1997; Stålhös, 1968; Stålhös, 1969). Furthermore, amphibolites of supracrustal origin and metamorphosed gabbros and diorites occur locally. Along the water passage between Sätra and Kungshatt a major deformation zone with normal faulting is present (Fig. 7).
The metamorphic conditions of the area have been constrained to 700°C and 4 kbar (Stålhös, 1969). This is based on the mineral assemblage biotite, muscovite, garnet, cordierite, sillimanite and microcline present in the veined gneisses.

Generally, the most important orientation of geological features in the Stockholm area are E-W, WNW and NW (Stålhös, 1969; Persson, 1998), which gives a good match with the regional structures. These dominant orientations are also confirmed by structural trends and lineament interpretation (Persson, 1998). Fault zones show two main sets of orientations, WNW to ENE, and NW to NNW (Morfeldt, 1997). Joints and joint sets studies from the Stockholm area where carried out by Hildebrand (1994) which described three dominating fracture orientations: NW to WNW, NE-ENE and N-S. Furthermore, Stålhös (1969) described that the fault planes in the area are characterized as soil filled valleys and elongated lakes. Structural trends of the bedrock and lineament interpretations of the study area show two main structural orientations: SE-NW and E-W (Persson, 1998).
3.2 Stress field

3.2.1 Scandinavia

Through in-situ stress measurements and focal mechanisms investigations of earthquakes, the Scandinavian stress field has been identified (Gregersen et al., 1991; Zoback et al., 1989). The recent horizontal stress field has been concluded to be generated by tectonic forces attributed to ridge push forces from the North Atlantic Ridge and the Alpine collision between the European and African plate (Gregersen, 1992 and Müller et al., 1992).

As an effect of these tectonic forces the general horizontal compressional stress ($\sigma_1$) orientation in Scandinavia is 140° or NW-SE (Fig. 8), which follows the direction of the absolute plate motion (Gregersen et al., 1991; Gregersen & Voss, 2009). Stress determination conducted in the offshore regions of Norway also concluded that a rotational component in the horizontal stress ranging from N-S in the northern parts of Norway to WNW-ESE in the southern parts (Fejerskov, 2000). The NW-SE direction is also in agreement with the horizontal stress directions found in northern Europe.

![Figure 8. Orientation of maximum horizontal stresses, associated fault regime and methods (Heidback et al., 2008).](image-url)

There are uncertainties in the measured in-situ stresses in Norway, Sweden and Finland which show scattered directions. Stephansson (1988) presented three possible explanations for these variations: (1) irregularity of natural fault and fracture patterns, (2) change in magnitude and orientation of stresses near faults and, (3) scatter in roughness and frictional strength in the upper crust. Furthermore, it has been concluded that the dominating NW-SE stress field direction is only
obtained if measurements shallower than 300 m are excluded (Stephansson et al., 1991; Gregersen et al., 1991).

In addition to the horizontal tectonic induced stress the postglacial isostatic uplift, resulting in a predominantly vertical movement, is also affecting the dynamics of the crust. The maximum uplift is found in the area around the Gulf of Bothnia with rates of 10-12 mm/yr whereas uplift in the study area range between 4-6 mm/yr (Steffen, 2006). In addition to the vertical component associated with the uplift, a horizontal (1-2 mm/yr) component exists as well, due to the “doming” nature of the uplift movement. Hence, the Scandinavian stress field is a combination of both tectonic and static forces.

1.2.2 Paleostress Scandinavia

Based on a study by Heeremans et al., (1996), paleostress reconstruction has been performed from analysis of different kinematic indicators, obtained in the Oslo Graben. From this data, it was found that the stress field in the area has changed drastically over time and consisting of five different phases. Phase 1 has been constrained to Caledonian age (490-390 Ma) and is characterized by pure to radial NW-SE compression were the radial shear is interpreted as two separate compressional phases. Phase 2 is characterized by N-S oriented compression and constrained to the Hercynian Orogeny (416-359 Ma). Phase 3 is subdivided into three phases with WNW-ENE oriented transpression (compressional strike-slip) found in rocks of Silurian age (443-419 Ma), NNE-SSW oriented transpression (compressional strike-slip) occurring in the Late Carboniferous, and N-S transpression (compressional strike-slip) in the Late Permian. Phases 4 and 5 are attributed to extensional forces occurring during Early Permian with NW-SE to ENE-WSW pure extension, followed by radial extension (Heeremans et al., 1996).

3.2.3 Bergslagen

Focal mechanism studies by Arvidsson & Kulhanek (1994) concluded that the faulting style of the Bergslagen province consists of both normal - and strike-slip faulting. The area is also affected by both NW-SE oriented compressional stresses attributed to ridge push forces (Arvidsson & Kulhanek, 1994). Furthermore, stress measurements conducted at Forsmark indicate that the main horizontal stress orientation is 145° (SKB, 2007). This fits with the regional NW-SE oriented horizontal stress direction and the NE-SE extensional direction attributed to the postglacial uplift.

4. Background data

Below data is presented that was available for this thesis, which was used to gather information about the rock mass and its geological framework.
4.1 Drill core data

4.1.1 08F152K

The drill core is dominated by fine – to medium grained veined gneiss with chlorite altered biotite. Quartz veins and pegmatite are frequently occurring while granite is found in smaller amounts. The rock mass is slightly too heavily weathered (W1 – W4), showing chlorite and graphite alteration in weakness zones. The mineral infilling in the drill core is dominated by chlorite and graphite. Pyrite, clay minerals and calcite are less frequent but occur in relatively large amounts. Signs of foliation are weak or non-existing, therefore few foliation measurements are provided.

Brittle to ductile deformation zones are found at four places in the drill core, (39.46 m, 47.40 m, 50.13 m and 61.61 m), the two former include cataclastic rocks. The orientation of two of the deformation zones where successfully measured at depth 48.06 m and 53.37 m. Both show a steep dip (definition in Table 3), with a WSW-ENE and SW-NE orientation. Another occurrence of cataclastic rocks is found at the depth of 40.74 m showing a WSW-striking orientation and a sub-vertical dip.

Crushed rock is found at seven places: 53.54 m, 62.51 m, 63.04 m, 66.62 m, 69.04 m, 69.25 m and 72.86 m. The width of these zones of crushed rock varies between 9 - 60 mm, and consists of fraction sizes between 7 – 50 mm. The crushed rock show two different orientations but are dominated by a general WSW-striking orientation and a steep to sub-vertical dip. The mineral infillings are dominated by graphite and clay minerals, but calcite and chlorite occur as well. In addition to this, core loss is noted at four intervals (35.49 – 36.00 m, 37.10 – 37.23 m, 58.68 – 58.79 m and 72.25 – 72.56 m.

4.1.2 08F153K

The drill core is dominated by fine – to medium grained, chlorite veined gneiss. Granite occurs in smaller amounts in the drill core and is mainly concentrated in the first 8 m of the drill core which is solely composed of granite. Pegmatite is also present, partly displaying deformed quartz and chlorite healed fractures. The rock mass is slightly too heavily weathered (W1 – W4) showing quartz and graphite alteration in weakness zones. The drill core is dominated by the mineral infillings chlorite, clay minerals, graphite and pyrite. Calcite, zeolite, quartz and biotite occur but are less frequent. Signs of foliation are weak or non-existing, therefore few foliation measurements are provided. Between drill core length 76 m and 79 m occurrence of smaller (<1 m) parts of amphibolite, cataclastic rocks and breccia are found. Cataclastic rocks are also found at drill core length 34.35 m, with a SE-striking, gentle dipping orientation. At drill core length 70 m, gouge is found adjacent to a crush zone. The gouge-containing crush zone has a NW-striking orientation with a moderate dip.

Brittle to ductile deformation zones are found at four places in the drill core, (37.83 m, 50.65 m, 54.26 m and 61.45 m). Measurements were successful in the later deformation zone and show a
sub-vertical dip, and a WSW-strike. Cataclastic rock is found at the depth of 78.28 m showing a WNW-striking orientation and a moderate dip.

Crushed rock is found at eight places: 48.73 m, 48.93 m, 54.54 m, 54.75 m, 54.84 m, 55.22 m, 58.21 m and 69.88 m. The width of these zones of crushed rock range between 5 – 29 mm, and consists of fraction sizes between 3 and 15 mm. The crushed rock show two different orientations but are dominated by a general WSW-striking orientation and a steep to sub-vertical dip. The less pronounced orientation has an ENE-strike and a sub-vertical dip. Mineral infillings in the crushed rock consist of graphite, chlorite and clay minerals.

4.1.3 10F156K

The drill core is dominated by fine – to medium grained veined gneiss and gneissic granite. Pegmatite and granite occur in smaller amounts. The veined gneiss occasionally show occurrence of breccia, cataclastic rocks and brittle to ductile deformation zones. The two occurrences of cataclastic rock are oriented WSW-ENE, the four occurrences of breccia are oriented N-S and WSW-ENE, and the 2 occurrences of deformation zones are oriented SW-NE. The gneissic granite and granite contains a varying degree of laumontite and calcite healed fracture networks. The veined gneiss show chlorite and graphite altered foliation planes. The rock mass mainly displays visible foliation and/or occasional mylonitization. The most frequent mineral infillings are chlorite, pyrite, calcite, graphite, laumontite and clay minerals in respective order. Less frequent minerals are zeolite, quartz, prehnite and calcite.

Crushed rock is found at 28 sites along the drill core. The width of these zones of crushed rock range between 7 mm and 2.55 m and consists of fraction sizes between 6 – 50 mm. The crushed rock shows that the dominating orientations range from E-W to SSW-NNE. The dominating mineral infillings are clay minerals, graphite and chlorite, with occasional occurrence of pyrite, calcite and talc.

<table>
<thead>
<tr>
<th>Dip (degrees)</th>
<th>Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Horizontal dip</td>
</tr>
<tr>
<td>1-10</td>
<td>Sub-horizontal dip</td>
</tr>
<tr>
<td>10-30</td>
<td>Gentle dip</td>
</tr>
<tr>
<td>30-60</td>
<td>Moderate dip</td>
</tr>
<tr>
<td>60-80</td>
<td>Steep dip</td>
</tr>
<tr>
<td>80-90</td>
<td>Sub-vertical dip</td>
</tr>
</tbody>
</table>

4.2 Outcrop mapping

4.2.1 Sättra - Kungshatt

Sättra is dominated by light colored, medium grained, granitic gneiss and gneissic granite, with occasional granite. The area hosts depressions in the terrain at three different places with a general N-S
orientation as well as a 0.5 m wide fracture zone with a NW-strike and a sub-vertical dip. The southern part of Kungshatt is dominated by grey – to red colored granitic gneiss with occasional granite, and the northern part by grey – to red colored, coarse grained, foliated granite with dykes or random accumulations of pegmatites. Throughout the island, fractured rocks are found in depressions with a predominately westerly orientation whilst one occurrence of fragmented dolerite dyke with a NNW to SSE orientation is found in the southernmost part of the island.

5. Methods

For this thesis four main software’s was used: DIPS, OpenStereo, 3D MOVE and Bentley Powercivil. The software DIPS and OpenStereo are structural geological software’s where orientations (e.g. fractures, structures, and fabrics) can be displayed through stereographic projections and then used for further evaluation. Two main stereographic projection methods used within the software are Fischer projection and rosette projection. Both projections were used to identify the main structural trends, however, Fischer projection was used when more than one type of data was evaluated in the same projection, e.g. fracture orientation and mineral infillings, as well as when determining fracture sets. OppenStereo was used both with Fischer projections as well as great circle projections. 3D MOVE is software developed for structural 3D modeling and analysis which was used to model the major fracture zones. Bentley Powercivil is multifunctional CAD software, mainly used for producing both detailed 3D models and 2D drawings. The software was used in order to visualize and produce drawings over drill core - and outcrop mapping data.

5.1 Background data

5.1.1 Fracture and structure analysis – Outcrop mapping

The complementary outcrop mapping carried out by both WSP and ÅF included measurements from several other areas along the planned tunnel route, hence the data from outcrops located within the presented study area had to be extracted in order to get information on the relevant outcrops. The outcrop mappings comprise 89 outcrops. In places where the outcrops cover a large area several measurements were conducted at different locations within the outcrop, however, these are here regarded as different outcrops. The fracture measurements over Sättra and Kungshatt were plotted in stereographic projection plots separately in order to find characteristic orientation for each area. The few available foliation measurements were also examined using stereographic projection plots.

5.1.2 Fracture and structure analysis – Drill cores

First of all, the main fracture set orientations in the drill cores was established through stereographic projection plots. The fracture measurements where plotted separately for each drill core in order to detect any differences and similarities in fracture orientation. For drill core 10F156K the
stereographic projection plots were divided into two main intervals: 9-124 m since orientation and azimuth of the drill core resembles that of drill core 08F152K and 08F153K, and 125-289 m which reflects the more horizontal part of the drill core. The fracture sets where established for Fischer concentrations of 4% or higher, except in drill core 10F156K where a lower limit of 2% was chosen, due to the large number of fractures in this drill core. After establishing the main fracture orientation in the drill cores, the mineral infillings were added to the fracture stereographic projection plots. In total, over 2500 fracture measurements with associated mineral infillings were under examination. Only the main occurring fracture mineral for each fracture was used, therefore the fracture mineral for each fracture is defined by the main occurring mineral. By doing this the dominating mineral infillings for each drill core could be established, along with the dominating mineral infillings found in the determined fracture sets. After defining the main fracture orientation, the location of fracture zones along the drill cores were established by examining the fracture frequency where high fracture frequencies often are indicative of fracture zones (Gudmundsson et al., 2010), fracture spacing which should show the opposite pattern to the fracture frequency, water-loss measurements where water-loss is indicative of existing fractures and zones with crushed rock. Fracture zone determination was heavily based on the occurrence of zones of crushed rock, which is tangible evidence of active faulting. Zones of crushed rock <0.15 m were not considered as major fracture zones if not followed by additional zones of crushed rock within an interval ≤ 1 m. Furthermore, intervals between zones of crushed rock had to show a fracture frequency and fracture spacing smaller or equal to the overall fracture frequency of the drill core. By using the orientation measurements of the crushed rock found in the interpreted fault zones the orientation of the fracture zones could be determined. Foliation orientations measurements from both outcrop and drill core mapping were plot in stereographic projection plots and examined together with the main fracture sets. Fractures are predominately generated in weakness zones in the bedrock e.g. foliation planes. Therefor knowing how these fractures are related to the general foliation orientation in the area give further insight in the fracture characteristics.

5.1.3 3D modeling

In order to better visualize and interpret the major fracture zones they were modeled in 3D using the software 3D MOVE. The models were then used to define any linking fracture networks and how these major fracture zones cross the underlying Stockholm Bypass tunnel. The orientations of the major fracture zones were defined through the orientation of the occurring zones of crushed rock within each interval. The individual fracture zones where modeled as fracture planes with a constant width and do not represent the actual width of the characterized zone. Furthermore, the propagation and pattern of the crushed zones are simplified as straight, therefore possible bends occurring along the zones, or possible fracture patterns such as anastomosing or splaying are not considered.
5.2 Complementary studies

5.2.1 Kinematics – Field work

Both outcrop mapping and the drill core mapping provided information about the surface and subsurface geology e.g. foliation orientation, fracture orientation, fracture infill minerals, orientation and characteristics of the zones of crushed rock, however one crucial piece of information was lacking and that is kinematic data. In order to complement both outcrop – and drill core mapping with this information, additional field work was carried out. The drill cores (08F152K, 08F153K and 10F156K) were studied in detail looking for any signs of kinematic indicators along the fracture planes, which could give information about the sense of shear between the blocks. The style of shearing (strike-slip, dip-slip) is of great importance for the tunnel stability examination. In places where kinematic indicators were found BIPS pictures or drill core loggings where used to identify the fracture and the orientation. Additional outcrop mapping in Sätra and Kungshatt was also conducted with the main aim to find additional informations about the kinematics of the fracture zones. The outcrops where identified using existing topographic maps with associated outcrops produced by ÅF. The locations of the outcrops was acquired both through GPS positioning and map navigation. The fracture and foliation measurements were conducted by using the right hand rule.

6. Results

This chapter summarizes the results from analysis of the available background data (outcrop mapping and drill core mapping), as well as the results from the complementary fieldwork.

6.1. Drill cores

6.1.1 08F152K

6.1.1.1 Fractures

Stereographic projection plots over the fracture measurements conducted on drill core 08F152K indicate a main WSW-ENE fracture orientation in the drill core (Fig. 9). Almost all of the fracture measurements are consistent with this direction and very small scatter in orientations exists. The main fracture set is interpreted to strike WSW with a steep dip towards NNW (Table 4).
Figure 9. Stereographic projection showing fracture orientations and interpreted fracture sets shown in rosette plot (left) and Fischer plot (right). Lower hemisphere projection.

Table 4. Fracture sets and orientations.

<table>
<thead>
<tr>
<th>Fracture set</th>
<th>Strike (°)</th>
<th>Dip (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250</td>
<td>83</td>
</tr>
</tbody>
</table>

6.1.1.2 Mineral infillings

Stereographic projection plot (Fig. 10) shows the main occurring mineral infilling minerals and their distribution along fractures. The number of occurrences (n) for each mineral is presented in Figure 10. The main occurring mineral infillings within the drill core fractures are graphite (n=107) and chlorite (n=89). These dominating mineral infilling are in agreement with the dominating mineral infillings found in the fractures within the interpreted fracture set (Fig. 10). The dominating fracture infilling minerals are often accompanied by the accessory mineral calcite, pyrite and quartz in varying amounts.

Figure 10. Fischer projection of mineral infilling occurrences (right) and number of mineral infillings in determined fracture sets (left). Lower hemisphere projection.

6.1.1.3 Fracture frequency

The fracture frequency in the drill core is ~ 6 f/m (fractures per meter) with a relatively homogenous distribution along the drill core (Fig. 11). The diagram shows that the fracture frequency
is highest between drill core length intervals 45 – 50 m with ~ 9 f/m. The lowest fracture frequency is found at the interval 60-65 m with a fracture frequency of ~ 2.5 f/m.

6.1.1.4 Fracture spacing

Fractures within drill core 08F152K are generally closely spaced with a general fracture spacing of 0.15 m throughout the drill core (Fig. 12). Intervals with less frequently occurring fractures are found between 59-66 m and 70-74 m. Intervals with very closely spaced fractures are found scattered throughout the drill core with values ≥ 0.01 m.

6.1.1.5 Crushed rock

In total crushed rock are found at 5 intervals within the drill core: 53 m, 62-63 m, 66 m, 69 m and 72-73 m (Fig. 13). The narrowest occurrence of crushed rock is found at 53 m where 0.12 m of the 1 m interval consists of crushed rock. The widest occurrence is found at 62-63 m where 0.9 m of the 2 m interval is crushed.
6.1.2 08F153K

6.1.2.1 Fractures

Stereographic projection plots over the fracture measurements conducted on drill core 08F153K indicate a main WSW-ENE fracture orientation in the drill core (Fig. 14). Both the rosette and Fischer plot show that there is a small scatter in orientations ranging from E-W to SW-NE. The main fracture set is interpreted to strike WSW with a steep dip towards NNW (Table 5).

![Figure 13. Occurrence and length of crushed rock.](image)

![Figure 14. Stereographic projection showing fracture orientations and interpreted fracture sets shown in rosette plot (left) and Fischer plot (right). Lower hemisphere projection.](image)

<table>
<thead>
<tr>
<th>Fracture set</th>
<th>Strike (°)</th>
<th>Dip (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>255</td>
<td>67</td>
</tr>
</tbody>
</table>

Table 5. Fracture sets and orientation.
6.1.2.2 Mineral infilling

Stereographic projection plot (Fig. 15) shows the main occurring mineral infillings and their distribution along fractures. The main occurring mineral infillings within the drill core fractures are chlorite (n=212), graphite (n=126) and clay minerals (n=103). These dominating mineral infillings are in agreement with the dominating mineral infillings found in the fractures within the interpreted fracture set where clay minerals are underrepresented relative to graphite and chlorite (Fig. 10). The dominating mineral infillings are accompanied by the accessory minerals pyrite, calcite, laumontite, quartz, biotite, prehnite and zeolite in varying amounts.

![Fischer projection of mineral infilling occurrences (right) and number of mineral infillings in determined fracture sets (left). Lower hemisphere projection.](image)

**Figure 15.** Fischer projection of mineral infilling occurrences (right) and number of mineral infillings in determined fracture sets (left). Lower hemisphere projection.

6.1.2.3 Fracture frequency

The fracture frequency in the drill core is ~ 9 f/m, displaying a higher fracture frequency in the central parts of the drill core. A more detailed representation of the fracture frequency is shown in Figure 16. The diagram shows that the fracture frequency is highest between drill core lengths ~ 50 – 60 m with a fracture frequency of ~ 17 f/m, and the lowest fracture frequency is found at drill core lengths 40-45 m and 70-75 m with a fracture frequency of ~ 5 f/m.
Fracture frequency shown in 5 meter intervals for drill core 08F153K.

**6.1.2.4 Fracture spacing**

Fractures within drill core 08F153K are generally closely spaced with a general fracture spacing of 0.105 m throughout the drill core (Fig. 17). Intervals with less frequently occurring fractures are found between 32-36 m, 71-75 m and 81-82 m. Intervals with very closely spaced fractures are found scattered throughout the drill core with values $\geq 0.01$ m.

**6.1.2.5 Crushed rock**

In total crushed rock are found at 4 intervals within the drill core: 48 m, 54-55 m, 58 m and 69-70 m (Fig. 18). Two main intervals indicate the longest interval with crushed rock: 54-55 m where 0.63 m out of the 2 m interval consists of crushed rock, and 69-70 m where 0.25 m out of the 2 m interval consisting of crushed rock.
6.1.3 10F156K

6.1.3.1 Fractures

Stereographic projection plots over the fracture measurements conducted on drill core 10F156K indicate a general WSW-ENE fracture orientation throughout the drill core (Fig. 19). Both the rosette and Fischer plot show that there is scatter in orientations ranging from E-W to NE-SW, as well as less frequent N-S and NW-SE oriented fractures. Two main fracture set are interpreted between 9-298 m, the first with a WSW strike and a steep dip towards NNW and the second with a NE strike and a steep dip towards SE (Table 6). These fractures make up a conjugate set. Between 9-124 m the same scatter in fracture orientation is visible, ranging from an N-S to an E-W orientation (Fig. 20). The two interpreted fracture sets (Table 7) show a NNE strike with a moderate dip and a NE to ENE strike with a sub-vertical dip. The interval 125-298 m is dominated by a WSW striking fracture orientation, with a moderate dip (Fig. 21, Table 8).
Table 6. Fracture sets and orientations.

<table>
<thead>
<tr>
<th>Fracture set</th>
<th>Strike (°)</th>
<th>Dip (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>259</td>
<td>77</td>
</tr>
<tr>
<td>2</td>
<td>035</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 7. Fracture sets and orientations.

<table>
<thead>
<tr>
<th>Fracture set</th>
<th>Strike (°)</th>
<th>Dip (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>026</td>
<td>62</td>
</tr>
<tr>
<td>2</td>
<td>057</td>
<td>80</td>
</tr>
</tbody>
</table>
Figure 21. Stereographic projections showing fracture orientations and interpreted fracture sets shown in rosette plot (left) and Fischer plot (right) between 125-298 m. Lower hemisphere projection.

Table 8. Fracture sets and orientations.

<table>
<thead>
<tr>
<th>Fracture set</th>
<th>Strike (°)</th>
<th>Dip (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>260</td>
<td>76</td>
</tr>
</tbody>
</table>

6.1.3.2 Mineral infilling

The dominating mineral infillings within the drill core fractures is chlorite (n=823), followed by calcite (n=198), clay minerals (n=165) and graphite (n=124). Less frequent are laumontite, pyrite, quartz, talc and zeolite.

Figure 22. Fischer projection showing mineral infillings occurrences for the whole length (9-298 m) in drill core 10F156K). Lower hemisphere projection.
6.1.3.3 Fracture frequency

The general fracture frequency for the whole drill core is ~ 6 f/m. A more detailed representation of the fracture frequency is shown in Figure 23. The diagram reveals that the highest fracture frequency is found between 70-80 m with a frequency of ~ 14 f/m, and the lowest between 40-50 m and 270-280 m with a frequency between 2-3 f/m.

![Figure 23. Fracture frequency shown in 10 meter intervals for drill core 10F156K.](image)

6.1.3.3 Fracture spacing

Fractures within drill core 10F156K are generally closely spaced with a general fracture spacing of 0.15 m throughout the drill core (Fig. 24). Intervals with less frequently occurring fractures are found between 42-51 m and 263-288 m with general fracture spacing of 0.4 m and 0.33 m respectively. Intervals with very closely spaced fractures are found scattered throughout the drill core with values ≥ 0.001 m.
6.1.3.4 Crushed rock

In total crushed rock are found at 28 sites within the drill core (Fig 25). Eleven sites show intervals with crushed rock ≥ 0.5 m, whereas the longest intervals with crushed rock ≥ 2 m are found at 63.2 m and 162.8 m.

6.1.4 Water-loss measurements

Table 10 shows the amount of water-loss recorded in boreholes 08F152K and 08F153K over a 10 minute period. The intervals, which did not show any water-loss, are not included in the table. Within borehole 08F152K there are two main intervals, 69.00-72.00 m and 72.00-75.20 m, which show considerable amounts of water-loss. The former shows a 19.4 liter water-loss whereas the latter shows the most prominent water-loss, yielding 54 liters. Large amounts of water-loss are detected throughout borehole 08F153K with the lowest water-loss: 23.2 liters found between 66.4-69.4 m, and the highest water-loss: 44.7 liters found between 33.4-36.4 m. Overall borehole 08F153K shows a
higher degree of water-loss compared to borehole 08F152K. In drill core 10F156K only two intervals, 92-95 m and 197-207 m show high hydraulic conductivity values ($10^{-7}$ - $10^{-6}$ m/s).

Table 9. Detected water-loss during 10 minutes in borehole 08F152K and 08F153K.

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Borehole length (m)</th>
<th>Water-loss (l) per 10 minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>08F152K</td>
<td>45.00 – 48.00</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>48.00 – 51.00</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>66.00 – 69.00</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>69.00 – 72.00</td>
<td>19.4</td>
</tr>
<tr>
<td></td>
<td>72.00 – 75.20</td>
<td>54</td>
</tr>
<tr>
<td>08F153K</td>
<td>33.40 – 36.40</td>
<td>44.7</td>
</tr>
<tr>
<td></td>
<td>66.40 – 69.40</td>
<td>23.2</td>
</tr>
<tr>
<td></td>
<td>69.40 – 79.40</td>
<td>34.5</td>
</tr>
</tbody>
</table>

6.1.5 Fracture orientation in the water passage

Based on the results from the stereographic projection plots the main fracture orientation in the water passage is determined. The projections for every drill core (08F152K, 08F153K and 10F156K), except for the interval 9-124 m in drill core 10F156K, shows a dominating E-W to WSW-ENE striking orientation with a steep dip towards N to NNW (Fig. 26).
Figure 26. Rosette stereographic projection plots over fracture orientation for all drill cores.
The general orientation from all the drill core measurements (strike: 255°, dip: 75°) generates a WSW-ENE fracture orientation (Fig. 27).

![Figure 27](image.png)

FIGURE 27. Main fracture orientation in the water passage (3D MOVE) and rosette plot over all fracture measurements from the drill cores.

### 6.1.6 Major fracture zones

Major fracture zones visible in the drill cores have been defined through correlation of the parameters: Crushed rock, fracture frequency, fracture spacing and water-loss measurements. The major fracture zones that have been identified are presented below for each drill core. Since crushed rock is the most tangible evidence for existence of fracture zones, this has been the main parameter during determination of the major fracture zones when no or weak correlation between the other parameters are found.

#### 6.1.6.1 08F152K

The major fracture zones in drill core 08F152K are:

- The 62.50 – 63.64 m interval: The 1.14 m long section contains 2 intervals with crushed rock with a total length of 0.9 m. The section is composed of veined gneiss with chlorite filled fracture networks. The main fracture infilling minerals are clay minerals and chlorite. Fracture frequency and fracture spacing could not be measured in this section. The section does not correlate with any water-loss.

- The 66.62 – 67.41 m interval: The 0.79 m long section contains 1 interval with crushed rock with a length of 0.25 m. The section is mainly composed of veined gneiss with clusters of chlorite and pegmatitic rock. The main fracture infilling minerals are graphite and chlorite. The section correlates to one of the intervals with the highest fracture frequency in the drill core. The fracture frequency of the section is 18 f/m and fracture spacing is 0.06 m. The section correlates to the interval 66.00-69.00
m with the lowest detected water-loss measurements (not including intervals with no water-loss) in the drill core.

- The 68.50 - 69.90 m interval: The 1.4 m long section contains 2 intervals of crushed rock with a total length of 0.26 m. The section is composed of veined gneiss with clusters of chlorite and pegmatitic rock, as well as pegmatitic granite with chlorite filled fracture networks. The section correlates to one of the intervals with the highest fracture frequency in the drill core and to the interval with the second highest water-loss. The fracture frequency of the section is 15 f/m and fracture spacing is 0.063 m.

- The 72.63 - 73.10 m interval: The 0.47 m long section contains 1 interval of crushed rock with a total length of 0.27 m. The section is composed of chlorite and biotite rich, veined gneiss. The section correlates to the interval 72.00-75.20 m in the water-loss measurements, which has the absolute highest water-loss.

### 6.1.6.2 08F153K

The major fracture zones in drill core 08F153K are:

- The 54.54 - 55.51 m interval: The 0.97 m long section contains 4 intervals with crushed rock with a total length of 0.63 m. The section is composed of veined gneiss with signs of brittle to ductile deformation. The main fracture infilling minerals are graphite and clay minerals. The general fracture frequency of the interval is 17.6 f/m and fracture spacing is 0.025 m. Water-loss measurements within this interval show no detectable water-loss.

- The 69.57 - 70.20 m interval: The 0.63 m long section is composed of veined gneiss dominated by the fracture infilling minerals graphite and clay minerals. Within the section, one 0.25 m long interval with crushed rock is found. The general fracture frequency of the interval is 26.3 f/m and fracture spacing 0.063 m. The section correlates to the water-loss measurement interval 69.4-79.4 m with a general water-loss of 3.45 l/m.

### 6.1.6.3 10F156K

The major fracture zones in drill core 10F156K are:

- The 58.28 - 67.26 m interval: The 8.98 m long section contains 6 intervals with crushed rock with a total length of 4.53 m. The section is composed of red to grey colored veined gneiss, which occasionally is brecciated or shows signs of brittle to ductile deformation. The main fracture infilling minerals are chlorite and clay minerals. Fracture frequency in the section is 6 f/m and the fracture spacing 0.115 m.
• The 78.93 - 83.62 m interval: The 4.69 m long section contains 4 intervals with crushed rock with a total length of 1.32 m. The section is composed of pink colored, mylonitic, veined gneiss. Healed fracture networks filled with chlorite and calcite as well as chlorite alteration along the whole section is found. The main fracture infilling minerals are chlorite and clay minerals. The section correlates to the interval with the highest fracture frequency in the drill core. The fracture frequency in the section is 12.16 f/m and the fracture spacing is 0.071 m, which is more than twice the general fracture spacing.

• The 125 – 128 m interval: The 3 m long section contains 1 interval with crushed rock with a length of 0.5 m. The section is composed of mylonitized, geneissic granite, with clusters of chlorite, and veined gneiss with chlorite healed fracture networks as well as open fractures with graphite and talc. The main fracture infilling minerals are chlorite and pyrite. The interval 125-126 m has the highest fracture frequency in the drill core (18 f/m). The fracture frequency for the whole section is 10.4 f/m and fracture spacing is 0.0096 m.

• The 149.09 - 156.51 m interval: The 7.42 m long section contains 2 intervals of crushed rock with a total length of 1.61 m. The section is composed of grey to dark grey colored, cataclastic, veined gneiss with graphite coated healed and open fractures. Throughout the section clusters of biotite and chlorite are found, as well as pyrite. The main fracture infilling minerals are chlorite and graphite. The general fracture frequency in the section is 6.7 f/m and the fracture spacing is 0.162 m.

• The 162.80 – 170.68 m interval: The 7.88 m long section contains 3 intervals with crushed rock, making up a total length of 3.36 m. The section is dominated by grey to dark grey colored sedimentary veined gneiss. The veined gneiss is cataclastic with chlorite and graphite healed fracture networks between 162.8-165 m and foliated between 167-169 m. The section also contains granite and a 2 m wide quartz vein. The general fracture frequency in the section is 6.63 f/m and the fracture spacing is 0.146 m.

• The 202.36 - 207.84 m interval: Within this section 6 intervals with crushed rock occur. Out of the 5.48 m long section, 2.21 m is crushed rock. The section is composed of grey colored, slightly foliated, veined gneiss with clusters of biotite and chlorite. The section also hosts garnets and laumontite filled, healed, fracture networks. The main fracture infilling minerals are chlorite and clay minerals. Fracture frequency in the section is 7.65 f/m and the fracture spacing 0.108 m. The section correlates with one of two intervals with the highest water-loss measurements exceeding high hydraulic conductivity values of $10^{-7}$ m/s.
6.1.7 Foliation

The foliation from all of the drill cores (08F152K, 08F153K and 10F156K) is characterized by a WSW strike with a steep dip towards NNW (Fig. 28, Table 10).

Table 10. Fracture sets and orientations.

<table>
<thead>
<tr>
<th>Fracture set</th>
<th>Strike (°)</th>
<th>Dip (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>252</td>
<td>73</td>
</tr>
</tbody>
</table>

6.2 Outcrop mapping

6.2.1 Fractures

Stereographic projection plots over the fracture measurements in Sätra indicate a main NE-SW fracture orientation (Fig. 29). The rosette plot clearly shows that there is a subordinate fracture set with a WNW-ESE orientation. The main fracture set is interpreted to strike NE with a steep dip towards NW (Table 11). The fracture measurements in Kungshatt show a large scatter however two main fracture sets are interpreted (Fig. 30). Fracture set 1m with a WSW oriented strike and a sub-vertical dip towards NNW and fracture set 2m with a SE oriented strike and a sub-vertical dip towards NE (Table 12).
Table 11. Fracture sets and orientations.

<table>
<thead>
<tr>
<th>Fracture set</th>
<th>Strike (°)</th>
<th>Dip (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>046</td>
<td>77</td>
</tr>
</tbody>
</table>

Figure 29. Stereographic projections showing Sätra fracture orientations and interpreted fracture sets shown in rosette plot (left) and Fischer (right). Lower hemisphere projection.

Table 12. Fracture sets and orientations.

<table>
<thead>
<tr>
<th>Fracture set</th>
<th>Strike (°)</th>
<th>Dip (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>256</td>
<td>86</td>
</tr>
<tr>
<td>2</td>
<td>136</td>
<td>89</td>
</tr>
</tbody>
</table>

6.2.2 Foliation

The foliation in both Sätra and Kungshatt is characterized by a steep to sub-vertical dip and shows a strike orientation towards NE or ENE (Fig. 31 and 32). Strike and dip are shown in Table 13-14.
Table 13. Foliation trend and orientations. Lower hemisphere projection.

<table>
<thead>
<tr>
<th>Foliation trend</th>
<th>Strike (°)</th>
<th>Dip (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>039</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 14. Foliation trend and orientations.

<table>
<thead>
<tr>
<th>Foliation trend</th>
<th>Strike (°)</th>
<th>Dip (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>074</td>
<td>80</td>
</tr>
</tbody>
</table>

6.3 Complementary outcrop mapping

The results from the complementary outcrop mappings performed on Sätra and Kungshatt are presented below. The locations of the mapped outcrops are presented in Figure 33.
6.3.1 Sätra

The outcrops that were examined in Sätra consisted of sedimentary granites, gneissic granites and occasional quartzite. The gneiss granite occasionally showed a strong foliation fabric with a WSW-ENE orientation, whereas the sedimentary granite showed signs of both brittle and ductile deformation. The outcrops where examined for kinematic indicators that would provide information about the sense of shearing, as well as give information about the main horizontal stress direction ($\sigma_1$). Outcrops that revealed both sense of shear and the direction of main horizontal stress were found.

6.3.1.1 Stress direction

Careful outcrop examination revealed that an NW-SE to N-S oriented horizontal compressional stress has affected the area. At outcrop 1, which was dominated by sedimentary granite with some patches of quartzite, evidence for an N-S directed horizontal stress was found in the form of a mullion (Fig. 34). Mullions are structures that are developed in rocks with contrasting mechanical competences and which have been subjected to deformation. These structures are generally parallel to fold hinges and can therefore tell about the main horizontal compressional direction (Fossen, 2010). The fold hinge of the observed mullion had an E-W oriented fold hinge.
6.3.1.3 Kinematic indicators

At outcrop 2, Riedel shears were found on a vertical surface (Fig. 35). The main shear surface (Y-fracture) is striking 360° and R’ 064°. These fault structures are formed in a strike-slip regime and forms a set of differently oriented faults, such as R’. The angle of these R’ faults indicate a dextral sense of shear, generated by an N-S directed horizontal stress.

Figure 34. Outcrop 1, showing mullion in sedimentary gneiss. Competent layer (outlined) and incompetent layer (striped).

Figure 35. Outcrop 2, showing Riedel shears on outcrop scale showing dextral sense of shear and the fracture sets R’ and Y.
At outcrop 3, signs of sinistral sense of shear were found on a vertical outcrop wall (Fig. 36). The outcrop wall was heavily weathered making rock type identification hard. The stair stepped striations had a SE strike (140°) and a 015° dip and is interpreted as a sinistral strike-slip fault.

![Figure 36. Outcrop 3, vertical section showing striations (yellow lines) with sinistral sense of shear. The red line indicates the horizontal plane.](image)

At outcrop 4, stair stepped striations showing dextral sense of shear was found in a vertical fracture surface (Fig. 37). The striation had an easterly oriented strike (090°) and a gentle to moderate dip (030°).

![Figure 37. Outcrop 4, vertical section showing dextral strike-slip in a major fracture. The red line indicates the horizontal plane.](image)

6.3.2 Kungshatt

The examined outcrops on Kungshatt consisted of granites and gneissess. The majority of outcrops where completely covered by moss and lichens inhibiting foliation measurements, structure and rock type identification. The area has two main fracture orientations, WSW-ENE coinciding with
the general foliation orientation and NW-SE to WNW-ESE coinciding with large-scaled open fractures (Fig. 38) and topographic depressions. Conjugate fracture sets were also found (Fig. 39).

6.3.2.1 Stress direction
At outcrop 5, there is a small-scaled chevron type fold composed of mica rich layers (Fig. 40). The fold was found in an area dominated by sedimentary gneiss. The axial plane strikes 110°.

Figure 38. Outcrop 7, showing large scaled open fractures, oriented NW-SE found on Kungshatt. The fracture has opened approximately 30-40 cm.

Figure 39. Outcrop 8, showing conjugate fracture set on Kungshatt.
6.3.2.2 Kinematic indicators

At outcrop 6, weakly defined stair stepped striations striking 330° were found on a vertical surface (Fig. 41). The kinematic direction of the striations is interpreted as sinistral.

6.4 Kinematic investigation drill cores

Kinematic indicators on fracture surfaces, in the form of striations were found at 42 positions the three examined drill cores (08F152K, 08F153K and 10F156K). Striations were found on 9 fracture surfaces in drill core 08F152K, 8 surfaces in drill core 08F153K and on 25 surfaces in drill core
They were mainly found on fracture surfaces covered with the dominating mineral infilling graphite and chlorite. Sense of shear was found to be related to both strike-slip and dip-slip.

The dominating sense of shear in all of the three drill cores is dextral, occurring in 36 of the 42 fractures. In drill core 08F152K dextral sense of shear is dominating in fractures oriented WNW-ESE to WSW-ENE, whereas sinistral sense of shear is found in two fractures oriented NNW-SSE to NW-SE (Fig. 42a). In drill core 08F153K the orientations of the fractures with recorded striations is more scattered. All fracture surfaces show dextral sense of shear except for one fracture with sinistral shear oriented NW-SE (Fig. 42b).

Drill core 10F156K also shows a large scatter in the orientation of fracture surfaces with recorded striations. Sinistral sense of shear is only found in 3 out of the 25 fracture surfaces and are oriented NNE-SSW to ENE-WSW and NW-SE. Most of the fracture show dextral sense of shear (Fig. 43).

Studying the difference in orientations between fractures dominated by graphite and chlorite respectively can potentially be used to define different generations of fractures and their preferred...
orientation. The fractures dominated by chlorite show some scatter, however two preferred orientations can be distinguished (Fig. 44a). The first set of fractures strike between 080° and 100° with a steep to sub-vertical dip. The second set of fractures strike between 200° and 220° with a steep dip. The fractures dominated by graphite show less scatter than the chlorite healed fractures (Fig 44b). The fracture set has a strike ranging between 045° and 075° with a moderate to steep dip.

![Fischer projection showing fracture concentration of fractures dominated by a. chlorite (left) and b. graphite (right). Lower hemisphere projection.](image)

Fractures with recorded strike-slip movement show one main fracture orientation with opposite dip (Fig. 45a). The fracture set strikes between 060° and 105° with a steep to sub-vertical dip and between 250° and 285° also with a steep dip. Fractures with dip-slip movement show a larger scatter, with no preferred fracture orientation distinguishable (Fig. 45b).

![Fischer projection showing fracture concentration of a. strike-slip fractures (left) and b. dip-slip fractures (right). Lower hemisphere projection.](image)

A weakly defined correlation in preferred fracture orientation can be found between shearing style (strike-slip, dip-slip) and the fractures dominated by graphite and chlorite. The preferred orientation for fractures with dip-slip movement (strike: 205-225°) shows similarities in orientation to
one of the fracture sets in the chlorite dominating fractures (strike: 200-220°). For graphite dominating fractures and fractures with strike-slip movement similarities is found between one of the two fractures sets with strike-slip movement (strike: 060-105°) and the fracture set in the graphite dominating fractures (strike: 045-075°). However, these similarities are fairly weak.

6.5 Fracture networks major fracture zones

Zones of crushed rock which are defined to make up major fracture zones in the water passage (see 6.1.6) show that fracture linkup and fracture networks are found within each of the drill cores (08F152K, 08F153K and 10F156K) assuming that the fracture zones are shorter than 10 m in all directions (Fig. 46). Fracture networks in drill core 08F153K are found between drill core lengths 61-70 m, from the linkage of 5 zones with crushed rock. The zones of crushed rock are oriented WSW-ENE to SW-NE, as well as N-S with a moderate to steep dip. Fracture networks in drill core 08F152K are found between drill core lengths 54-55 m, from the linkage of 4 zones with crushed rock. The zones of crushed rock are oriented WSW-ENE to SSW-NNE with a steep to sub-vertical dip. In drill core 10F156K fracture networks are found at 5 intervals along the drill core: 58-67 m, 79-83 m, 149-156 m, 162-170 m and 202-207 m. The orientation of the zones of crushed rock varies between WSW-ENE to NE-SW with a gentle to sub-vertical dip for all of the intervals except for the interval 79-83m where the orientation is scattered. All of these fracture networks are found in the vicinity of the Stockholm Bypass tunnel with a maximum horizontal distance of 10 m and maximum vertical distance of 35 m found between the fracture network interval 202-207 m in drill core 10F156K and contact with the Stockholm Bypass tunnel.
Figure 46. Position and orientation of zones with crushed rock, making up fracture networks.
6.6 Impact of major fracture zones on the Stockholm Bypass tunnel

If assuming that all of the zones of crushed rock interpreted as a part of major fracture zones, have a horizontal and vertical extent of maximum 35 m, all except one of the total 33 fracture zones will cross the Stockholm Bypass tunnel. Stereographic projection plot shows the orientation of the Stockholm Bypass tunnel and how the fracture zones will cross the tunnel (Fig. 47a). Based on kinematic investigations the majority of the fracture zones can be assumed to have a dextral horizontal shear component. The orientation of the zones of crushed rock shows that the dominating orientations range from ENE-WSW to NNE-SSW (Fig. 47b). Both of these clusters show similarities to orientations found within the fractures strike-slip and dip-slip movement (Fig. 45), as well as graphite and chlorite dominating fractures (Fig. 43). Hence the zones of crushed rock cannot be correlated to a specific shearing style and therefore fractures can be expected to have reactivated both as dip-slip and strike-slip faults.

The cross section along the length of the Stockholm Bypass tunnel shows how the zones of crushed rock are predicted to cut the tunnel (Fig. 48). Generally the interval between 96-196 m which corresponds to the middle of the water passage is the most fractured interval. Between 0-96 m 14 fractures cuts the tunnel, between 96-196 m 22 fractures cut the tunnel and between 196-269 m only two fractures cut the tunnel.

Figure 47. a. Great circles showing how the zones of crushed rock will cut the Stockholm Bypass tunnel marked with the red line (left), and b. Fischer concentration showing the orientations of the zones of crushed rock (right). Lower hemisphere projection.
Figure 48. Section showing the projected zones of crushed rock, which cut the planned Stockholm Bypass tunnel. The red lines mark zones of crushed rock belonging to drill core 10F156K, green from drill core 08F152K and blue from 08F153K.
7. Discussion

7.1 Outcrop analysis

Fracture analysis from outcrop mapping performed on Sättra and Kungshatt show that there are similarities in fracture orientation between the two areas. In Sättra, the dominating orientation is NE-SW oriented fractures with a steep dip, whereas on Kungshatt two dominating fracture orientations are found, which form a conjugate fracture set. Both have a sub-vertical dip, oriented WSW-ENE and NW-SE. Conjugate fracture sets with similar orientations to the WSW-ENE and NW-SE oriented fractures have also been described in Högdalen, Stockholm by Ryttberg (2015), however, with evidence of dip-slip faulting. The WSW-ENE oriented fractures show similar orientation to the NE-SW oriented fractures in Sättra and correlates to the dominating fracture orientations found during the complementary outcrop mapping on Kungshatt. These two fracture orientation (WSW-ENE and SW-NE) can either represent two different fracture sets, or just one single. Comparing the foliation orientations found on Sättra and Kungshatt it is clear that the fractures on Sättra is parallel to the NE-trending foliation, which is also the case for the foliation on Kungshatt which has a WSW-ENE orientation. This is also supported by the complementary mapping where the WSW-ENE oriented fractures were found to be parallel to the foliation. Correlating this to the general structures of the surrounding areas, fracture orientations coincide with both ductile and brittle structures in the area (Fig. 49). The two fracture set orientations (WSW-ENE and NE-SW) found in the drill cores are comparable to the orientation of the WSW-ENE to NE-SW oriented main fault, structural form lines, granite dykes, veined gneiss and the xenoliths on the geological map. The NW-SE oriented fractures on Kungshatt correlate to the NW-SE oriented main fault, granite, and dolerite dykes on the geological map (Fig. 49).
7.2 Drill core analysis

Fracture measurements from the drill cores show that the dominating fracture orientation within drill core 08F152K and 08F153K is WSW-ENE oriented fractures with a steep dip. This is also valid when combining all of the fracture measurements from all of the three drill cores (Fig. 27). There are also two steeply dipping subordinate fracture sets oriented NNE-SSW and NE-SW found in drill core 10F156K at the interval 9-124 m, but for the fractures for the whole drill core only the NE-SW oriented fractures are dominating out of the two sets (Fig. 19 and 20). The WSW-ENE and NW-SE oriented fractures are in good agreement with the large scale lineament interpreted as weakness zones (Fig. 4), and structural trends described by Persson (1998) including major faults (Fig. 49). The main fault varies in orientation from a NW-SE orientation to a WSW-ENE (Fig. 53). The WSW-ENE and NE-SW oriented fractures in the drill core can therefore be interpreted to be a part of the same system of fractures that follows the changes in orientation as of the main fault, or they may comprise of two different fracture systems. The combined foliation measurements from the three drill cores show a dominating WSW-ENE orientation, which lies parallel to the dominating fracture orientation, meaning that fracture orientation is parallel to the foliation. Kinematic investigation shows that fractures in the
area have been reactivated mainly as dextral strike-slip faults with a dominating WSW-ENE orientation. Sinistral strike-slip faulting was found for fractures oriented NW-SE and NNE-SSW where the latter is only supported by two occurrences and not considered in the interpretation of the large-scale framework. The faulting style within the fractures was also found to consist of both strike-slip faulting and dip-slip faulting, meaning that the area has experienced different episodes of reactivation accompanied with changes in faulting style and/or stress field.

7.3 Mineral-infilling

Finding a correlation between fracture infilling minerals and the dominating fracture orientations within the drill cores in an attempt to define different generations of fractures is difficult. This is also the case when trying to link the dominating fracture orientations found on the surface with the sub-surface fractures based on mineral-infilling, since mineral-infilling was not detected during the outcrop mappings and may not be present due to weathering and/or reactivation. Overall the dominating fracture infill minerals for all the fractures in the drill cores are chlorite and graphite, and the dominating fracture orientation throughout all the drill cores are WSW-ENE to SW-NE. Changes in mineralogy in the mineral infillings between different fracture orientations or within the same fracture orientation could indicate different generations of fractures and by finding the same mineral infillings for the surface and sub-surfaces fractures with similar fracture orientations it might have been possible to link these fractures to the same system. However, due to similarities in dip and orientation, the surface and sub-surfaces fractures can be expected to correlate. Given that no changes could be found between the mineralogy in the fracture infilling minerals, may indicate that the WSW-ENE and NE-SW oriented fractures are of the same generation. Nevertheless, correlation between the style of shearing (strike-slip and dip-slip) and the dominating fracture infilling minerals in these fractures could not be found. A very weak connection can be found between the orientation of fractures with dip-slip faulting and fractures with chlorite infilling, and between fractures with strike-slip faulting and fractures with graphite infilling. Fractures with dip-slip faulting and fracture with chlorite infilling show one correlating fracture orientation, NNE-SSW to NE-SW, and fractures with strike-slip faulting and fractures with graphite infilling show correlating fracture orientation for fractures oriented WNW-ESE to WSW-ENE. A stronger connection or further investigation is needed in order to determine if these two fracture orientations comprise one or two different fracture systems.

7.4 Major fracture zones and implications on the Stockholm Bypass tunnel

Major fracture zones consisting of zones of crushed rock has been defined in the water passage. In an attempt to try and define a wider zone based on correlation between (fracture frequency, fracture spacing, width of crushed rock and water-loss), which could be defined as a major fracture zone, 12 major fracture zones consisting of 33 zones of crushed rock was defined based on the
parameters above. In this process 10 out of the total 43 zones of crushed rock found in the drill cores were ignored since they did not match the criterions used for establishing the major fracture zones (see 5.1.2). However, it must be noted that zones thinner <0.15 m of crushed rock can sometimes represent highly active faulting zones with large displacements. The defined major fracture zones orientation correlates to both the overall dominating fracture orientation WSW-ENE and the fracture orientation NE-SW. The structures found in the drill cores such as cataclastic rocks and breccia which are all signs of movements also match the two different fracture orientations, confirming that faulting has occurred along these fractures. The orientation of the dominating WSW-ENE oriented fractures also matches the orientation of the main fault situated in the water passage, which further supports the presence of a fault zone in the water passage. The kinematic investigations on the drill cores show that the WSW-ENE oriented fractures have undergone reactivation as strike-slip faults with a dextral sense of shear whereas fractures with dip-slip faulting show several different orientations which can be attributed to several different reactivation episodes caused by changes in the horizontal stress field. Since the deformation history of the area is characterized by several stages of reactivation and major changes in the stress field it is very likely that the area has experienced several episodes of reactivation. Given the present day stress field with a NW-SE orientation of the horizontal stress field and a NE-SW orientation of the extensional forces resulting from the postglacial uplift and doming (Heidbach et al., 2008; Stephens, 2007), fractures oriented ~ 45⁰ to the horizontal stress field can be expected to reactivate as strike-slip faults, whereas fractures oriented normal to the horizontal stress field can be expected to be reactivated as dip-slip faults. Previous studies also show that dip-slip faults located at depth are generally reactivated as strike-slip faults whereas reactivation is limited at the surface (Richard and Krantz, 1991). Due to the water passage, it was not possible to determine the extent of the fractures found in the drill cores in order to define if the fractures extend to the surface or not.

The majority of the zones of crushed rock within the major fracture zones that cut the tunnel, and the fracture networks shows dominating WSW-ENE orientations, which in turn are oriented ~ 90⁰ to the present day horizontal stress field. At this angle these fractures are more likely to experience closure since they are oriented approximately normal to the stress field. The optimal angle between fractures and the stress field in order to initiate shearing is 45⁰ or smaller (Ziegler, 1995). The zones of crushed rock within the major fracture zones that are either oriented E-W or NNE-SSW are therefore more likely to reactivate as strike-slip faults. The very few fractures that are oriented NW-SE in the drill cores and correlate to fractures with sinistral shearing are likely to reactivate as dip-slip faults as they are oriented parallel to the present day maximum horizontal stress forces or as strike-slip faults if they are located at depth. The central part of the water passage hosts the most fracture zones that cut the tunnel, hence, this part of the tunnel will be most affected by these zones. Due to the positioning of the drill cores 08F153K and 08F152K which are situated in the central part of the water passage, the amount of detected fracture zones can be expected to be higher at this part. Furthermore, the
orientations of the boreholes in the water passage are oriented favorably in order to detect a larger number of the WSW-ENE and NE-SW oriented fractures (Fig. 50), since the drill cores are oriented approximately normal to the WSW-ENE and NE-SW oriented fractures. The boreholes however make a very low angle with the NW-SE oriented fractures. This may explain the less frequent occurrence of the NW-SE oriented fractures in the boreholes. Due to this, the NW-SE oriented fractures can be expected to be highly underrepresented and be more abundant than seen in the drill cores.

The WSW-ENE and NE-SW oriented fractures are as previously mentioned oriented so that they will experience closure of the fractures during the present day stress field, and they also cut the tunnel almost vertically which is the most favorable fracture orientation for the tunnel stability. The NW-SE oriented fractures however, can be expected to experience reactivation as dip-slip faults and/or as strike-slip faults at depth, and cut the tunnel at a low angle which is unfavorable, meaning that these fractures will propagate a large distance through the tunnel and have a negative effect on the tunnel stability. The existing fracture networks collectively can have a negative effect on the tunnel stability. Even though, the orientation of some fracture sets (WSW-ENE and NE-SW) may not cause an immediate threat to the tunnel. However, intersection of fractures with other orientations (e.g. NW-SE) may have a negative impact on the stability of the tunnel by dissecting the bedrock into separate blocks bounded by fractures.

7.5 Structural model

In an attempt to try and produce a structural model over the study area based data from this study, two different models are presented. In both models the main stress orientation ($\sigma_1$) can be expected to have been oriented more towards WNW-ESE when the fractures where established than the present day NW-SE stress field originating from the Atlantic ridge push forces.
7.5.1 Conjugate shearing

This first model promotes conjugate shearing along the fractures oriented WSW-ENE to NE-SW and NW-SE. The WSW-ENE and NE-SW oriented fractures are in this model interpreted as one single fracture set with changes in the fracture orientation matching the changes of the main fault, which is located in the water passage (Figure 51). Both of the combined fracture sets show dextral shearing, with the WSW-ENE oriented fractures making up the dominating fracture orientation in the area. The NW-SE oriented fractures however, show a sinistral sense of shear which was found both in the drill cores and in the field. In conjugate shearing systems, shearing should be opposite between the two shearing surfaces and make an angle of approximately 60° (Mason, 1992). This relationship can be found between the two fracture orientations. Given the fact that conjugate fractures have been found both in the drill cores and in the field (Fig. 38), and visible in the stereographic projection plots, this model seems highly plausible. For example the fractures on Kungshatt form a conjugate fracture set with a sub-vertical dip which is expected in conjugate shearing. Since these two fracture orientations are inferred to make up a conjugate set it is not unlikely that they belong to the same generation. These two shearing surfaces also correlate to the large scaled main faults in the area (Fig. 51).

![Figure 51. Conjugate shearing along the main faults (modified after Persson et al., 2001).](image)

7.5.2 Riedel shear fractures

The second model bases the structural model of the area on Riedel shear fractures which are fractures formed in shear zones. Evidence of Riedel fractures was found in the field (Fig. 34) and has been described from fracture analysis conducted on Lovön and Lambarfjärden (Vass, 2012) and over...
Lake Mälaren as a whole (Tirén & Beckholmen, 1990). The observed fracture orientations can be assigned to all of the different Riedel shear fractures. For further information about the different Riedel shear fractures, their angular relationship and characteristics consult e.g. Fossen (2010) and Coelho et al., (2006).

The dominating shearing in the area has been established to be dextral and the Riedel shear model must thus fit this configuration. Combining the dominating fracture orientations from the drill cores and major fracture surfaces found in the field on Sätra and Kungshatt, all of the five different sets of Riedel fractures can be identified (Figure 51). The P, Y and R fractures are all dominating fracture orientations in the drill cores (Fig. 27), if these are considered as three different fracture orientations and not just changes in orientation within on fracture set. The Y-fracture correlates to the main fracture orientation, which is assumed to represent the main shearing surface that in this case is, oriented WSW-ENE. The R´ fractures represent two fracture surfaces with striations at outcrop 3 and 6. The T-fractures correlate to large scaled open fractures and depressions in topography of Kungshatt, which indicate that these fractures have been subjected to opening (Fig. 38). In this model all of the fractures are expected to have a dextral sense of shear, except for the R´ fractures, which should have sinistral sense of shear, and T-fractures, which should lie normal to the main stress field and be subjected to extension. Fracture orientations with dextral shearing related to the orientation of the P, Y and R fractures are found in the drill cores (Fig. 42a and 42b), and dextral shearing with orientation related to the R-fracture was found in the field on Sätra (Fig. 37). Sinistral sense of shear with orientations related to the R´ fractures where found both in the field on Sätra and Kungshatt (Fig. 36 and 41) as well as in the drill cores (Figure 42a and 42b).

Figure 52. Stereographic projection showing Riedel shear fractures in a dextral shearing setting, related to fractures from drill cores and outcrops.
8. Conclusions

The engineering geological prognosis over this area has predicted that the rock mass in the water passage is of very poor quality, which is why further investigation of the large-scaled structures has been undertaken. The aim of this Master thesis was to identify the large-scale structures, predict how these structures will affect the tunnel and suggest a structural model of the area.

From this study the following conclusions have been drawn:

- The dominating fracture orientation throughout the study area is steeply dipping, WSW-ENE oriented fractures with a subordinate NE-SW oriented fracture set, that is in good agreement with the lineament interpreted weakness zones and structural trends described by Persson (1998).

- The water passage is characterized by steeply dipping, WSW-ENE oriented fractures and consists of major fracture zones defined through correlation with water-loss, fracture frequency, fracture spacing and occurrence of crushed rock.

- In the different parts of the study area (Kungshatt, Fiskarfjärden and Sätra) the fractures are oriented parallel to the local foliation orientation, except for Kungshatt where only one (WSW-ENE) of the two fracture sets follow the foliation.

- Deformation structures (e.g. breccia, cataclastic rock and zones of crushed rock) match the orientation of the dominating WSW-ENE fracture orientation supporting faulting along these fractures which correlates to the main fault found in the geological map.

- Different generations of fractures could not be established through fracture infilling mineral analysis, however a weak connection could be found between dip-slip faulting and chlorite infilling and between strike-slip faulting and graphite infilling.

- The area has experiences several stages of reactivation accompanied by changes in faulting style and/or changes in the stress field.

- The area is interpreted 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.
• Seven fracture networks and 33 zones of crushed rock can be expected to affect the tunnel with the central part of the tunnel being most affected.

• Due to the orientation of the boreholes (NNW-SSE) in relation to the different fracture orientation in the water passage, the NW-SE oriented fracture can be expected to be highly underrepresented in the drill cores and to may have the strongest impact on the tunnel stability.
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