The geological evolution of Stockholm – bedrock, Quaternary deposits and experience from infrastructure projects

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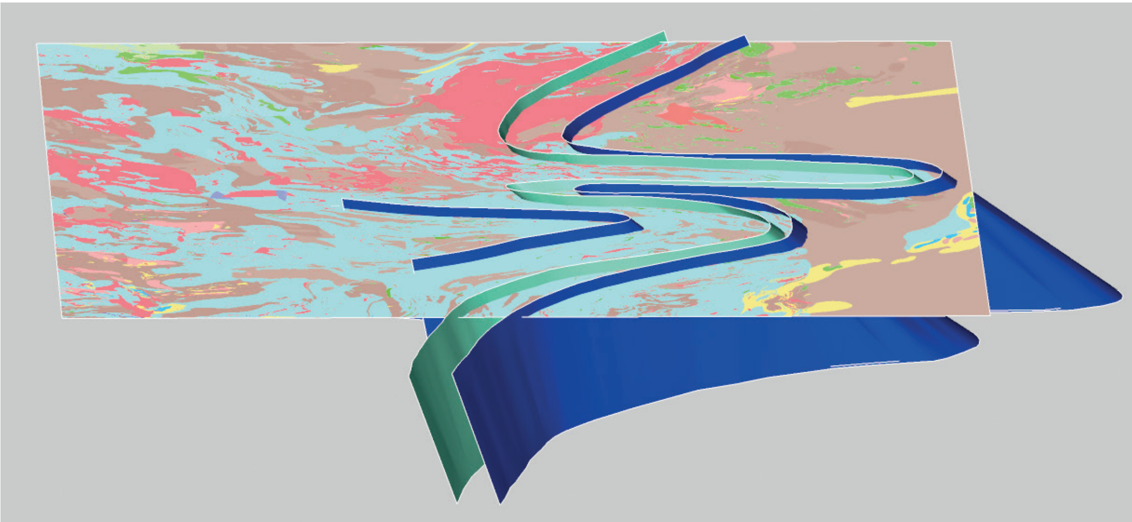
December 2019

SGU-rapport 2019:18



SGU Geological Survey of Sweden

Cover figure: Schematic 3D model of the regional folding in the Stockholm region. The model is produced at SGU.

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PREFACE

This report complements the updated construction geological map of the Stockholm region (www.sgu.se). The content is based on available internal (SGU) and external geological information. The purpose of the report is to provide a brief description of the bedrock and Quaternary deposits, as well as geological evolution in the Stockholm area. The main report is divided into two sections, the first dealing with bedrock geology and the second with drift-Quaternary deposits. In addition, there are two appendices describing experiences from infrastructure projects in the Stockholm area. Authorship of the different parts is as follows:

Carl-Henric Wahlgren – bedrock geology
Kristian Schoning – Quaternary geology
Mats Tenne and Lars M Hansen – construction experience

The need for knowledge of the geological soil conditions and the understanding of their interaction with groundwater is now well established. However, earlier failure to appreciate the significance of this interaction resulted in significant ground subsidence, damaging infrastructure in Stockholm, with costly consequences. In the same way, knowledge of geological conditions and an understanding of the bedrock's ductile and, above all, brittle tectonic evolution is an aid to any assessment of rock stability and groundwater movements as highlighted by the following quotes.

In order to understand the impact of the fracture system on hydrogeology, it must be borne in mind that:

- *The older the rock mass, the more phases of fracturing it has probably undergone.*
- *During any phase, existing fractures are reactivated and new ones may be generated.*
- *In general, the longer the fracture zones and fractures, the larger the movements they have usually undergone and the more complex their structure.*
- *Understanding why the fracture system looks the way it does is best achieved by studying the geological history of the enclosing rock mass.*

(Modified after Hydrogeologi för bergbyggare, Gustafson 2009).

SGU is trying to improve its own understanding of the geology of Stockholm in order to provide a better service to the community, of which the construction industry is an important part. With this in mind, SGU welcomes your comments on this report, as well as any geological information generated during construction projects that we can use to improve our own interpretations and models.

We thank Philip Curtis, Claes Mellqvist, Susanne Grigull and Gustav Sohlenius for reviewing the report. Claes Mellqvist and Susanne Grigull have also helped with the drawing of charts and diagrams, etc. Björn Lund (Uppsala University) has been helpful with the information on recent seismicity.

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SAMMANFATTNING

Denna rapport utgör ett komplement till den uppdaterade byggnadsgeologiska kartan över Stockholmsområdet som finns på Sveriges geologiska undersöknings webbplats (www.sgu.se). Innehållet är baserat på tillgänglig intern (SGU) och extern geologisk information. Syftet med rapporten är att ge en kortfattad beskrivning av de berggrundsgeologiska och jordartsgeologiska förhållandena, samt den geologiska utvecklingen i Stockholmsområdet. Rapporten är uppdelad i två huvudkapitel där det första behandlar berggrundsgeologin och det andra jordartsgeologin. Därefter följer två bilagor som redogör för erfarenheter från infrastrukturprojekt i Stockholmsområdet.

Rapporten finns även tillgänglig på svenska på SGUs webbplats (SGU-rapport 2018:08)

BEDROCK GEOLOGY

Bedrock geological maps of Stockholm

The oldest geological map of the Stockholm area is a combined Quaternary deposits and bedrock map from the second half of the 19th century (Fries et al. 1863). A bedrock map at a scale of 1:60 000 covering the southeastern part of the Stockholm archipelago, with an accompanying description, was presented by Sundius (1939), and a bedrock map of the Stockholm area at a scale of 1:50 000, together with a description, was later published (Sundius 1948). Combined Quaternary deposits and bedrock maps, at a scale of 1:50 000, of the map areas Stockholm NO, NV, SO and SV were described by Möller and Stålhös (1964, 1965, 1969a, b). The bedrock in the four map areas was compiled at a scale of 1:100 000 by Stålhös (1968) and described by Stålhös (1969). When a bedrock quality map comprising the map areas Stockholm NO, NV, SO and SV was produced (Persson et al. 2002), the bedrock map was updated at a scale of 1:100 000 (Persson et al. 2001). The update is based on new field work and access to aerial geophysical survey data. Both bedrock maps of Stockholm (Stålhös 1968, Persson et al. 2001) are available as printed products. The newer map (Persson et al. (2001) also exists in vectorised digital format, whereas the older map (Stålhös 1968) is only available as digital raster files (e.g. pdf or TIFF).

In addition to the above mentioned maps of the Stockholm area, there is also a compilation at a scale of 1:250 000, available as a pdf (Wik et al. 2004), as well as simplified information that can be obtained from the map generator and map viewer on the SGU website (www. sgu.se).

Regional geological background

The bedrock in the Stockholm area belongs to the Svecokarelian orogen (Fig. 1), which is the result of a 2.0–1.8 Ga orogeny (mountain building), during which most of the bedrock in eastern Sweden was formed, metamorphosed and deformed to varying degrees. The Svecokarelian orogen can be divided into different lithotectonic units that are distinguished by differences in bedrock origin, and by structural, metamorphic and chronological development within the orogenic belt (Fig. 1). In most cases the lithotectonic units are bounded by regional deformation zones (belts). As shown in Figure 1, the bedrock in the Stockholm area belongs to the Bergslagen lithotectonic unit.

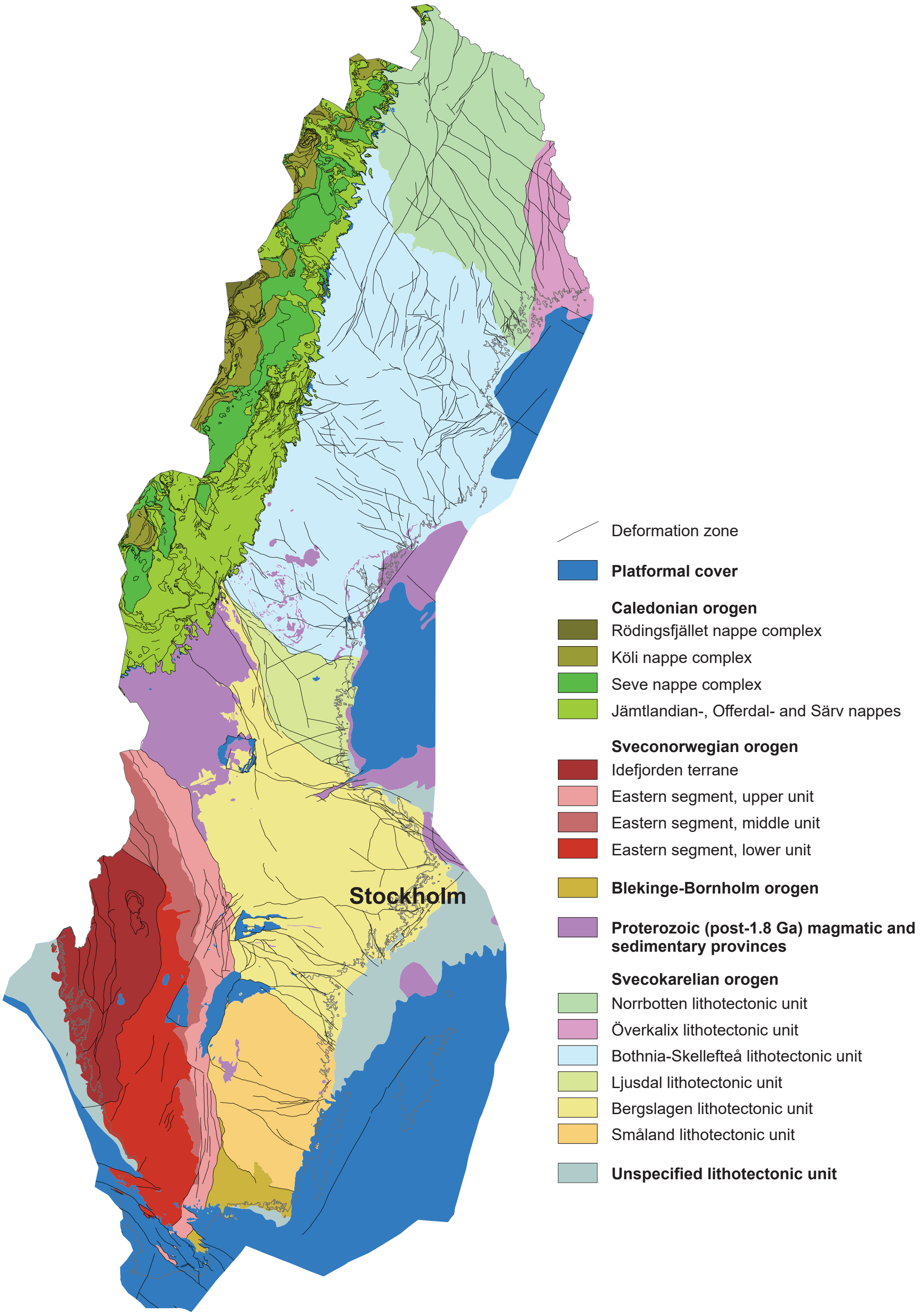


Figure 1. Classification of Sweden's bedrock into orogens, lithotectonic units, Proterozoic (post-1.8 Ga) and Neoproterozoic to Phanerozoic rocks (SGU bedrock geological map database). A 3D model based on the above map, along with a descriptive report, is presented in the SGU map viewer "Bedrock 1:1 M" (www.sgu.se). The 3D model is also published on the SGU website (www.sgu.se) in the 3D map tool City planner and as a 3D pdf.

Rock types in the Stockholm area

Supracrustal rocks

The bedrock in the Stockholm area, in particular the central and southern part, predominantly comprises 1.91 Ga metasedimentary rocks (light blue in Fig. 2), which were originally deposited as muddy to sandy sediments. The proportions between mica and quartz-feldspar vary, and the rocks are usually strongly metamorphosed and have undergone partial melting. Migmatitic varieties therefore predominate (Fig. 3A). The veining is defined by light quartz and feldspar-rich bands to veins alternating with darker mica-rich bands. The predominantly quartz-feldspar metasedimentary rocks (metagreywacke) are usually better preserved and not as severely migmatised as the mica-rich rocks (meta-argillite).

Metavolcanic rocks (yellow in Fig. 2), which are 1.9 Ga, are subordinate in the bedrock of Stockholm. They consist primarily of quartz and feldspar-rich layered deposits, and their occurrence is concentrated in the Stockholm archipelago in a northeast-orientated belt from Utö in the southwest, across Ornö, and further to the northeast to Nämdö and Runmarö (Fig. 2). The metavolcanitic rocks are usually associated with crystalline limestone (dark blue in Fig. 2), e.g. on Utö, Nämdö and Runmarö, and are locally ore-bearing. The layers of crystalline limestone are usually thin, up to tens of metres thick. There are a number of areas marked as metavolcanic rock on the older bedrock map of Stockholm (Stålhös 1968), e.g. north and northwest of Vaxholm, on Lovön and south of Tullinge. On the bedrock map by Persson et al. (2001), these and other metavolcanic rocks, except for those in the Stockholm archipelago, have been reinterpreted as fine-grained, to fine to medium-grained granitoids, i.e. they are not of volcanic origin.

The youngest supracrustal rock in the Stockholm area consists of 1.50–1.25 Ga sandstone (purple in Fig. 2), known as "Mälar sandstone". It is found on northwestern Ekerön, where conglomerates also exist, and on some small islands to the west in Lake Mälaren.

Intrusive rocks

In addition to the metasedimentary rocks, 1.9 Ga metamorphosed and deformed granitoids ("metagranitoids", Fig. 3B) constitute a predominant rock type in the Stockholm area (brown in Fig. 2). Granitic to granodioritic compositions are most common, but granodioritic to tonalitic varieties also occur, e.g. in northern Lidingö and in the area north and west of Danderyd (Fig. 2). Like the metasedimentary rocks, the metagranitoids are generally fairly strongly metamorphosed and deformed, gneissic in character and locally migmatitic. As shown in Figure 2, they often form elongated bodies, except in the north, where they form larger coherent massifs. Inclusions of metasedimentary rocks are frequent in the metagranitoids, especially in the southern to southeastern part of the Stockholm area. Quartz is an essential mineral in the metagranitoids, but in the Åkersberga area, just north of Stockholm, there is a quartz-poor variant, a "syenitoid" (dark brown in Fig. 2).

Associated with the metagranitoids are scattered occurrences of usually fairly small bodies of mafic rock types that vary in composition from ultrabasite to quartz diorite (green in Fig. 2). However, in the Vaxholm area in the northeastern part of the Stockholm NO map area, larger bodies of mafic rocks are an important constituent in the otherwise predominantly metagranitoid bedrock.

In the north of the Stockholm area, 1.8 Ga granite (light red in Fig. 2) constitutes an essential constituent in the bedrock, whereas younger granite is entirely subordinate in the south. The younger granites are predominantly grey, but red varieties are also present. They are usually more or less massive but are locally foliated. Two varieties of younger granite occur. One is equigranular, fine to medium-grained ("Stockholm granite", Fig. 3C), whereas the other is medium-grained and finely porphyritic. The equigranular variety occurs as elongated or irregular bodies in the strongly

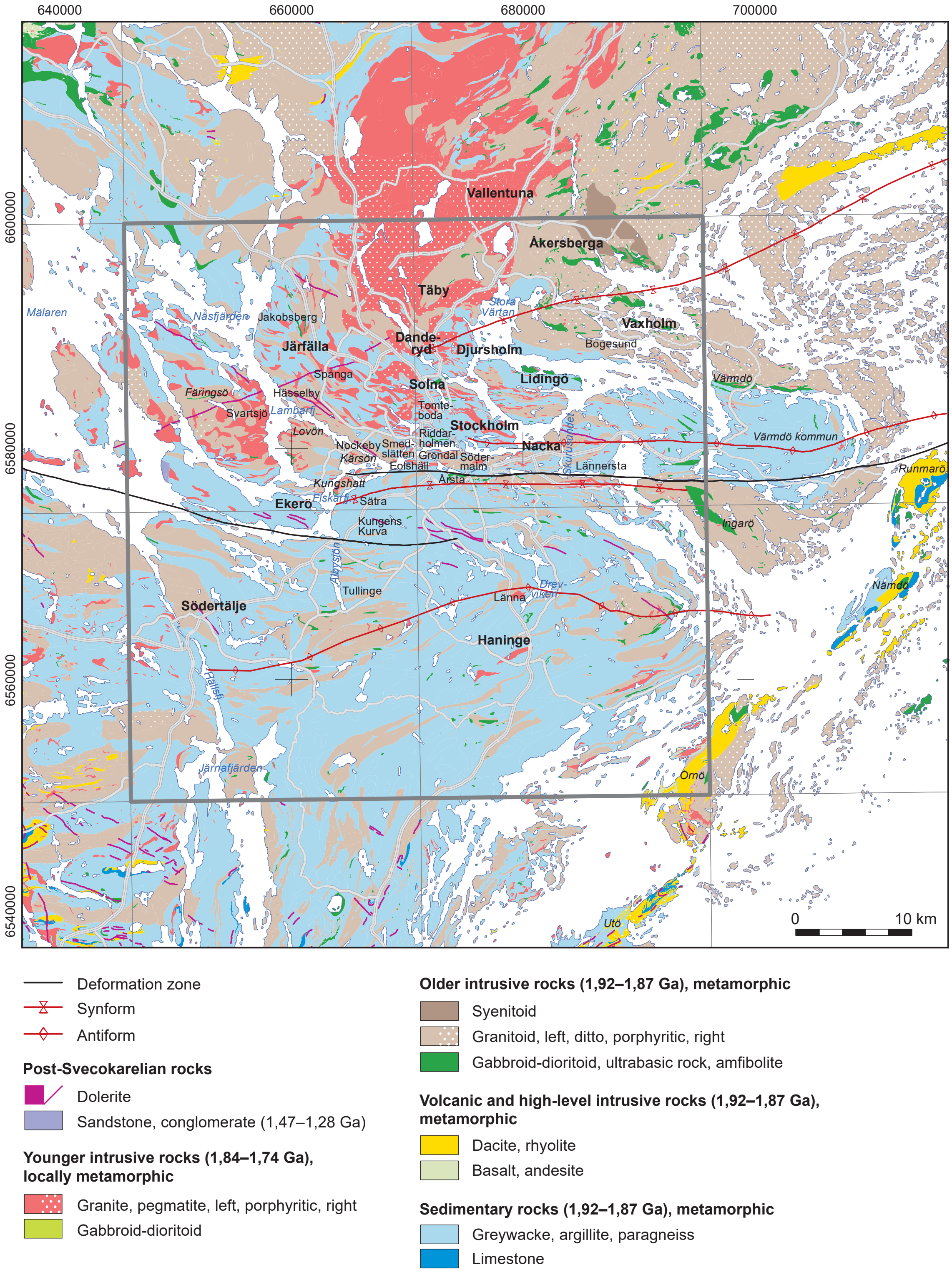


Figure 2. Overview bedrock map of the Stockholm area. The area within the thicker frame corresponds to the four map areas Stockholm NV, SV, NO and SO. The light grey grid is based on the RT90 coordinate system, with the four map areas Stockholm NV, SV, NO and SO within the thicker grey frame. The coordinates of the outer frame are SWEREF 99 TM.

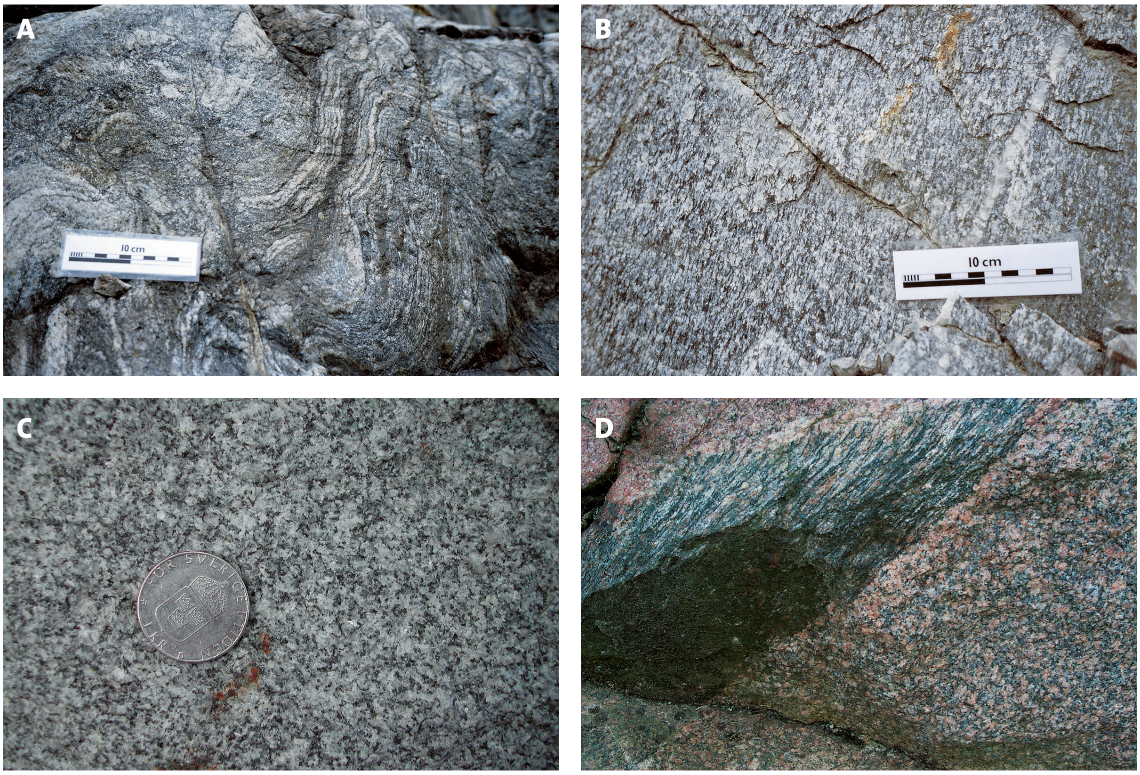


Figure 3. Examples of rock types from the Stockholm area (Wik et al. 2004). **A.** Metasedimentary veined gneiss. Photo: Malin Sträng. **B.** Metagranitoid. Photo: Malin Sträng. **C.** Younger granite ("Stockholm granite"). Photo: Benno Kathol. **D.** Finely porphyritic younger granite from the Täby–Rotebro–Vallentuna area in contact with strongly deformed metagranitoid. Photo: Lars Persson.

metamorphosed metasedimentary rocks in the Djursholm–Solna–Järfälla areas, for example, and in metagranitoids in places such as Lovön and the southern part of Svartsjölandet. The younger granites have intruded after the main phase of the deformation, but their elongate shapes and the fact they are sometimes foliated, conforming to the overall deformation pattern, suggest they were emplaced during a late stage of the orogenic deformation. The porphyritic variety forms a large massif in the Täby–Rotebro–Vallentuna area (Figs. 2, 3D). Associated with the younger granites are aplite and pegmatite dykes (Fig. 4A), which locally form frequent constituents in the older rocks (Fig. 2). The pegmatites also appear as irregularly shaped smaller bodies.

Amphibolite (metadolerite)

Mafic rocks in the form of amphibolite lenses, bands and dykes are a frequent feature in the metasedimentary and metagranitoid rocks in the Stockholm area (Fig. 4B). The amphibolites are primarily found in the Stockholm NO map area and have a predominantly east–west orientation (Stålhös 1969). Age determinations of amphibolites (metadolerites) in northeastern Uppland have yielded ages of 1.89 and 1.87–1.86 Ga (Hermansson et al. 2008, Stephens et al. 2009).

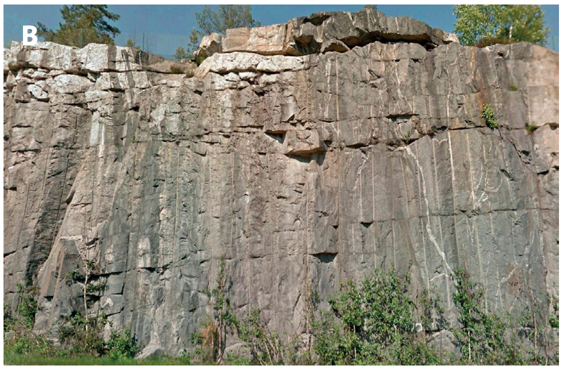


Figure 4. A. Pegmatite (pink), which is slightly discordant to the foliation in the wall rock. Photo: Google Maps. **B.** Amphibolite (dark elongated "bands" on the left of the picture) in the gneissic bedrock along Saltsjöbadsleden. Photo: Google Maps.

Dolerites

Individual dykes to smaller dyke swarms of dolerite occur in the Stockholm area (Fig. 2). They are usually a few decimetres to a few metres wide, but can be up to 50 metres wide. The majority are steeply to vertically dipping. The main strike direction is northwest to west-northwest, but north-northwest dykes are also fairly common (Stålhös 1969). Northeasterly-orientated dykes also occur but are completely subordinate. The different strike trends may represent different generations. Most of the dykes are orientated more or less parallel to the dominant fracture zones in the bedrock, particularly the northwesterly-striking dykes (Stålhös 1969). The age of the dolerites is unclear, but they were intruded after the bedrock stabilised following the Svecokarelian orogeny. They may be related time-wise to the 1.26 Ga, "Mackmyra" dolerite, which intrudes the Jotnian sandstone in the Gävle area (Söderlund et al. 2006).

A continuous long dolerite dyke runs from the Spånga area in a west-southwest direction through Färingsö (Fig. 2). The dolerite dyke has never been observed in outcrops in the Stockholm area, but is clearly indicated as a distinct linear positive magnetic anomaly in the left central part of Figures 6 and 7. The dolerite is therefore not marked on the older bedrock map (Stålhös 1968) since no geophysical data were available, but is marked on the updated version (Persson et al. 2001). Ground magnetic measurements southwest of Färjstaden on Färingsö indicate that the dolerite is 40 metres wide and dips steeply to the south (Persson et al. 2001). The magnetic anomaly indicates that the dyke is persistent, at least discontinuously, and can be followed for tens of kilometres in a west-southwesterly direction.

The oldest rocks formed and affected by the Svecokarelian orogeny generally have healed contacts. The much younger dolerites, which, put simply, may be said to be a type of fracture filling, have more or less fractured contacts against the wall rock (Fig. 5). Similarly, metadolerites that still retain much of their original character and also post-tectonic dykes of granite and pegmatite exhibit similar fractured contact conditions to the wall rock. It is therefore important to consider the presence of dyke rocks, particularly dolerites, in construction projects in or on the bedrock, since they can contribute to instability and be relatively permeable along the contact zones with the wall rock, while constituting hydraulic barriers across the dyke.

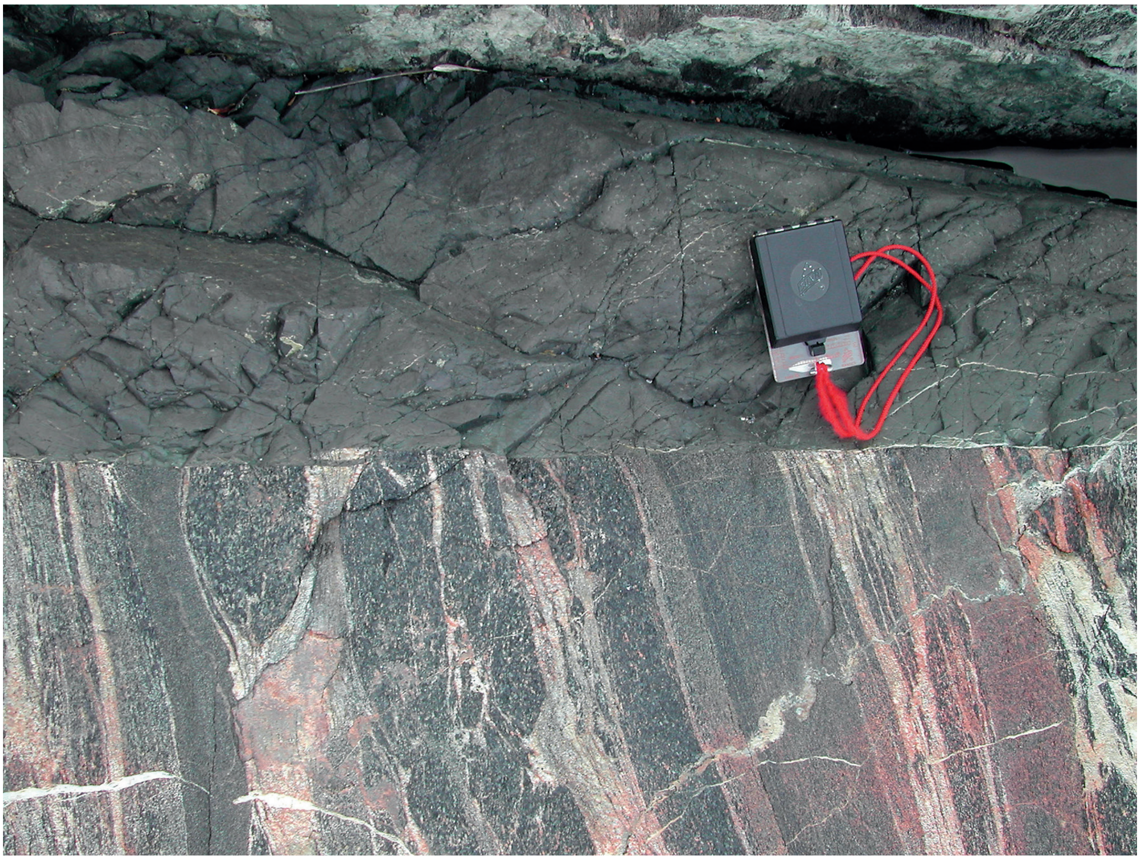


Figure 5. Dolerite cutting banded gneiss at Sjöstugan, NW Sorunda, Nynäshamn municipality. Note the upper fractured contact. Photo: Claes Mellqvist.

Bedrock homogeneity

The lithological homogeneity of the bedrock depends on the scale considered. Bedrock volumes that are locally highly heterogeneous, i.e. they exhibit large rock type variations, compositional variations, degree of banding or veining, presence of dolerites, high frequency of inclusions, etc., can be regionally judged to be ”homogeneous in their variability”. The bedrock map in Figure 2 shows that the metagranitoids and the younger granites in the northernmost part of the Stockholm area make up more homogeneous bedrock than the bedrock in the central and southern parts. Generally, the metasedimentary rocks are more heterogeneous than the metagranitoids due to banding, the presence of mafic lenses, as well as aplite, pegmatite and granite veins and dykes. In the south of the area, the metagranitoids also contain frequent inclusions of mafic and metasedimentary rocks, aplite, pegmatite and granite dykes, and are locally gneissic to migmatitic as well. However, this scale dependency means the significance of bedrock heterogeneity must be assessed on a case by case basis.

Natural gamma radiation

Natural gamma radiation is based on airborne radiometric measurements with follow-up on outcrops using a gamma spectrometer. The measurements give total gamma radiation and levels of potassium, uranium and thorium. The radium index is a measure of the radium content of a material and is calculated by determining the uranium concentration. 1 ppm uranium represents an activity concentration of 12.35 Bq/kg uranium-238 and 12.35 Bq/kg radium-226. An earlier recommendation issued by the Nordic Radiation Protection Authorities (Radiation Protection Authorities in Denmark, Finland, Iceland, Norway and Sweden 2000) indicates that the radium index for building materials should be less than 1.0, equal to 16.2 ppm uranium or 200 Bq/kg ^{226}Ra. Nowadays, an activity index is used to estimate the total gamma radiation from a material (rock). The Activity Index (AI) is calculated from the activity concentrations of ^{40}K, ^{226}Ra (^{238}U) and ^{232}Th.

The Activity index is calculated as follows:

$C_K/3000+C_{Ra}/300+ C_{Th} /200$

where C_K= activity of potassium in Bq/kg. 1% K = 313 Bq/kg K-40,

C_{Ra} = activity of radium in Bq/kg. 1 ppm U = 12.35 Bq/kg Ra-226, and

C_{Th} = activity of thorium in Bq/kg. 1 ppm Th = 4.06 Bq/kg Th-232.

The activity index formula is calculated so that the radiation dose from a building with floors, walls and ceilings constructed using a material with AI = 1 received by a person living there will definitely be less than 1 mSv/year, which is the reference dose for gamma radiation from building materials under the new radiation protection legislation. It should be noted that a high activity index does not necessarily represent a high radium index, since a high activity index may be due to high thorium content in the rock. For further information on radiation from rock materials, see Jelinek & Eliasson (2015).

The varied bedrock in the Stockholm area is reflected in the variation in natural gamma radiation. Gamma radiation from migmatitic metasedimentary rocks varies greatly. Granitic veins are the main source of higher radiation, but there is great variation. The main rocks giving rise to uranium anomalies, and thus higher radium and activity indices, are the younger granites, e.g. the large granite body in the Täby–Rotebro–Vallentuna area, and pegmatites, aplites and granitic veins in the migmatitic gneisses, primarily the metasedimentary rocks, but also in smaller areas predominantly consisting of metagranitoids. On the bedrock map (Persson et al. 2001) and the bedrock quality map (Persson et al. 2002), the radium index is reported as the mean and standard deviation for different rock groups based on a spread of measurements. Measurement points are also reported for a small area in northwest Färingsö, where the radium index is > 1.0. Due to the uneven frequency of subordinate rocks, such as veins, pegmatite, aplite and granitic dykes in the dominant rock types, the frequency of subordinate rock types must be considered when a specific rock volume is assessed for radon risk, for example for underground projects or use of bedrock as aggregate in concrete for buildings.

Deformation

Introduction

Deformation of the bedrock can be divided into three main types: ductile, brittle-ductile and brittle. Ductile deformation may be regionally developed and pervasive, for example gneissosity, but it may also be concentrated in zones, known as ductile deformation zones (shear zones). The higher the metamorphic grade (temperature), usually associated with a greater depth in the earth's crust, the more pervasive the deformation tends to be.

Ductile deformation zones can develop at different depths in the earth's crust. They can vary in size from millimetres to several kilometres. Since deformation more easily "propagates" with increased temperature, the zones are usually wider the higher the metamorphic grade is during deformation. If the zones are formed at lower temperatures higher up in the earth's crust, deformation is more concentrated, and the zones are usually narrower and more distinct. As well as being distinct individual zones, ductile zones may also be related to folding through stretching in the fold limbs.

Brittle-ductile zones are formed at a depth in the earth's crust where the temperature represents the transition from ductile to brittle deformation. Note that a ductile deformation zone that has been reactivated under brittle conditions higher up in the earth's crust during subsequent geological evolution does not constitute a brittle-ductile zone, but a brittle reactivation of a ductile zone.

Brittle deformation zones (fracture zones, faults) are formed at a depth in the earth's crust where the temperature is too low for rocks to be deformed by ductile deformation. The zones are usually narrower and more distinct. Many zones characterised by brittle deformation, particularly more persistent regional zones, originated as ductile zones that have been reactivated under brittle conditions. Brittle deformation zones are usually highly heterogeneous, and they can vary greatly both laterally and vertically. Like dolerites, brittle zones, depending on their character, can create hydraulic barriers across the zone with preferred hydraulic pathways along the zone.

Ductile deformation

In general, with the exception of the younger dolerites and the Jotnian "Mälar" sandstone, and to some extent also the younger 1.8 Ga granites, all of the rocks in the Stockholm area are strongly metamorphosed and deformed. The ductile deformation structures in the bedrock were formed 1.9–1.8 Ga during the Svecokarelian orogeny. Pioneering work on models for ductile structural evolution, based on detailed geological mapping in eastern Mälardalen and adjacent areas of Uppland and Södermanland, has been presented by Stålhös (e.g. 1969, 1976, 1991). Ductile structural evolution in the Stockholm area and the surrounding parts of the Bergslagen lithotectonic unit (cf. Fig. 1) essentially comprises two deformation phases (Stålhös 1969, 1976, 1991, Stephens et al. 2009). In the tectonic models in Stålhös (1969, 1976), the first phase of folding (F_1) was interpreted to be temporally associated with the formation of the approximately 1.9 Ga metagranitoids, whereas the second phase of folding (F_2) was interpreted to have occurred under high-grade metamorphic conditions when regional metamorphism peaked during the Svecokarelian orogeny. In later work (Stålhös 1991), this was reinterpreted and the F_1 folding was interpreted to have taken place much later and closer in time to the F_2 folding phase.

Recently presented results from U-Pb zircon dating of samples from the Stockholm area show two high-grade metamorphic events, one at about 1.86 Ga and one at about 1.84–1.81 Ga, in which the F_2 folding was interpreted to be related to the younger metamorphic event (Stephens & Andersson 2015). Whereas Stålhös (1991) interpreted the regional structural pattern to be a result of east–west compression, later work in the Stockholm area and in other parts of the Bergslagen lithotectonic unit, as well as to the north and south within the Svecokarelian orogen, explained the structural evolution as resulting from mainly north–south compression (Persson & Sjöström 2002, Stephens & Wahlgren 2008, Stephens et al. 2009). For a more detailed description of the ductile structural development in the structural domain to which the Stockholm area belongs, the reader is referred to Stephens et al. (2009 and references therein.

The orientation of the planar structures in the Stockholm area, i.e. the gneissic foliation, banding, veining etc., as well as the contacts between the various rock types, vary depending on regional folding and related local folding, as well as locally due to deflections into ductile deformation zones. On the other hand, linear structures, i.e. fold axes and lineations, generally plunge moderately to gently towards the east, except in the Stockholm NV map area, where the spread is somewhat larger (see Figs. 34 and 35 in Stålhös 1969). As shown in the bedrock map (Fig. 2), the regional variation in the orientation of planar structures is related to their position in the different parts of a large regional easterly-plunging S-shaped fold structure. The regional structural trends in the bedrock also appear clearly in the magnetic anomaly pattern (Figs. 6 and 7), and are also reflected in topographic data (Fig. 8). Within the map area of Stockholm NO, the main trend of the planar structures is west-northwest, but in the neighbourhood of Djursholm–Stora Värtan, the structures veer to the northeast (Figs. 2, 6 and 7). Note that the younger granite in the Täby–Rotebro–Vallentuna area, directly north of the point where the orientation changes (Fig. 2), partially ”extinguishes” the banded magnetic anomaly pattern (Figs. 6 and 7).

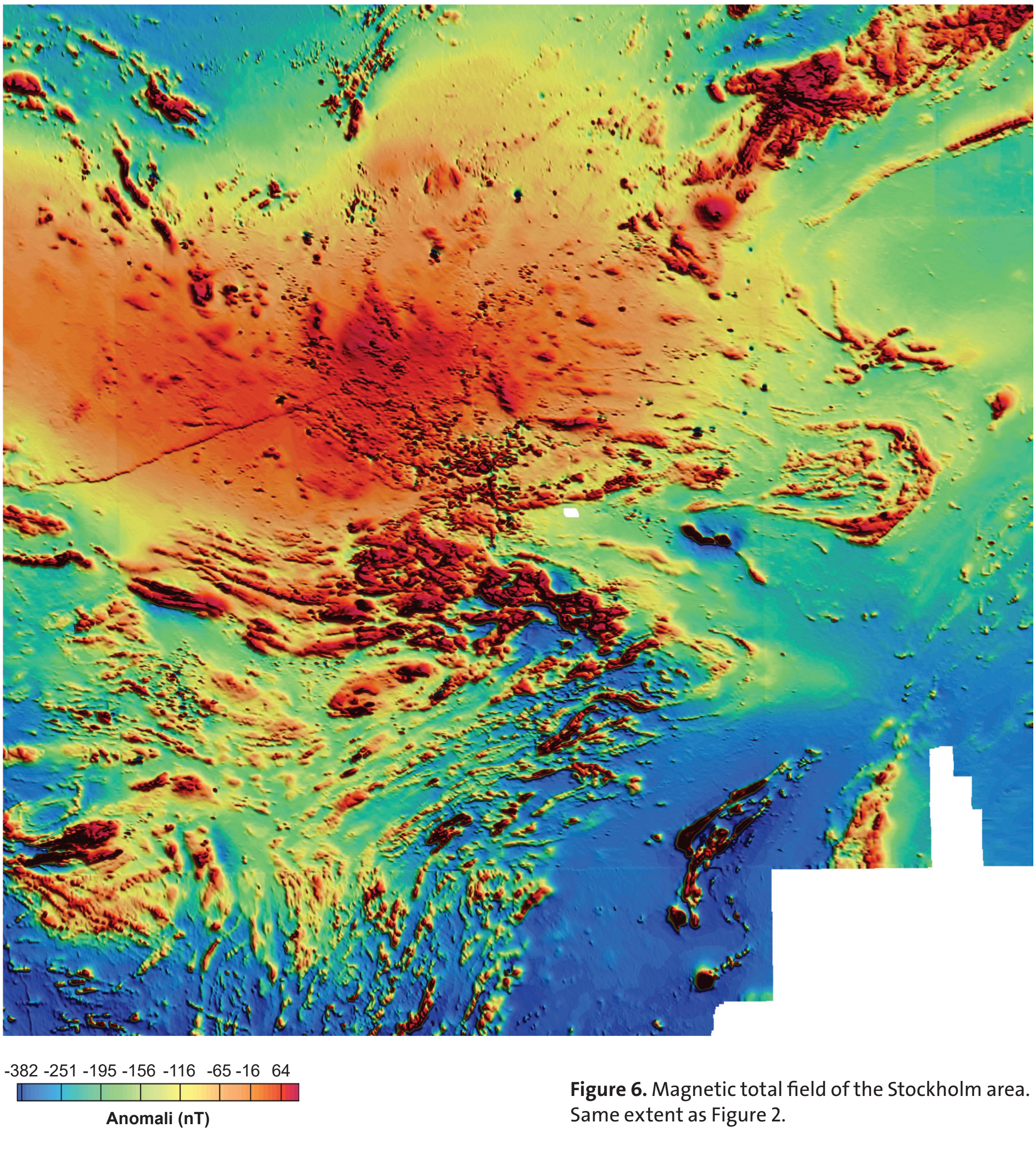


Figure 6. Magnetic total field of the Stockholm area. Same extent as Figure 2.

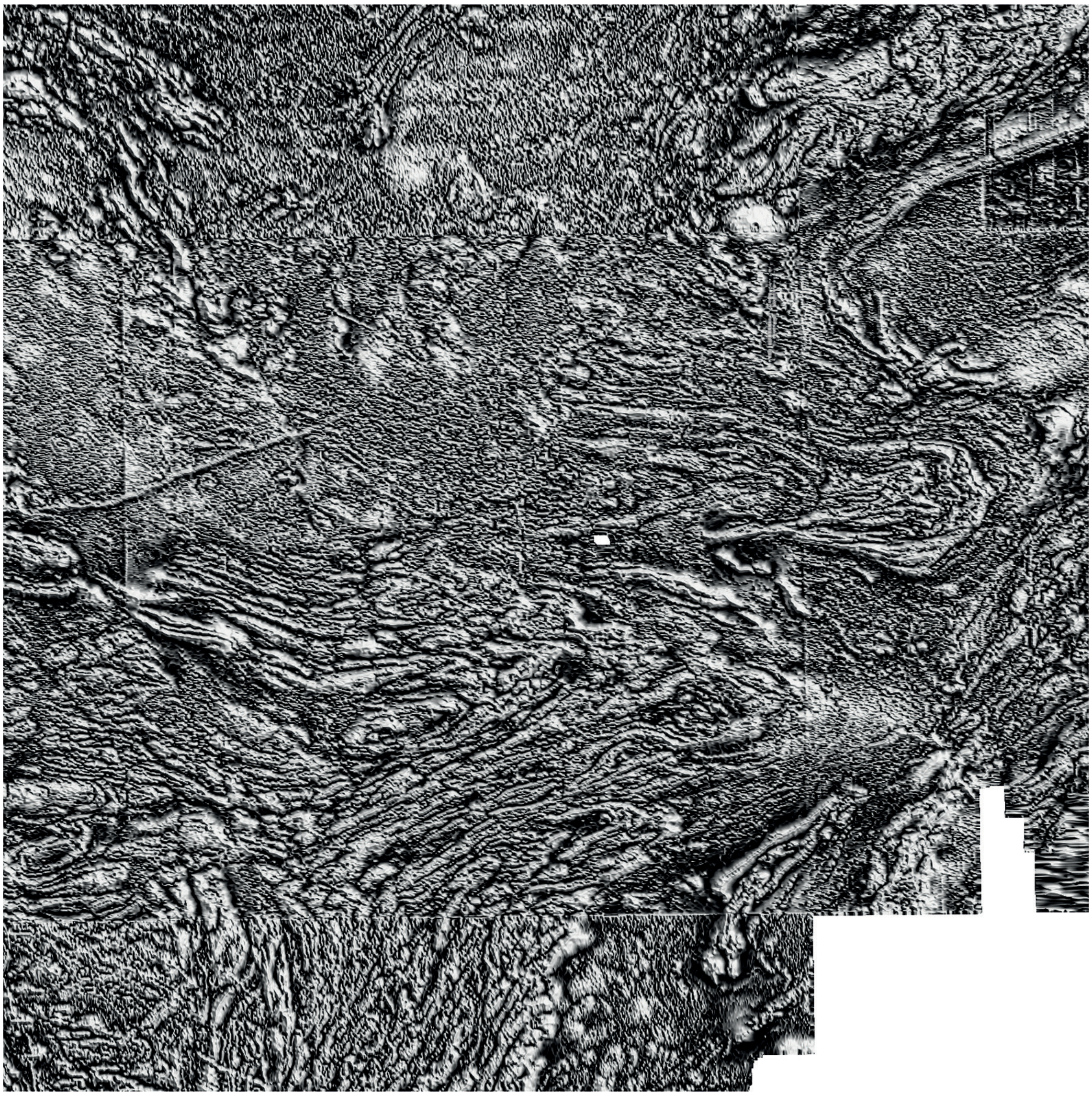


Figure 7. Tilt derivative (TDR) of the magnetic total field. TDR emphasises weaker anomalies near the surface level. Same extent as Figure 2.

The northeastern orientation then predominates to the northeast in Uppland and forms the northern limb of the large regional S-fold. The main orientation of the planar structures within the Stockholm NV map area is northwesterly. The orientation of the planar structures varies greatly in the core of the large regional S-fold in the central part of the Stockholm area, and then swings back to a northeasterly orientation southwards, i.e. forming the southern limb of the large regional S-fold.

In the core of the large regional S-fold, a number of east to east-northeast, moderately plunging km-scale antiforms and synforms can be distinguished in the central part of the Stockholm area (Fig. 9). These are related to the east-west to east-northeast short fold limbs in the large regional S-fold. From north to south, the individual synforms and antiforms are called the Norrtälje synform, Värmdölandet antiform, Ingarölandet synform and Södertörn antiform (Fig. 9, Persson & Sjöström 2002). The Värmdölandet antiform and the Ingarölandet synform are more or less isoclinal (tight) fold structures. The Värmdölandet antiform comprises Solna–Nacka–Lidingö and further eastwards

Figure 8. Elevation data over the Stockholm area. National Survey elevation model with 2 m resolution. The blue grid follows the RT90 coordinate system, with the four map areas of Stockholm NV, SV, NO and SO within the thicker blue frame. The coordinates of the outer frame are SWEREF 99 TM. Same extent as Figure 2.

out to Värmdölandet. The eastern hinge of the antiform essentially follows the eastern part of Värmdölandet. The Ingarölandet synform covers the Enskede–Johanneshov–Saltsjöbaden area and further east to Ingarö (Fig. 9). The western hinge of the synform is located in the Gröndal area. The transition between the synform and the antiform runs in an east–west direction along Årstaviken–Järlasjön–Lännerstasundet and further eastwards. There are also related minor synforms and antiforms in 1 m–100 m scale, which means that the planar structures may differ locally more or less strongly from the regional structural trend (cf. Figs. 3A and 10).

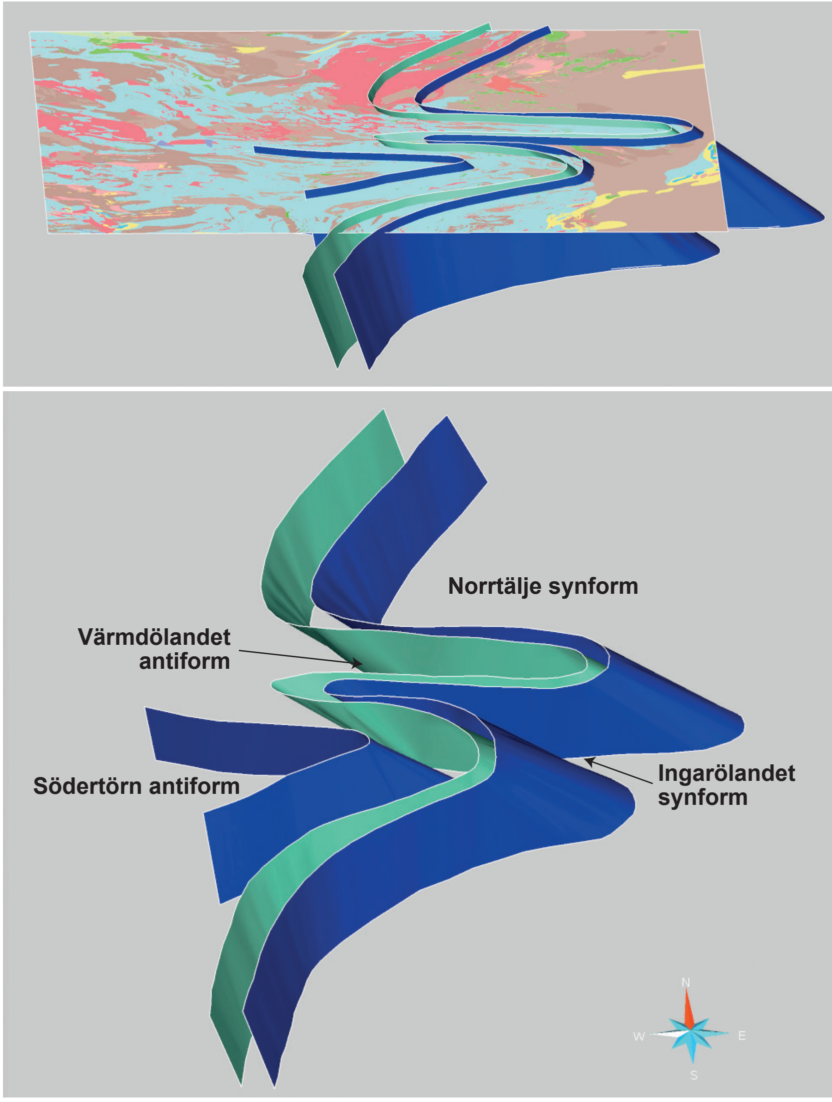


Figure 9. Schematic three-dimensional model of the easterly, moderately plunging antiforms and synforms in the central part of the Stockholm area. The three-dimensional visualization is produced at SGU.

Figure 10. Folding in m-scale in metasedimentary veined gneiss. Nynäsvägen close to Haninge, southern Stockholm. Photo: Google Maps.

Ductile deformation zones

The ductile deformation zones were formed during the Svecokarelian orogeny, and thus have a minimum age of approximately 1.8 Ga. The most prominent ductile deformation zone in the Stockholm area consists of the 80 km long, northeast–southwest, heavily deformed belt along Utö, Ornö, Nämdö and Runmarö in the archipelago southeast of Stockholm, called the Ornö banded series by Sundius (1939). The belt was formed under high-grade metamorphic conditions, but has also been affected by retrograde ductile deformation (Persson & Sjöström 2002, Stephens et al. 2009). The Ornö banded series is characterised by sinistral movements (Persson & Sjöström 2002) and can thus be judged to be a conjugate deformation zone to the dextral, northwesterly-orientated Singö zone along the coast near Forsmark in northeastern Uppland (Fig. 11, Persson & Sjöström 2002). Independently of each other, the kinematics of both zones indicate they are the result of approximately north–south compression. In addition, Figure 11 shows the conceptual horizontal component of

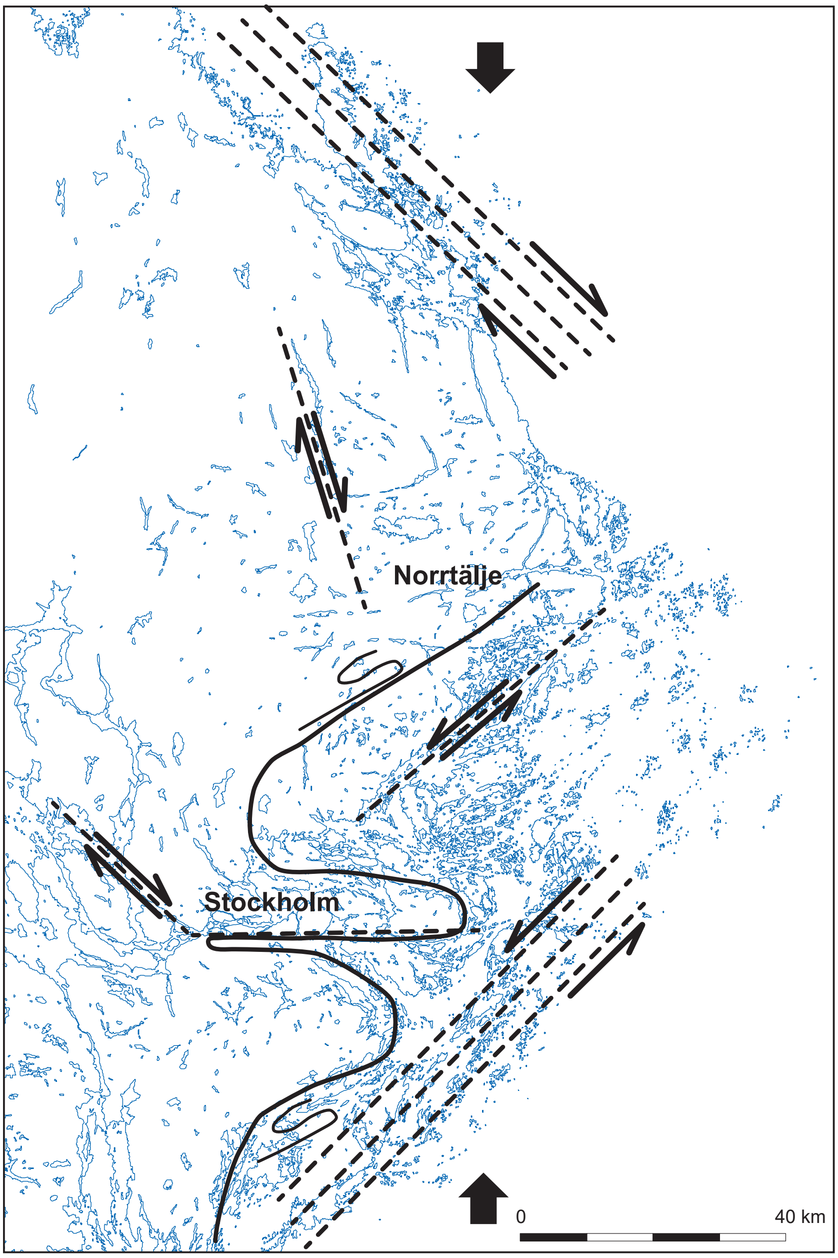


Figure 11. Schematic figure showing the horizontal component of movement in the ductile zones during the Svecokarelian orogeny, and also the conjugate relationship between the dextral and the sinistral ductile deformation zones in northeastern Uppland (Singö zone) and southeastern Stockholm archipelago (Ornö banded series), respectively.

movement in ductile zones depending on their orientation relative to the indicated north–south compression (bulk crustal shortening) during the Svecokarelian orogeny.

The occurrence of mylonite is marked on the bedrock maps of Stockholm (Stålhös 1968, Persson et al. 2001) in several places, indicating that zone-related intense ductile deformation occurred at multiple locations in the area. Below are a number of examples of supposed ductile deformation zones. It should be noted that all of them were probably later reactivated under brittle conditions.

- Along the transition between the Värmdölandet antiform and Ingarölandet synform, along the line of Årstaviken–Järlasjön–Lännerstasundet (1 in Fig. 12), which indicates that a ductile shear zone formed by extensive stretching and shearing along the fold limbs.
- northeasterly-striking zone south of Länna, through Drevviken, where mylonite was documented (2 in Fig. 12). The zone is parallel to and part of the southern limb of the Södertörn antiform. No kinematic information exists, but its location in the northeasterly-orientated fold limb and parallel trend to the Ornö banded series indicates that a sinistral component of movement is likely.
- In Bogesundslandet, west of Vaxholm (3 in Fig. 12) and between Hässelby Strand and Jakobsberg (4 in Fig. 12), mylonite has been marked on the bedrock maps, indicating the presence of more local strong ductile zone-related deformation.
- Mylonite has been marked close to the shore at northern Lovön, indicating that a northwestern deformation zone, originally formed under ductile conditions, runs in the water between Kärsön–Lovön and Nockeby–Hässelby strand and further northwest through Lambarfjärden and Näsfjärden (5 in Fig. 12). Documentation of mylonite in a drill hole bored in a northerly direction from northern Lovön, during preliminary investigations for the Förbifart Stockholm (bypass) project (Vass 2012), supports the presence of a zone formed under ductile conditions, which was later reactivated under brittle conditions.
- Low-grade ductile deformation zones with northeasterly strike have been documented in boreholes associated with the Förbifart Stockholm bypass project under Fiskarfjärden between Sätra and Kungshatt (Ignea 2015), indicating there is also an originally ductile zone that has been reactivated under brittle conditions (6 in Fig. 12).
- The above-mentioned zones in Lambarfjärden and Fiskarfjärden may constitute northwesterly and southwesterly splays, respectively, of the east–west zone along Årstaviken–Järlasjön–Lännerstasundet.

The mylonites marked on the bedrock maps (Stålhös 1968, Persson et al. 2001) appear in most cases to be concordant with the foliation and the folding pattern in the wall rock (see Möller & Stålhös 1964). Since mylonites are usually fine-grained to very fine-grained, this indicates they were formed under lower temperature than during the metamorphic peak that gave the bedrock its gneissic character. This indicates a zone-related concentration of ductile deformation, probably related to stretching in the fold limbs, under cooler temperature conditions at shallower crustal levels, at a late stage of the orogeny.

In some of the zones, the younger granite (”Stockholm granite”) is also strongly foliated, for example west of Järnafjärden and Hallsfjärden, south of Södertälje. This also indicates that the deformation occurred at a late stage of the orogeny.

Documentation and characterisation, including kinematic studies, of ductile deformation zones are inadequate in the Stockholm area, except in the Ornö banded series and along the northern and southern fold limbs in the easternmost part of the Värmdölandet antiform (Persson & Sjöström 2002). Kinematic data from the fold limbs and the eastern hinge zone in the Värmdölandet antiform indicate that the fold hinge has been shifted eastwards in an “eastward hinge escape” (Persson & Sjöström 2002). This is also suggested by the elongated shape (large amplitude) of the fold (Fig. 9).

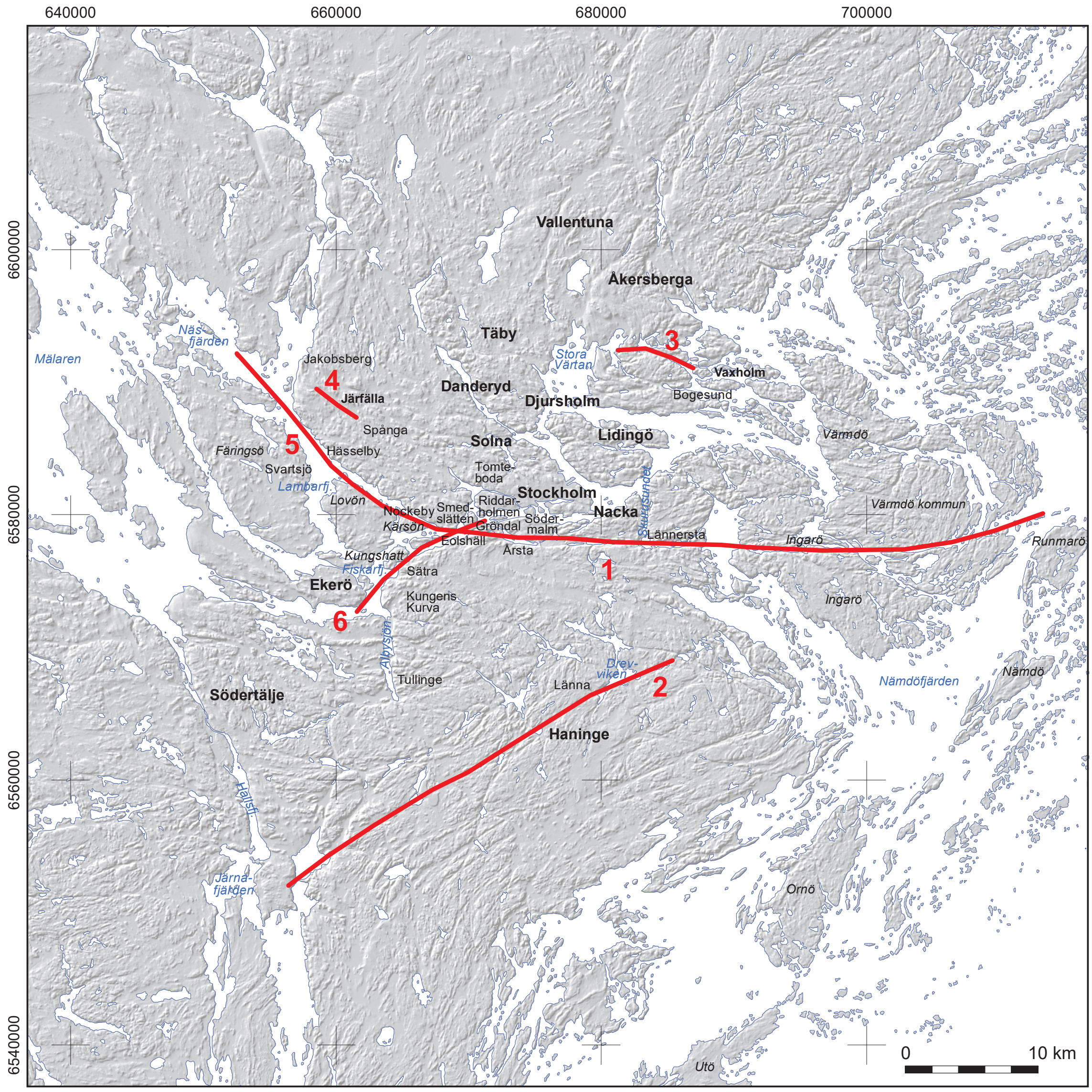


Figure 12. Examples of assumed ductile deformation zones in the Stockholm area, based on mapped mylonite occurrences marked on the bedrock maps (Stålhös 1968, Persson et al. 2001).

Brittle deformation

Dating of biotite using the ^{40}Ar-^{39}Ar method in Forsmark in northeastern Uppland indicates that the bedrock at the present ground surface cooled below approximately 300°C at 1.8–1.7 Ga, and that the bedrock then deformed solely under brittle conditions (Stephens & Wahlgren 2008, Söderlund et al. 2009). The oldest brittle structures, particularly those filled with epidote, are interpreted to have formed in the waning stages of the Svecokarelian orogeny at approximately 1.8 Ga (Saintot et al. 2011). Additionally, age determinations and analysis of paleostress have indicated brittle reactivations at about 1.7–1.6 and 1.1–0.9 Ga, and that movements occurred during the Phanerozoic as well (Stephens & Wahlgren 2008, Sandström et al. 2009, Saintot et al. 2011). Reactivation is a presumed distal effect of younger orogenic events to the present west of the then stabilised crust after the Svecokarelian orogeny, for example the 1.1–0.9 Ga Sveconorwegian orogeny, which markedly affected and altered the bedrock in southwestern Sweden (Fig. 1). In contrast to the prevailing north–south bulk crustal shortening during the Svecokarelian orogeny, bulk crustal shortening was orientated west-northwest–east-southeast to northwest–southeast during the Sveconorwegian orogeny (Saintot et al. 2011). This caused ductile zones that were, for example, dextral during the Svecokarelian orogeny, to be reactivated sinistrally under brittle conditions during the Sveconorwegian orogeny (see Saintot et al. 2011).

Since the brittle tectonic development has been found to be very similar in the Forsmark and Oskarshamn areas (Viola et al. 2009, Saintot et al. 2011), and also in Olkiluoto in southwestern Finland (Mattila & Viola 2014), it is reasonable to assume that the results of age determinations and paleostress analyses of brittle tectonic evolution in the nearby Forsmark area also apply to the bedrock in the Stockholm area. The studies mentioned in Forsmark, Oskarshamn and Olkiluoto (cf. Munier & Talbot 1993) also indicate that the bedrock in this part of the Fennoscandian Shield reached a brittle tectonic ”maturity” early in its geological history, i.e. around 1.6 Ga, and since then stresses in the bedrock have primarily been released by reactivation of existing fractures/faults/zones, with few new structures being formed.

It is important to note, not least from the engineering geological point of view, that brittle deformation zones are usually heterogeneous in nature, both laterally and vertically. For example, the zone core is usually discontinuous, the transition zones are generally not symmetrically distributed around the core, the thickness varies and the zone may splay into different branches enclosing better preserved rock within the zone (Fig. 13, cf. Caine et al. 1996). Figure 13 shows that drilling through a zone may reveal it to be of a completely different character, depending on where the drill hole penetrates the zone. From a hydrogeological point of view, experience has shown that the transition zones are often more permeable than the actual zone core (e.g. Gustafson 2009), which, with clay alteration, may act as a hydraulic barrier.

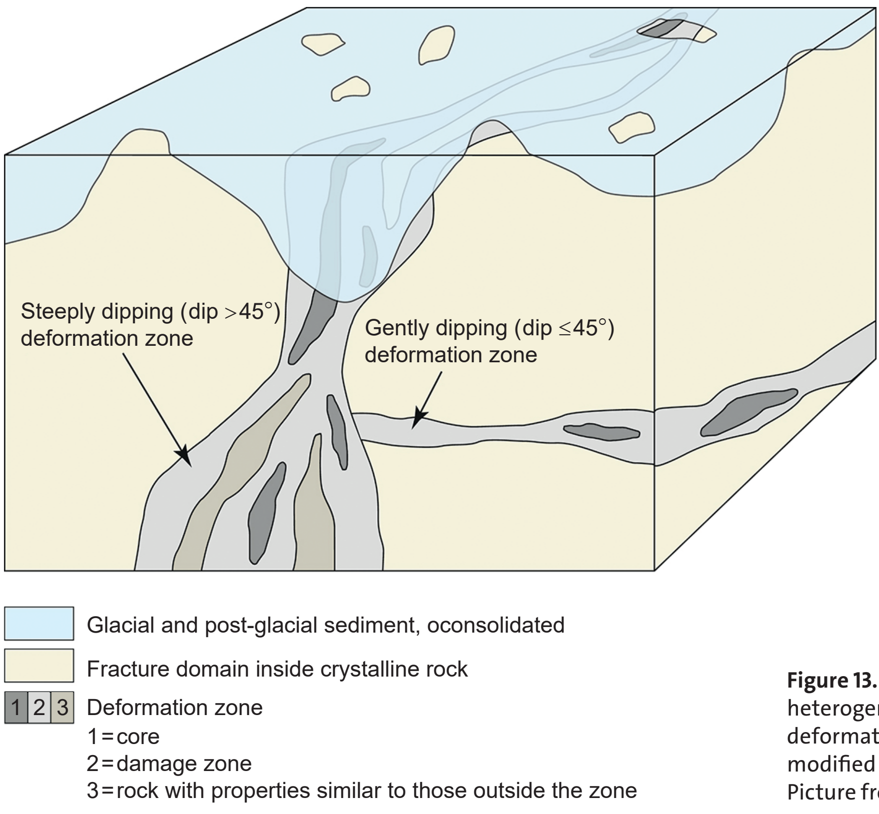


Figure 13. Schematic cartoon of the heterogeneous character of brittle deformation zones. The figure is modified from Caine et al. (1996). Picture from SKB (2008).

Fracture zones–faults

A comparison of elevation data of the Stockholm area (Fig. 8), which primarily reflects more persistent brittle structures in the bedrock, with the orientation of the rock types on the bedrock map (Fig. 2) and the magnetic anomaly pattern (Figs. 6 and 7), reveals a general consistency. That is to say, the regional topographic lineament pattern coincides well with the orientation of the metamorphosed and deformed rocks and the ductile planar structures in the bedrock. This suggests that built-up stresses in the bedrock during the brittle-tectonic geological evolution have primarily been released along the existing ductile anisotropy (cf. Andersson & Swindell 2008). However, brittle zones that disrupt the ductile structures also occur, e.g. the north–south zones through Skurusundet, east of Nacka and through Tullinge–lake Alby (see Stålhös 1968, 1969, Persson et al. 2001). A good example of a brittle reactivation (faulting) of an older ductile deformation zone (mylonite marked on the bedrock map) is along Årstaviken–Järlasjön–Lännerstasundet (cf. Stålhös 1968, 1969), the zone in the water between Kärsön–Lovön and Nockeby–Hässelby strand and further northwest through Lambarfjärden and Näsfjärden, as well as the northeasterly zone south of Länna through Drevviken, where breccia has been noted (Persson et al. 2001). The east–west zone along Årstaviken–Järlasjön–Lännerstasundet is considered to be an eastern branch of a regional east–west discontinuous system, south of Lake Mälaren through Södermanland and further west to Närkeslätten (Stålhös 1969, Lidmar-Bergström 1994, Stephens et al. 2009). This fault system affects the sub-Cambrian peneplain and is characterised by the northern block being downthrown in relation to the southern one. The fault system also restricts the extent of the Cambrian–Ordovician sedimentary rocks in Närke. This suggests that movements may have occurred in the zone along Årstaviken–Järlasjön–Lännerstasundet even after the Ordovician period.

The contact between the Jotnian Mälar sandstone on western Ekerön and the older crystalline bedrock is fault controlled. This shows that the movements occurred after the deposition of the sandy sediments and their lithification. A further example of relative age determination of movements in faults is seen in a northwestern fault in northern Svartsjölandet, along which dolerite fragments occur in a quartz-healed breccia (Möller & Stålhös 1965). The age of the dolerite has not been determined, but it probably belongs to a generation in the interval 1.5–1.3 Ga. It may belong to the same generation as the Mackmyra dolerite (Söderlund et al. 2006) in the Gävle area and movements along the fault may thus have taken place after 1.3 Ga. Stålhös (1969) also points out that in several places in the Stockholm area the dolerites are fractured and crushed, indicating a more general brittle reactivation in the bedrock after the dolerite intrusions. The existence of dolerites also indicates that tectonic movements are likely to have occurred during emplacement of the dolerite intrusions into weakness zones in the bedrock. Most of the dolerites are aligned more or less parallel to the predominant fracture zones in the bedrock, particularly the northwesterly dolerites, but also the subordinate northeasterly ones (Stålhös 1969). This may indicate that the dolerite magma exploited and intruded existing weakness zones in the bedrock that were established earlier in the geological evolution. The dolerite's mainly northwest strike and steep to vertical dips indicate that the weakness zones were reactivated in a stress field in which the main principle stress was orientated northwest–southeast and the least principle stress northeast–southwest. Hypothetically, this could indicate that the dolerites are temporally related to the Sveconorwegian orogeny, during which the main compression (bulk crustal shortening) was approximately northwest–southeast. Dating of the dolerites is necessary to confirm or reject this hypothesis.

According to Stålhös (1969), the Stockholm area predominantly comprises brittle deformation zones with mainly northeast, northwest and east–west orientation (Fig. 14). As shown in Figure 14 (see also Persson et al. 2001), which is based on Sundius (1948), some of the faults and fracture zones have a more or less arcuate form and follow shorelines, for example. In many cases, these arcuate zones represent morphological features in the terrain rather than reflecting a brittle-tectonic

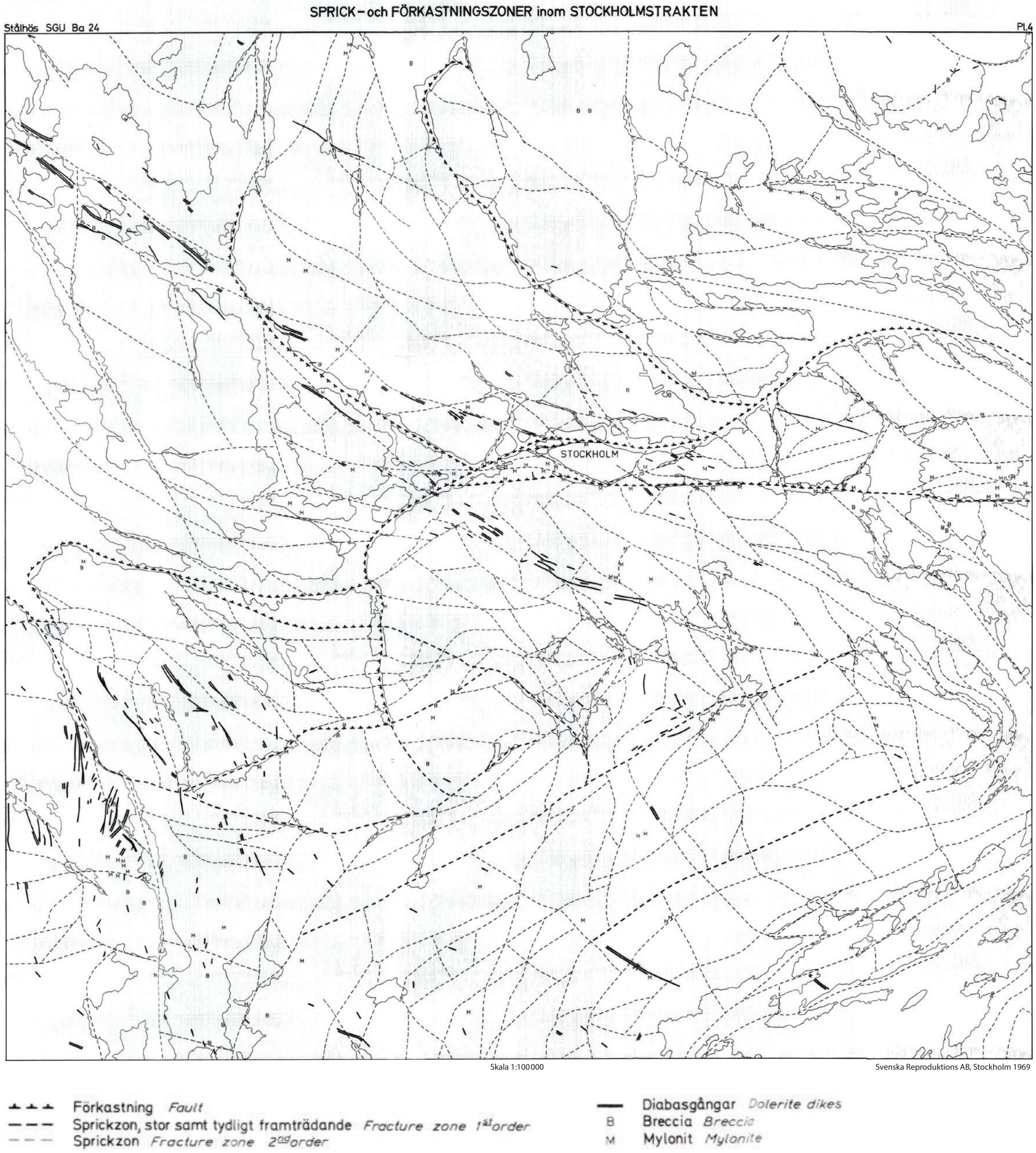


Figure 14. Fracture and fault zones in the Stockholm area (Stålhös 1969).

geometry. Stålhös (1969) also points out that these arcuate zones should be regarded as linked, separate zones with different directions rather than continuous single features. A clear example of an arcuate zone (fault) runs from Tullinge northwards, through Fiskarfjärden, then deflects to the northeast and eastwards along the northern shore of Södermalm (Söderström fault) and further east along the north shore of Värmdölandet. The fault has been verified in the north-northeast-orientated drill hole (13GA01) drilled from northern Södermalm (old railway tunnel) towards Gamla Stan for the Slussen project, and the two inclined drill holes (KB01 and 13VEC06K) drilled from Stadsgårdskajen northwards into Strömmen as part of the CityLink project (Golder Associates 2014). Based on information from the cored boreholes, about 100 m of the bedrock south of what is considered to be the core of the zone is strongly fractured and constitutes the damage zone to the unaffected country rock.

According to Golder Associates (2014), the Söderström fault is characterised by dextral horizontal displacement and south-side-up movement. As mentioned above, brittle reactivation has been documented along the arcuate ”fault” in Fiskarfjärden between Sätra and Kungshatt (Ignea 2015), as well as in a northwest-orientated cored drill hole from Eolshäll towards Smedslätten (Alfvén 2015). However, these confirmed zones are considered to be different segments in the arcuate fault marked in Figure 14 and on the bedrock maps.

Figure 15 shows the ductile deformation pattern in the bedrock using ‘form lines’ that reflect the more regional variation of orientation of foliation (gneissosity). Method-specific lineaments > 5 km are also identified in magnetic data, VLF data and in the National Survey elevation model with 2 m resolution. As shown in Figure 15, the orientation of the lineaments, which are believed

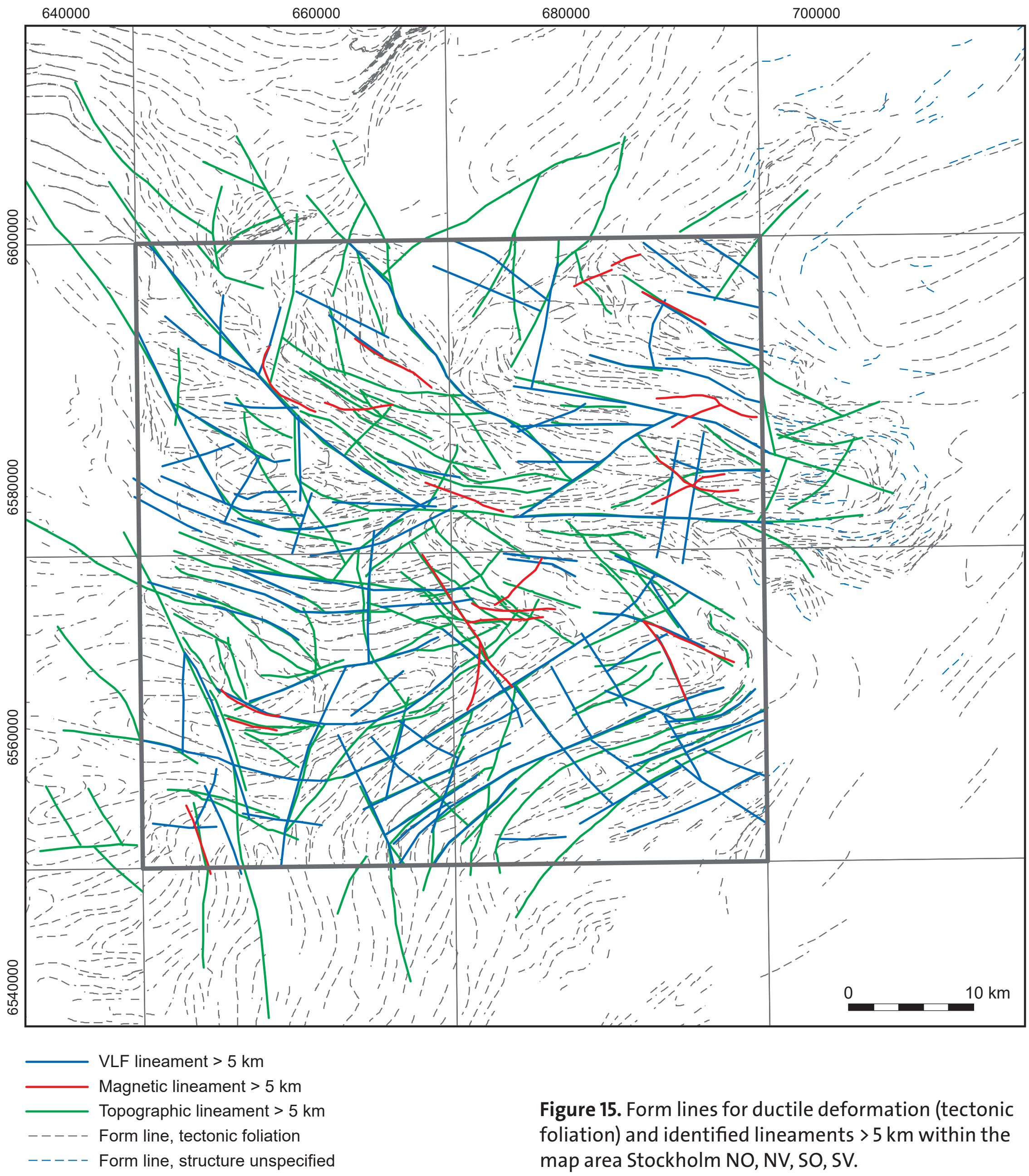


Figure 15. Form lines for ductile deformation (tectonic foliation) and identified lineaments > 5 km within the map area Stockholm NO, NV, SO, SV.

to largely reflect brittle or brittle reactivated ductile zones, reflects the orientation of the ductile deformation zone pattern in the bedrock. This suggests that the older, established ductile anisotropy in the bedrock influenced the location of younger brittle structures. It should be noted that the identification of lineaments is scale-dependent. This dependency affects their interpreted positioning and length, but regardless of this uncertainty, their pattern clearly shows a correlation between the orientation of the lineaments and ductile deformation. In the SGU map viewer Construction Geology, presented on the SGU website, all identified lineaments are displayed, irrespective of length.

Figure 16 shows the conceptual movements for brittle reactivated ductile or newly formed brittle zones as a distal effect of the stress field, interpreted to have been active during the Sveco-

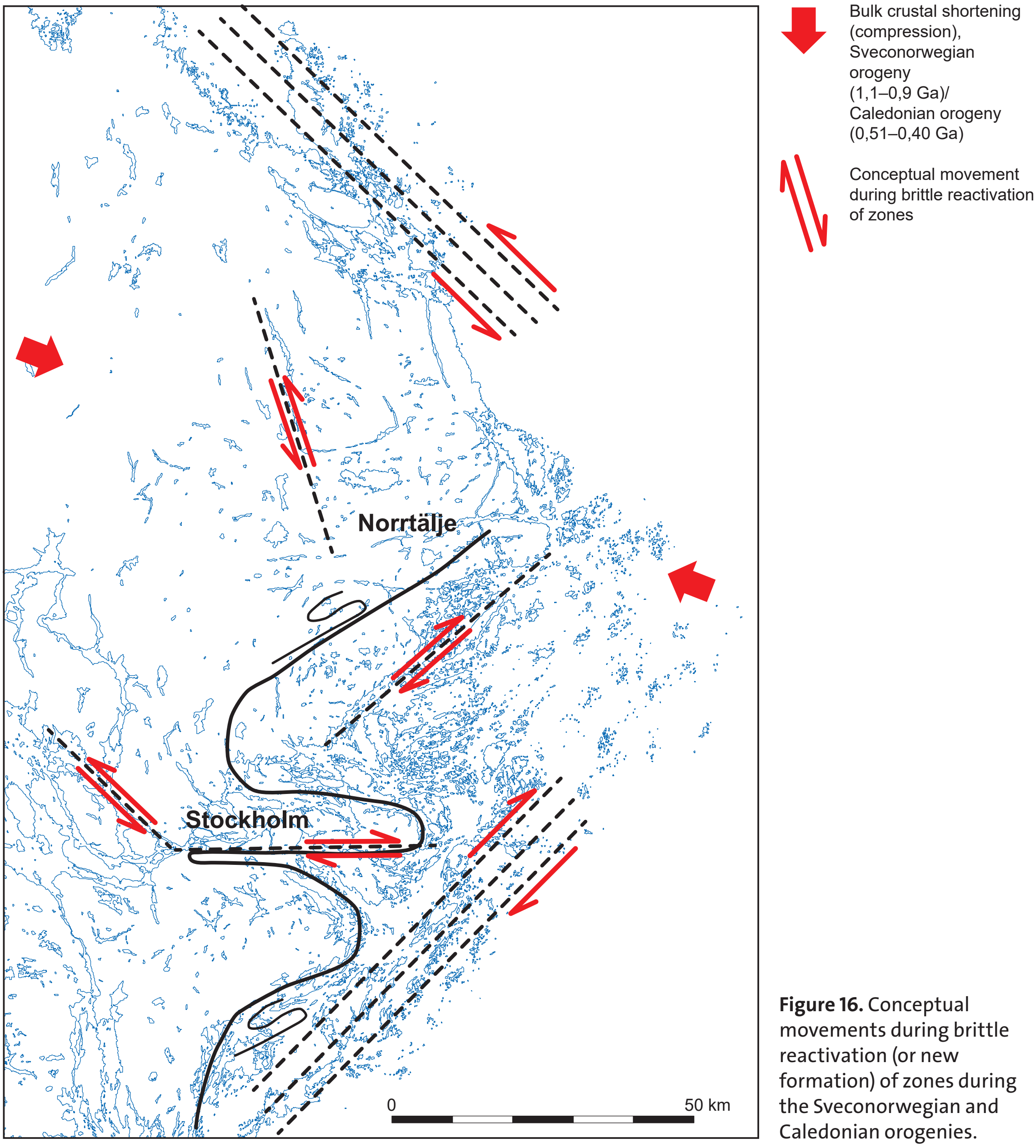


Figure 16. Conceptual movements during brittle reactivation (or new formation) of zones during the Sveconorwegian and Caledonian orogenies.

norwegian and Caledonian orogenies. Note that the northwest to southeast main stress leads to an inversion of the movement along the zones, relative to the movement during the Svecokarelian orogeny (see Fig. 11), i.e. ductile zones with dextral components of movements during the Svecokarelian orogeny were reactivated as brittle faults with sinistral movements and vice versa.

Fractures

An overall analysis of fractures in the rock mass between well-defined zones does not exist for the Stockholm area. However, fracture information has been documented locally in focused studies in isolated areas, often linked to completed or ongoing infrastructure projects. Fracture orientation information from a number of studies and compilations in various parts of the Stockholm area is summarised below.

Map area Stockholm NO

Mapping of fractures (> 2 m) in the Stockholm NO map area shows that northwest–west-northwest and northeast fracture sets with moderate to steep dips predominate. The fracture frequency is similar for all rock types, but the frequency of horizontal fractures was higher in homogeneous granites than in the veined metasedimentary rocks (Hildebrand 1994). For further information from the surveys in the Stockholm NO map area, see Hildebrand (1994).

Södermalm area

Fracture measurements on outcrops in the Södermalm area, associated with the Citybanan project, showed the presence of four fracture sets: northwest, northeast, north–south and east–west, with dips ranging from steep to horizontal (Armengol 2012). Fracture orientations in a drill core from Dykärret in the same area also showed four fracture sets: east–west and west-northwest with steep dips, east–west with gentle dips and east-northeast with moderate dips (Armengol 2012). The northwest, northeast and east–west-striking fracture sets are parallel to the local foliation orientation. For further information from the surveys in the Södermalm area, see (Armengol 2012).

Citybanan

Before the construction of the Citybanan railway line, detailed geological mapping was carried out, including mapping of 7842 fractures, along the planned tunnel alignment (Andersson & Swindell 2008). The fractures were mapped and characterised in line with the recommendations of the International Society for Rock Mechanics (ISRM). The mapping was conducted along a 5 km stretch between Tomteboda in the north and Riddarholmen in the south, and included drill cores, existing tunnels and outcrops. After analysis of fracture orientations, the investigated stretch was divided into 17 preliminary brittle structural domains characterised by distinct combinations of fracture sets. Three main fracture directions predominated along the planned tunnel route: sub-horizontal, northeast-striking with steep dips and west-northwest to northwest-striking with varying dips. The sub-horizontal and northeasterly fractures predominate in the northern and southern areas, which mainly comprise granite and metagranitoid, whereas the west-northwest to northwest fractures are most prevalent in the middle gneiss dominated area. In both cases, the orientation of the fractures tends to be largely controlled by the ductile anisotropy (foliation) in surrounding rocks. According to Andersson & Swindell (2008), the sub-horizontal fractures are considered to be stress relief structures.

For a compilation of fracture information along Citybanan before construction, see (Andersson & Swindell 2008).

Lambarfjärden area

The study is part of a survey of a supposed northwest-trending deformation zone and its immediate surroundings for the Förbifart Stockholm bypass project (Vass 2012). Fracture measurements on both sides of Lambarfjärden, i.e. on Lovön and Hässelby, show a predominance of steep northeast fractures, but subordinate northwest-striking steep fractures also occur (Fig. 17). Thus, the predominant fractures on land do not reflect the orientation of the northwest-trending deformation zone in Lambarfjärden.

Fracture orientations have also been documented in three drill holes: a 421 m long hole orientated northwards (10F353K) from Lovön out into Lambarfjärden towards Hässelbystrand, and two 99 m long moderately inclined holes, in opposing directions, one towards the north-northeast (08F351K) and one towards the south-southwest (08F352K) in Lambarfjärden. The two moderately inclined holes predominantly feature west-northwest to northwest fractures, as well as north–south-orientated fractures in borehole 08F352K (Fig. 18). Moderately to steeply dipping towards the southwest and steeply dipping fractures towards the northeast predominate in the borehole drilled towards the north-northeast (08F351K), while gentle to sub-horizontal dips predominate in the borehole drilled towards the southwest, but steep west-northwest fractures also occur (08F352K). In the long borehole drilled from Lovön (10F353K), gently dipping to sub-horizontal fractures predominate in the upper part between 3 and 207 m borehole length, but steep northwest and northeast fractures also occur (Fig. 19). West-northwest to northwest fractures with moderate dips to the northeast then predominate between 208 and 358 m (Fig. 19). The change in predominance of west-northwest to northwest fractures in the lower part of the borehole may be related to, and influenced by, the fault in Lambarfjärden. For further information from the investigations in Lambarfjärden, see Vass (2012).

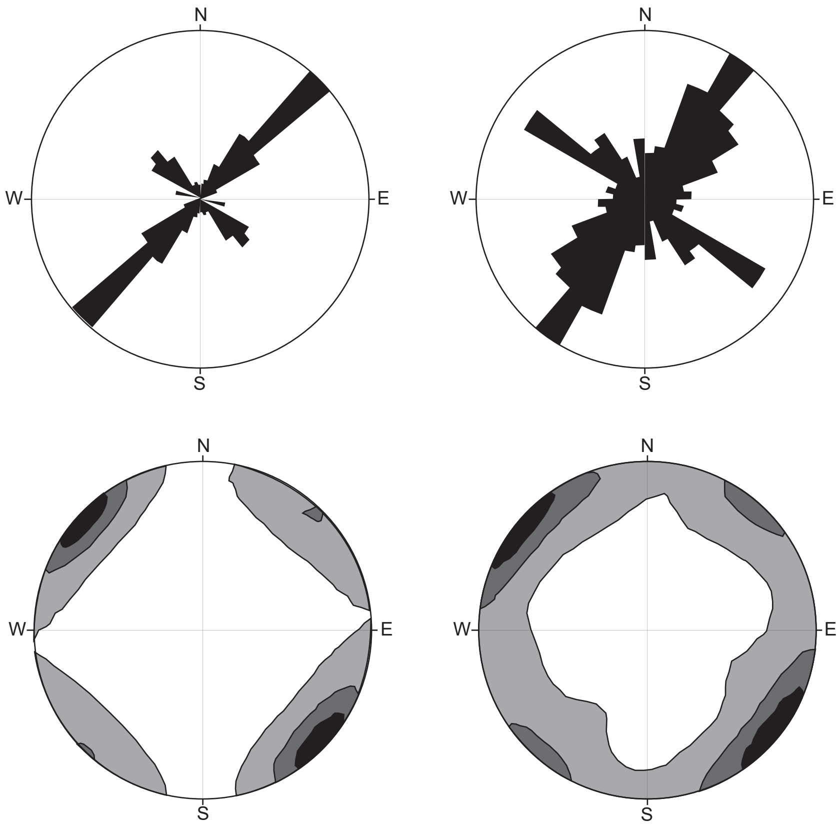


Figure 17. Orientation of fractures in outcrops in the Lambarfjärden area. Left, Hässelby (n = 264); right, Lovön (n = 168). Figure redrawn and simplified after Vass (2012).

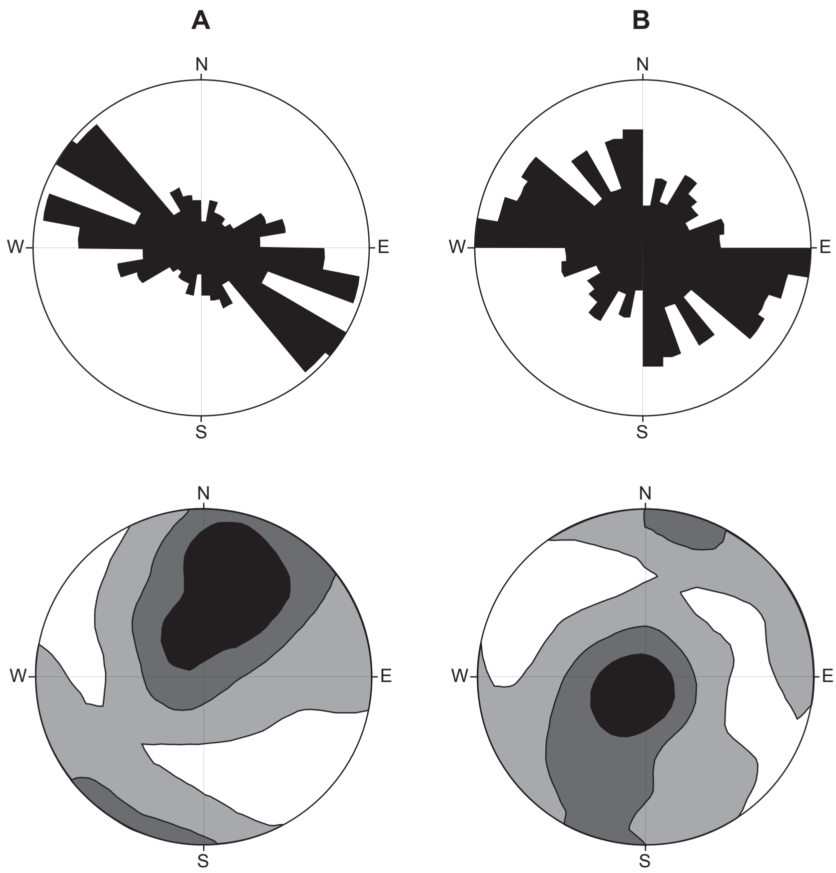


Figure 18. A. Orientation of fractures in borehole 08F351K (n = 247). **B.** Orientation of fractures in borehole 08F352K (n = 235). Figures redrawn and simplified after Vass (2012).

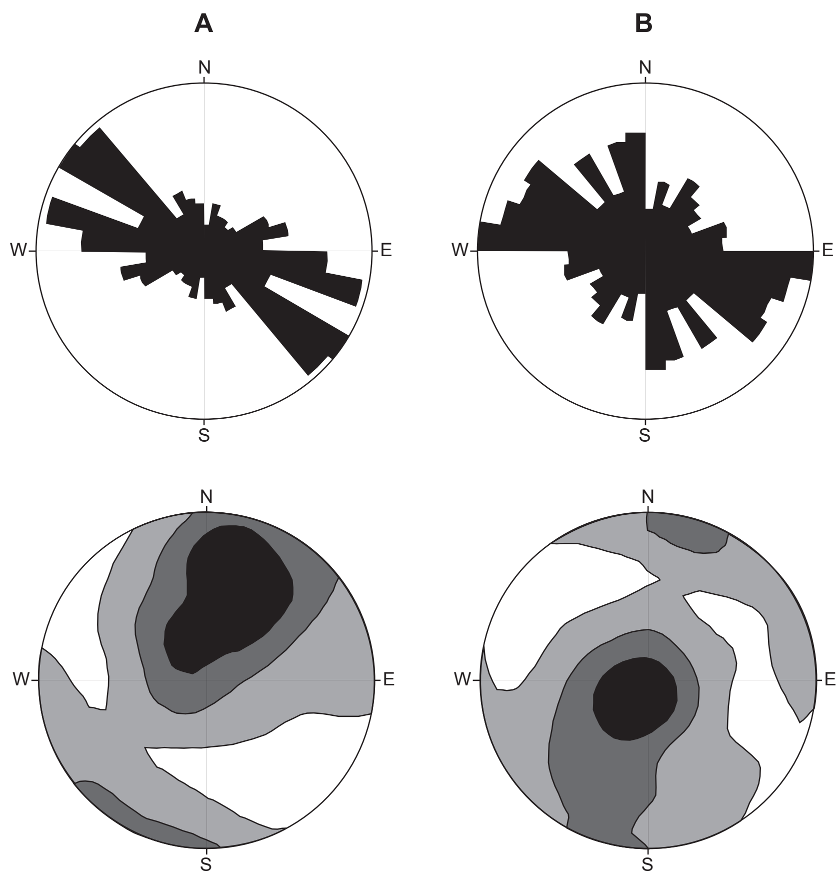
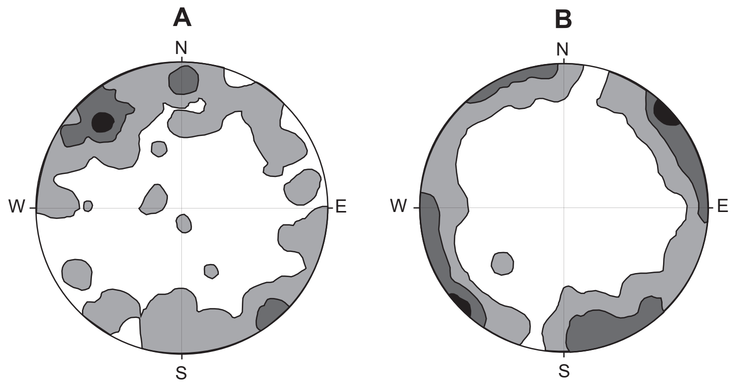


Figure 19. Orientation of fractures in borehole 08F353K in Lambarfjärden.
A. 3–207 m (n = 343).
B. 208–358 m (n = 405).
Figures redrawn and simplified after Vass (2012).

Fiskarfjärden

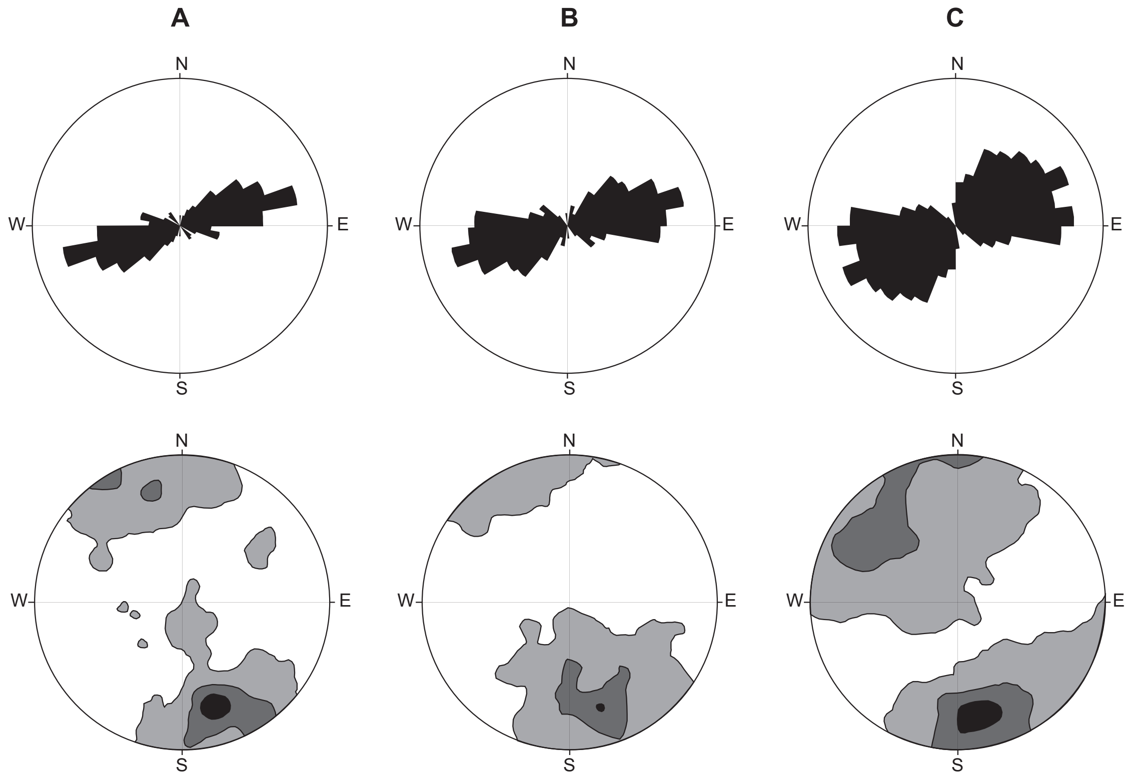
At Sätra and Kungshatt, fractures have been documented on outcrops for the Förbifart Stockholm bypass project (Ignea 2015). Fractures have also been documented in a borehole drilled in a north-northwest direction, across Fiskarfjärden from Sätra towards Kungshatt. The hole started with a 45° inclination and then became flatter and almost horizontal towards its base. In addition, fractures have been documented in two moderately inclined drill holes (inclination 50°) drilled out in Fiskarfjärden, one pointing to the north-northwest, the other to the south-southeast (Ignea 2015).

Northeast fractures with steep northwesterly dips predominate on outcrops in the Sätra area, although subordinate steeply dipping west-northwest fractures also occur (Fig. 20A). At Kungshatt, on the other side of Fiskarfjärden, subvertical east-northeast and northwest-striking fracture sets predominate (Fig. 20B). In the two facing, moderately inclined drill holes, east-northeast fractures with mainly steep to moderate dips towards the north-northwest to northwest predominate, but also dip steeply towards the south-southeast (Figs. 21A and B). In the long borehole that crosses Fiskarfjärden, east-northeast-orientated fractures predominate, with a certain spread between east–west and northeast, with mainly moderate to steep dips, both towards the north-northwest and south-southeast (Fig. 21C).



◄ **Figure 20. A.** Orientation of fractures in outcrops in the Sätra area (n = 146). **B.** Orientation of fractures in outcrops at Kungshatt (n = 379). Figures redrawn and simplified after Ignea (2015).

▼ **Figure 21.** Orientation of fractures in the boreholes in Fiskarfjärden. **A.** 08F152K (n = 228). **B.** 08F153K (n = 492). C. 08F156K (n = 1784). Figures redrawn and simplified after Ignea (2015).



In summary, relatively steep, east-northeast fractures predominate in the Fiskarfjärden area (Ignea 2015), indicating a relation to the east-northeast zone in Fiskarfjärden. For further information from the investigations in Sätra, at Kungshatt and in Fiskarfjärden, see Ignea (2015).

Eolshäll–Smedslätten

Fractures have been documented both in outcrops in the area and in a cored borehole (14RKB06) drilled from Eolshäll towards Smedslätten, in a northwest direction and with a 23° inclination (Alfvén 2015). The borehole documentation available only covers the first 271 m of the planned 400 m long drill hole.

The fractures in the outcrops have a predominantly north to northeast strike with subordinate east–west fractures (Fig. 22). In the borehole, the interval 130–185 m is interpreted as penetrating a deformation zone. The fractures in the upper part of the borehole, southeast of the zone (0–130 m), have a predominantly northeast strike and mostly steep dips varying between northwest and southeast (Fig. 23A). Below and northwest of the zone, in the interval 185–271 m, the strike of the fractures is more varied, with some spread from east-northeast to northeast and west-northwest (Fig. 23B). The dips are mostly steep. For more information on the investigations at Eolshäll and Smedslätten, see (Alfvén 2015).

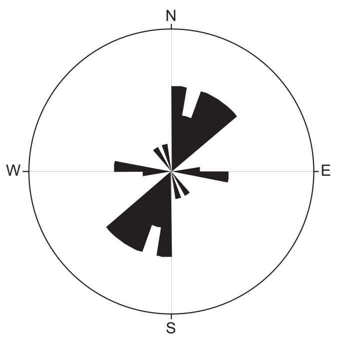


Figure 22. Orientation of fractures in outcrops in Eolshäll–Smedslätten (n = 19). Figure redrawn and simplified after Alfvén (2015).

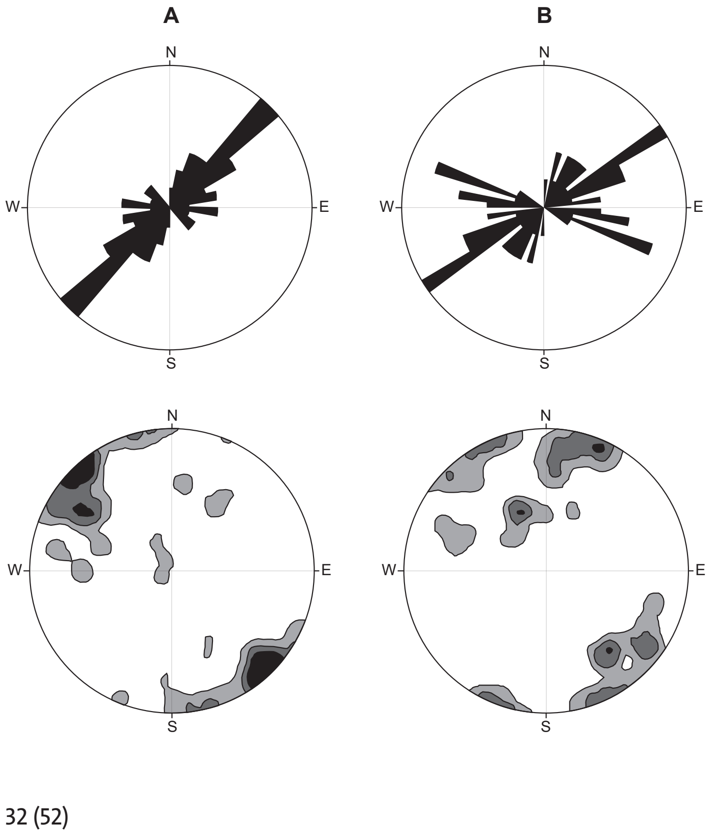


Figure 23. Orientation of fractures in borehole 14RKB06 at Eolshäll–Smedslätten. **A.** 0–130 m (n = 63 in the rose diagram, n = 79 in the stereonet. **B.** 185–271 m (n = 39 in the rose diagram, n = 46 in the stereonet). Figures redrawn and simplified after Alfvén (2015).

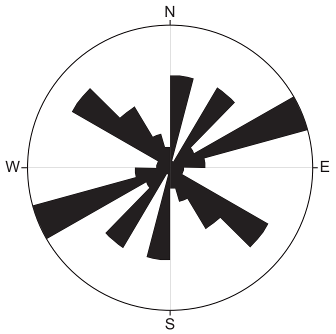


Figure 24. Orientation of fractures in outcrops at Kungens Kurva (n = 94). Figure redrawn and simplified after Guldstrand (2013).

Kungens Kurva

Fracture mapping has been carried out on outcrops within a 300 × 200 m area next to the Heron City shopping centre by Kungens Kurva (Guldstrand 2013). Four fracture sets have been documented within the limited area: northwest with predominantly moderate dips to the northeast; east-northeast with moderate to steep dips to the south; north–south with moderate dips to both east and west; and northeast with moderate dips to the southeast (Fig. 24). Fracturing along the foliation occurs throughout the area studied. For further information from the surveys at Kungens Kurva, see (Guldstrand 2013).

Summary

In comparing the orientation of fractures in the various surveys, it is generally found that fracture orientations are similar in most of the areas, but the frequency (intensity) of the different sets varies. By comparison, the fracture domains defined in Laxemar and Forsmark during SKB's site investigation in Oskarshamn and Östhammar municipality were based on differences in the orientation of the fracture sets, but also on relative differences in the intensity of fracture sets between the domains (Stephens et al. 2007, Fox et al. 2007, Wahlgren et al. 2008, La Pointe et al. 2008). Similarly, an evaluation and analysis can be based on existing information to investigate whether the bedrock of the Stockholm area can be divided into fracture domains. In the absence of more detailed and evenly distributed information in the field, the first step might be to make an overall analysis based on the orientation and intensity of identified lineaments. This analysis can then be supplemented with more detailed fracture data from outcrops, tunnels, boreholes, etc.

In the Stockholm area, northeast (east-northeast to north-northeast) and northwest (west-northwest to north-northwest) fractures predominate, while east–west and north–south orientations are subordinate. Thus, the predominant fracture sets have the same strike trends as the brittle deformation zones (see Stålhös 1969). From a geological evolution viewpoint, this may indicate that most of the zones and fractures were already formed during the waning stages of the Sveco-karelian orogeny, which in eastern-central Sweden and southwards was characterised by north–south bulk crustal shortening (Stephens & Wahlgren 2008, Viola et al. 2009, Saintot et al. 2011).

An important consideration in fracture orientation is that fractures that are parallel to a borehole are underrepresented in the documentation. Orientation bias has not been corrected in the stereonets and rose diagrams presented for boreholes in the above studies (see Terzhagi 1965). This leads to a bias in the resulting data set. The stereonets and rose diagrams in the above studies clearly indicate that fractures at an angle to the borehole axis predominate, whereas fractures parallel to the borehole axis are underrepresented. An example possibly due to this bias is the difference in the strike between fractures mapped on outcrops at Lovön and Hässelby and the mapped fractures in the drill cores from Lambarfjärden. In the outcrops, northeast fractures predominate on both Lovön and Hässelby, although subordinate northwest fractures also occur. However, in the north-

northeast and south-southwest-orientated boreholes in Lambarfjärden, west-northwest to northwesterly-striking fractures predominate, except in the upper part of the north-northeast-orientated borehole (Vass 2012). Correspondingly, east-northeast fractures are predominant in the boreholes in Fiskarfjärden, while in the outcrops at Kungshatt, in addition to the east-northeast fractures, there is also a northwest fracture set, i.e. the latter is parallel to the direction of the borehole axes (Ignea 2012). Correspondingly, in the case of surface mapping of outcrops, the presence of gently dipping to horizontal fractures is underrepresented. However, the combination of surface mapping and mapping of multiple drill cores means that all fracture sets are documented.

A clear link between the orientation of fractures and foliation (ductile anisotropy) is found in several places in the areas studied. In Fiskarfjärden, the foliation in the three boreholes has a predominantly east-northeast strike, i.e. parallel to the orientation of the fractures (Ignea 2012). In the Södermalm area, the foliation is parallel to the northwest, northeast and east–west fracture sets (Armengol 2012). In addition, the orientation of the fractures along the alignment of the Citybanan railway tunnel tends to be largely controlled by the foliation in surrounding rocks (Andersson & Swindell 2008). This suggests that the ductile anisotropy in the bedrock partially controlled the brittle deformation, i.e. the latter took advantage of existing weakness planes in the bedrock.

The most commonly occurring fracture fillings are chlorite, calcite and clay, although graphite, laumontite, prehnite, quartz and pyrite also occur. No correlation between fracture minerals and fracture orientation has been demonstrated (e.g. Vass 2012, Ignea 2015). For further information on fracture fillings, see Vass 2102, Ignea 2015). For detailed information of fracture fillings in the Forsmark area in northeastern Uppland, see Stephens et al. (2007) and Sandström et al. (2008).

Late to postglacial deformation

Mörner (2004, 2005) presented numerous locations in Sweden where signs of late- to postglacial paleoseismicity were observed, including the Stockholm area (see also Tröften 1997). The occurrences in the Stockholm area are primarily based on observed disturbances in varved (seasonally layered) clay deposits and liquefaction, which, according to Mörner were caused by earthquakes at the time of the latest deglaciation. No decisive evidence has been presented, except for the generally accepted late- to postglacial faults in northern Sweden, e.g. Pärvie, Lansjärv, Röjnoret and Burträsk, and the recently identified and described fault in the Bollnäs area (Smith et al. 2014, Mikko et al. 2015). Hence, there is no general acceptance for the occurrence of late- to postglacial fault movements in southern Sweden, including the Stockholm area (cf. Lagerbäck & Sundh 2008).

In situ stress

Regional stress field

The in situ stress field (paleostress) that has affected bedrock in Sweden and caused the formation and reactivations of ductile and brittle structures has varied during the geological evolution. The stress-related processes that are primarily relevant are the major orogenic events that created and deformed the bedrock, i.e. the Svecokarelian, Sveconorwegian and Caledonian orogenies (mountain building periods). The bedrock in the Stockholm area was formed and deformed during the Svecokarelian orogeny, during which the horizontal main compressive stress was approximately north–south (e.g. Stephens & Wahlgren 2008).

The current regional stress field in the Fennoscandian Shield is primarily caused by a horizontal tectonic pressure from the spread in the Mid-Atlantic Ridge. In addition to the pressure of the Mid-Atlantic Ridge, postglacial stress relief (unloading of the crust due to deglaciation) represents a second-order stress source (see Uski et. al 2003). Ignoring local variations, the largest horizontal stress (σ_1) is generally orientated in a northwest–southeast direction in the bedrock in the southern half of Sweden (Fig. 25). The vertical stress at any particular depth is primarily caused by the pressure from the overlying rock mass (e.g. Perman & Sjöberg 2007).

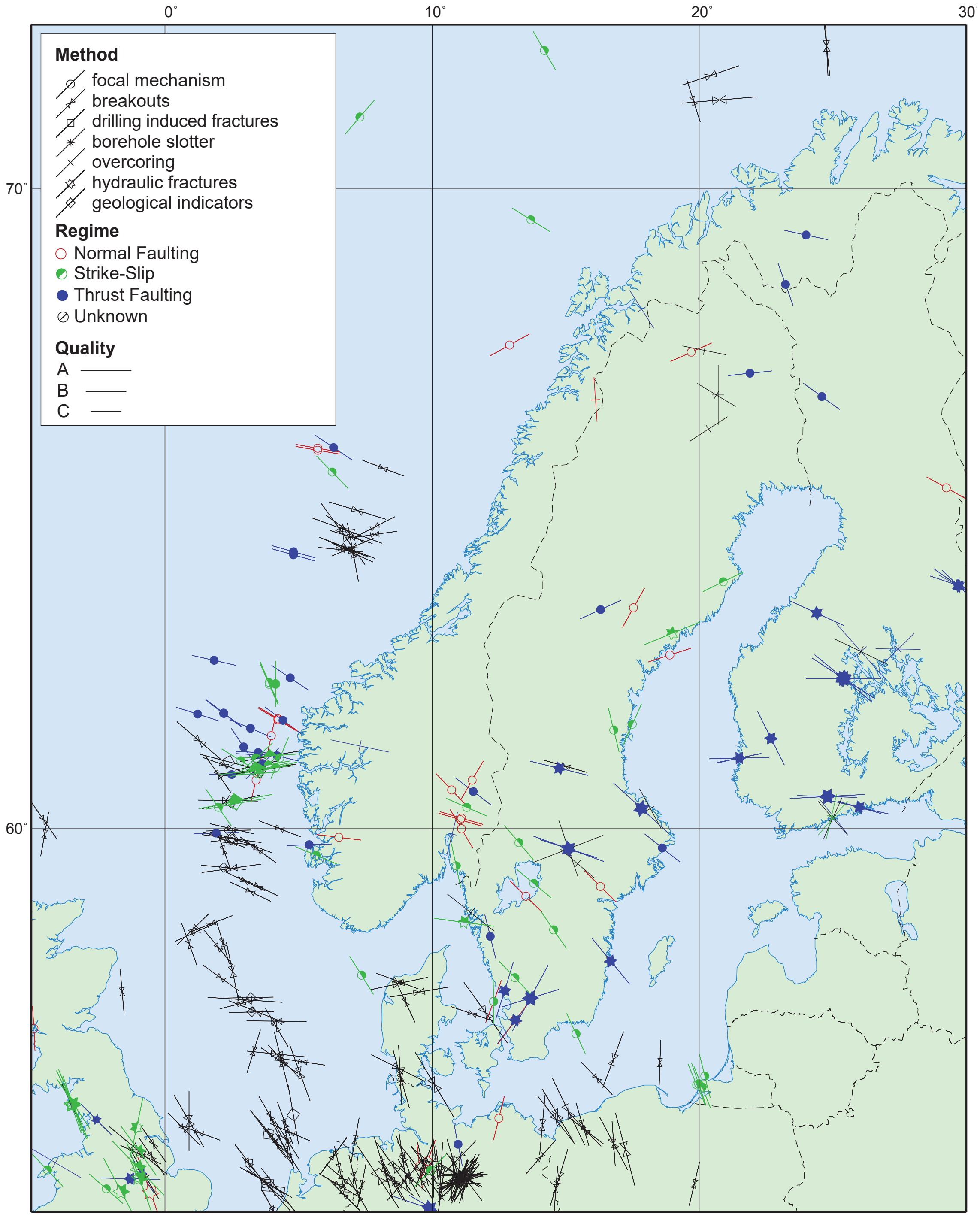


Figure 25. In situ stress in Scandinavia, World Stress Map (Heidbach et al. 2008).

Local stress field

Locally, the stress field may differ from the regional pattern, usually due to heterogeneities in the rock mass; e.g. the orientation of major deformation zones, topographic and lithological variations etc., and even the stress magnitude may vary considerably. The upper part of the bedrock (< 50m) often shows signs of stress relief, which affects the in situ stress in the rock mass. If the bedrock is heavily fractured, the rock stresses are considered to be zero or near zero, whereas single stress relief joints or fractures have less impact on the stress field (Berg 2005). Thus, rock stresses measured in deep boreholes (100–1000 m) or stresses from focal plane analyses of recent earthquakes at great depths are not always representative of the shallow, partially stress-relieved part of the bedrock (see Berg 2005, Perman & Sjöberg 2007) within which most infrastructure projects are located.

Perman & Sjöberg (2007) have compiled and interpreted shallow in situ stress information from various projects in the Stockholm area as a basis for the design of Citybanan (Fig. 26). All informa-

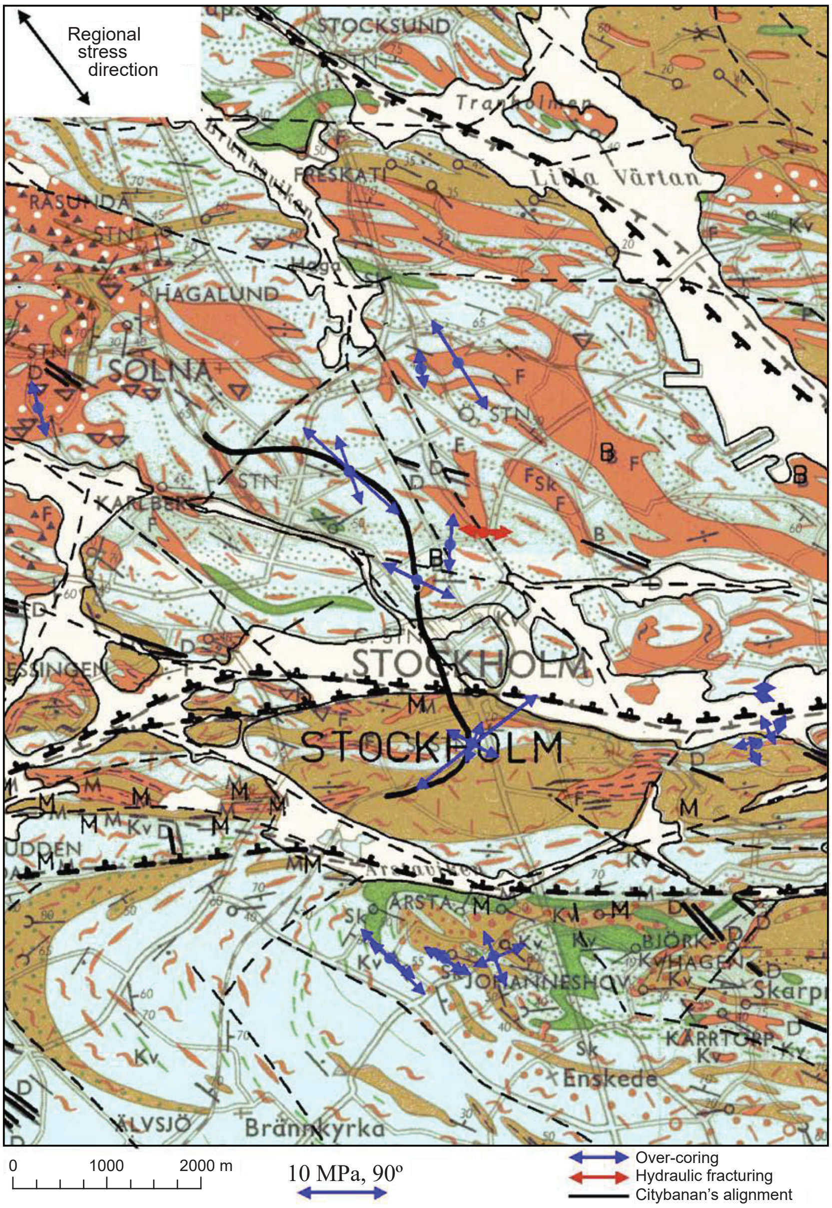


Figure 26. Direction and size of the greatest horizontal stress in the Stockholm area (after Perman & Sjöberg 2007).

tion derives from measurements carried out at a vertical depth of between 10 and 65 m. The direction of the maximum horizontal stress from all measurements in the Stockholm area varies mainly between west-northwest to east-southeast and north-northwest to south-southeast. Although there is a certain spread, the direction of the measured maximum horizontal stress is similar to that of the regional horizontal stress (σ_1). Based on geological information, with the Söder Mälarstrand fault ("Söderström fault") as an important boundary, as well as results from stress measurements, the Citybanan project corridor was divided into three stress domains: Norrmalm, Riddarholmen and Södermalm (Perman & Sjöberg 2007). At Norrmalm, the orientation of the largest horizontal stress was between 100° and 176°, whereas the spread at Södermalm was very large. The measurements at Södermalm pointed to a more east–west orientation, which could mean that the orientation is affected by the east–west fault zones south and north of Södermalm. However, there was considered to be a very high degree of uncertainty (Perman & Sjöberg 2007). At Riddarholmen, the stress profiles were judged to be similar to those in Norrmalm.

Recent seismicity

The Stockholm area and neighbouring eastern Svealand are characterised by only a few historical (1375–1970) and instrumentally (1971–2012) recorded earthquakes. Figure 27 shows the magnitude and year of earthquakes recorded in Stockholm and the surrounding area. Note the two

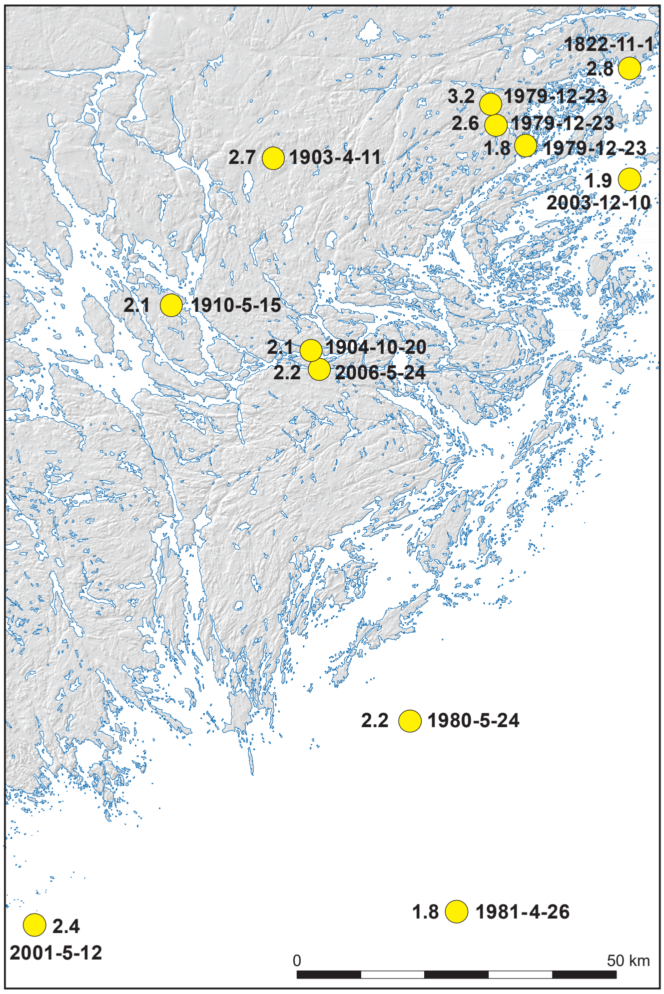


Figure 27. Magnitude and age of historical (1375–1970) and instrumentally recorded (1971–2012) earthquakes in Stockholm and the surrounding area. Data from Fencat (2016) and SNSN (1904). Note that uncertainty as to locations may be up to 2 km for instrumentally recorded earthquakes and even greater for historical ones.

earthquakes located along the faults bordering Södermalm to the north and south. This may indicate that the earthquakes are related to these faults. However, the uncertainty as to positioning may be up to 2 km for the instrumentally recorded quakes and even greater for the historical ones.

Summary of the geological evolution of the bedrock in the Stockholm area

Table 1 summarises the geological evolution in the Stockholm area, from the oldest processes when the bedrock was formed to geological processes and events that affected or may have affected the bedrock in the area up to the present day. After the bedrock was formed, metamorphosed and deformed during the Svecokarelian orogeny and then stabilised at 1.8–1.7 Ga, the effect of the subsequent geological evolution primarily consisted of reactivations and limited new formation of structures and weakness zones caused by built-up stresses in the bedrock. Stress changes in the stabilised bedrock may be a distal effect of younger orogenic processes, but are also caused by loading and unloading related to sedimentation/erosion and glaciation/deglaciation, for example.

As regards understanding the geological evolution, access to reasonably accurate age determinations of rocks, metamorphic alteration and deformation is fairly good for the older geological evolution, i.e. when the bedrock was formed, was still ductile and up to stabilisation. However, access to age determinations is limited for events and processes that have affected the bedrock in the subsequent geological evolution. This applies particularly to the age of reactivation and possible formation of new brittle deformation zones (faults). This means that usually only a relative age determination is possible or that age can only be confined to a fairly large time interval. The possibility of relative age-determined movements in brittle deformation zones is also limited by

Table 1. General summary of the geological evolution in the Stockholm area.

Age (million years)		Geological event
Present		Recent seismicity?
0.115–0		Glaciation-deglaciation; synglacial to postglacial fault movements?
510–400		Brittle reactivation of deformation zones/fractures as a distal effect of the Caledonian orogeny?
540–420		Sedimentation; Cambrian sandstone in fractures
700–600		Erosion, formation of the sub-Cambrian peneplain
1100–900		Brittle reactivation of deformation zones/fractures as a distal effect of the Sveconorwegian orogeny?
1260?		Intrusion of dolerite
1500–1250		Sedimentation (”Mälar sandstone”)
1660–1520		Brittle reactivation of deformation zones/fractures as a distal effect of the Gothian orogeny?
1800–1700		Transition from ductile to brittle deformation (bedrock cooled below approximately 300°C)
1840–1800	Svecokarelian orogeny	Intrusion of granite (”Stockholm granite”) and subordinate pegmatite and aplite
1840–1810		High-grade metamorphism (M2) and deformation (D2), formation of ductile deformation zones
1870–1860		Intrusion of dolerites
1880–1860		High-grade metamorphism (M1) and deformation (D1)
1900–1870		Intrusion of gabbroid-granitoid and subordinate syenitoid and dolerite
1910–1900		Sedimentation and volcanic activity
2000–1800		Svecokarelian orogeny

the lack of time markers in the form of rocks younger than 1 billion years in the Stockholm area. The only possibility of relative age determination of younger movements in brittle deformation zones is documented displacement of the sub-Cambrian peneplain or brittle overprinting of fractures filled with Cambrian sandstone, either of which would suggest that movements have occurred in Cambrian to post-Cambrian times. Thus, knowledge of possible movements in the bedrock over the past 1 billion years to the present day is very limited.

Future key issues in the Stockholm area

The lack of geological information in the Stockholm area from a geological evolution perspective primarily concerns the documentation and characterisation of ductile and brittle deformation zones, as well as an understanding of the brittle structures in the blocks between the major deformation zones. Below are a number of studies considered important to improve knowledge of the bedrock in the Stockholm area, not least from an engineering geological and infrastructure perspective, and to improve our understanding of the geological evolution:

- Mylonite is marked in several places on the bedrock maps across the Stockholm area, indicating zone-related strong ductile deformation. As a complement to the results of studies in the Ornö banded series and the eastern part of Värmdölandet (Persson & Sjöström 2002), there is a need for a study focusing on the indicated ductile deformation zones in the remaining part of the Stockholm area, including documentation and kinematic characterisation.
- Documentation and characterisation of brittle deformation zones (faults) by field control of strategic outcrops, as well as studies of drill cores and existing tunnels. This includes evaluating and compiling existing information from surface mapping, drill cores and tunnels, updating existing information, and integrating new documentation when available.
- Regional compilation of existing and available fracture information. Where information is lacking, there is a need for supplementary fracture mapping in strategically selected parts of the Stockholm area.
- An evaluation of the fracture, fracture zone and lineament information should then be made to attempt a rational subdivision of the bedrock in the Stockholm area into different fracture domains.

QUATERNARY GEOLOGY (SUPERFICIAL OR DRIFT DEPOSITS)

Regional geological background

The Stockholm area is situated in two regions of Quaternary deposits: the bedrock and clay region of the east coast and the bedrock, till and clay region of Östra Svealand (Persson 1995). These regions are characterised by their very limited cover of Quaternary deposits. This is in contrast to the lower lying areas and valleys, which are filled with fine-grained sediments. The greatest soil depths are found in the larger clay areas and in the glaciofluvial deposits (Fig. 28). The occurrence of the Quaternary deposits, land forms and characteristics reflects the dynamics of land-ice in the area, the environment in which the soils formed and the development of the area after the impact of glacial processes declined. In the Stockholm area, it is clear how the dynamics of the ice retreat affected the occurrence and properties of the glacial soils, and that the landforms and deglaciation represent the end of the last ice age and the transition to a warmer climate during the Holocene (Fig. 29).

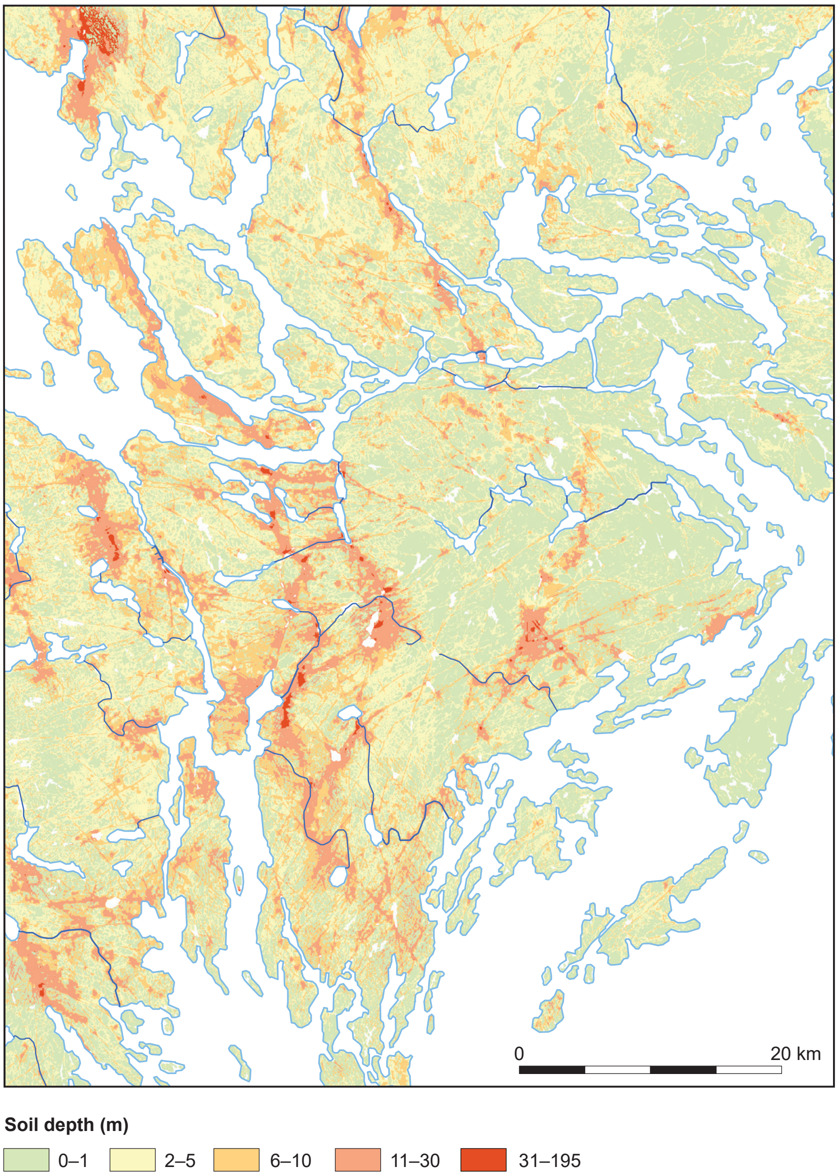


Figure 28. Overview of the depth of Quaternary deposits in the Stockholm area and surrounding region.

As the entire area is below the highest coastline, it is strongly characterised by soils deposited during the various stages of the Baltic Sea development up to the present day, as well as the coastal processes acting on the landscape as it emerged from the sea.

Deglaciation

The retreat of the last ice sheet from the Stockholm area took place over a period of about 1,000 years between 12,000 and 11,000 years BP (Brunnberg 1995, Stroeven et al. 2016). This means that the latest ice sheet left the area at the transition from the last cold period during the Pleistocene to the subsequent warm period, the Holocene, which continues to the present day (Fig. 29). In the southern parts of Södertörn, the ice retreated at a rate of 70–100 m per year, increasing to 200–300 m per year when it reached Lake Mälaren. At the end of the glacial period the ice flow movement was mainly from the northwest, but when the rate of ice retreat increased, the ice flow movement began to come from a more northerly direction. In the area there is also evidence of an older ice flow movement from the west-northwest. The latter represents an older glacial period and is linked to an older till, deposited from the west-northwest (Möller & Stålhös 1965).

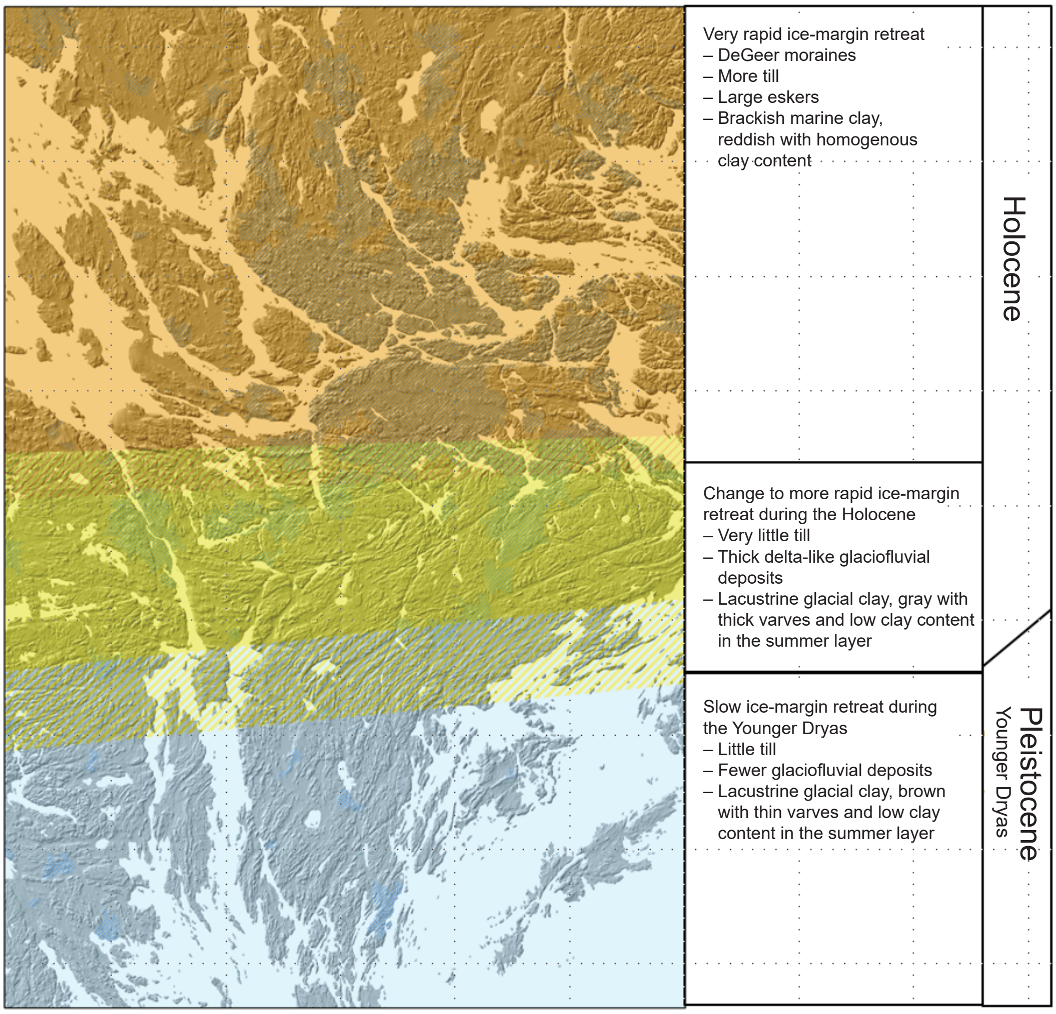


Figure 29. Generalised picture of the conditions during deglaciation in the Stockholm area and the main features of the glacially-formed soil type properties, extent and landforms typical of the different periods.

Baltic Sea evolution and sea level changes

The entire Stockholm area is situated below the highest coastline. At the time of deglaciation the Baltic Sea was about 150 m above its present-day level (Lundqvist 1995, Florin 1944). The area is characterised by the deposition of sediments taking place in the Baltic Sea up to the present day, as well as by beach and coastal processes active as the area emerged from the sea. The water depth during deglaciation was over 100 m in much of the area that is now land. As a result, the landscape is characterised by fine-grained soils deposited during the various stages of Baltic Sea evolution, from when the ice left the area to the present day. Environmental conditions during these stages have determined the extent of sediment formation, the types of sediment deposited and their properties. Glacial fine-grained sediments deposited in the Baltic Ice Lake and Yoldia Sea in the form of varved clays occur in the area. Postglacial clays were deposited on top of the glacial clay during the subsequent Ancylus Lake stage. The Ancylus Sea was in turn followed by the Littorina Sea. Organic mud was deposited during the brackish marine, milder conditions prevailing in the Littorina Sea. Brackish marine conditions have existed in the Baltic Sea since the formation of the Littorina Sea.

Quaternary deposits and their geomorphology

Since the area as a whole is below the level of the highest coastline, younger soils commonly cover the older deposits. Figure 30 depicts a generalised soil profile, typical of the region, showing the distribution of soil types with depth. The region is primarily characterised by a lack of soil cover in higher areas and thick deposits of fine-grained marine and lake sediments in valleys and at lower elevations (Fig. 31). Till is subordinate, and extensive areas with continuous till cover are rare. North–southerly large eskers are also characteristic of the area, testifying to the large quantities of sediment transported by the rapidly retreating ice sheet.

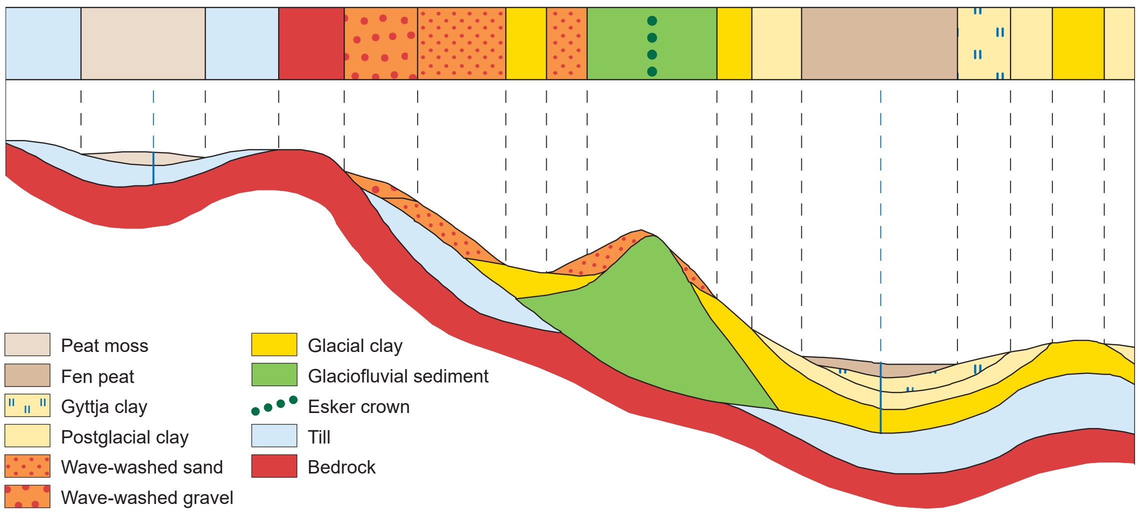


Figure 30. Generalised soil profile showing the distribution of soil types with depth in eastern Sweden.

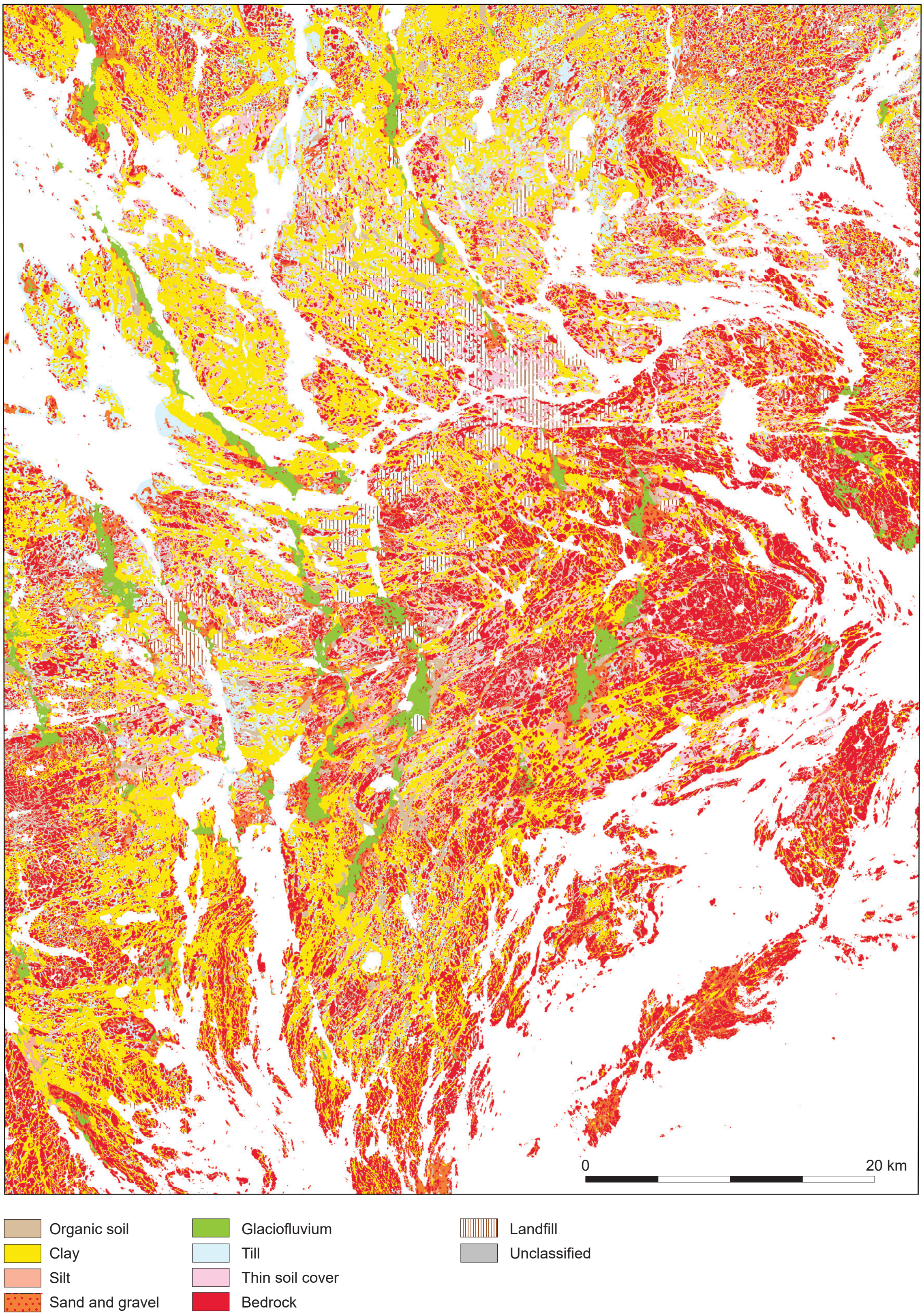


Figure 31. Simplified map of Quaternary deposits in the Stockholm area. Areas with exposed bedrock and thin cover and clay predominate.

Till

Till occurs sparsely at the ground surface in the area, but often at depth beneath younger soils (Figs. 30, 31). The till cover is usually not more than a few metres thick. Till deposits of greater thickness can occur on the downstream side of rocky areas in relation to the ice flow direction. Areas with a more continuous till cover are more common north of Lake Mälaren, and till occurs very sparsely at Södertörn (Fig. 31). A clayey and greyish till occurs in the area below the more common sandy-silty till. The former is often referred to as 'old blue' and probably represents an earlier stage of the latest deglaciation. 'Old blue' is often compact and over-consolidated, and is found mainly on the downstream side of rocky hills, in relation to the main ice flow direction during the last glaciation. In addition to the lee-side moraines with drumlin forms found in the area, there are numerous De Geer moraines (Fig. 32). These are characteristic of Mälardalen and often occur in swarms. The De Geer moraines are lower, 2–5 m high, and more irregular and winding than normal moraine ridges, in most cases no more than a dozen metres wide and essentially orientated parallel to the ice front (Fig. 33). In many cases, De Geer moraines are block-rich, particularly if they occur in farming areas where farmers have added boulders and stones removed from cultivated fields.

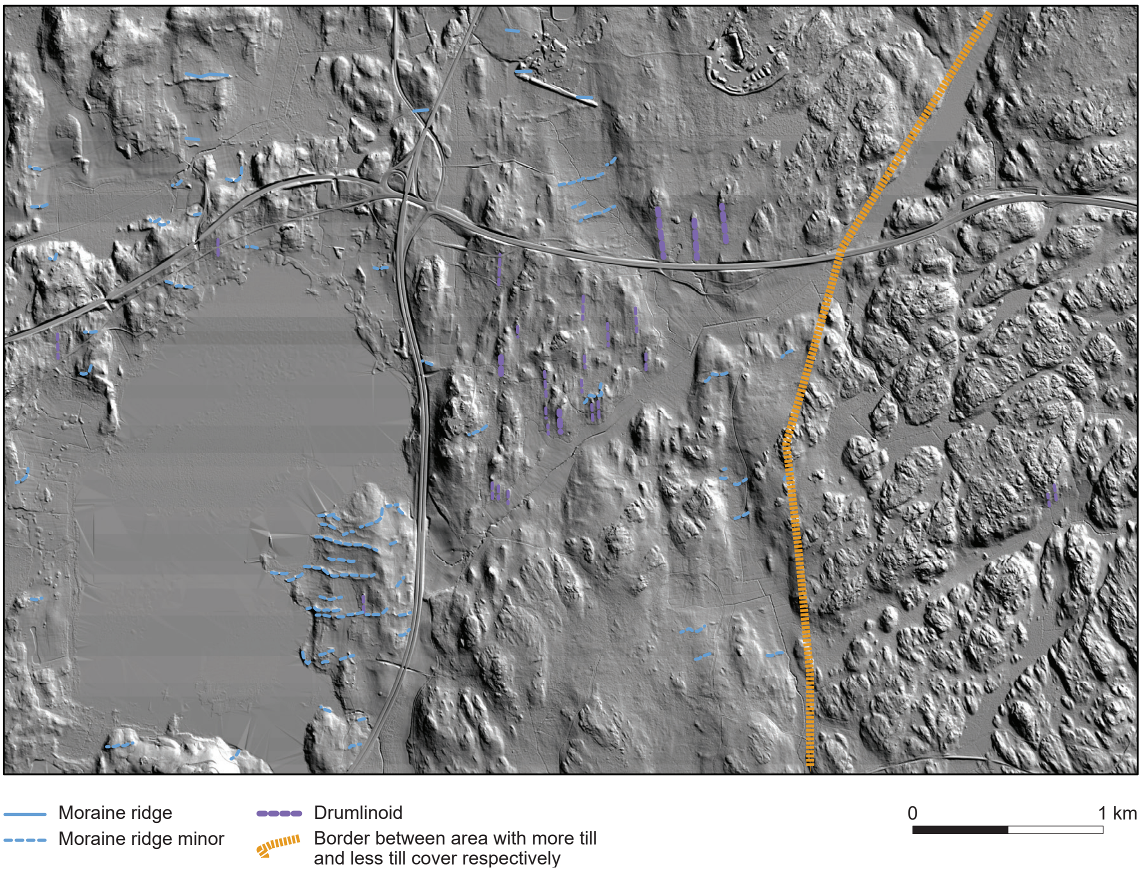


Figure 32. Elevation model over an area that in the east has very limited till cover and in the west much thicker till cover. Downstream drumlins are abundant in the west. These are missing in the east, where the till cover is thin. A number of De Geer moraines (in blue) can be seen, largely orientated across the latest ice flow direction.

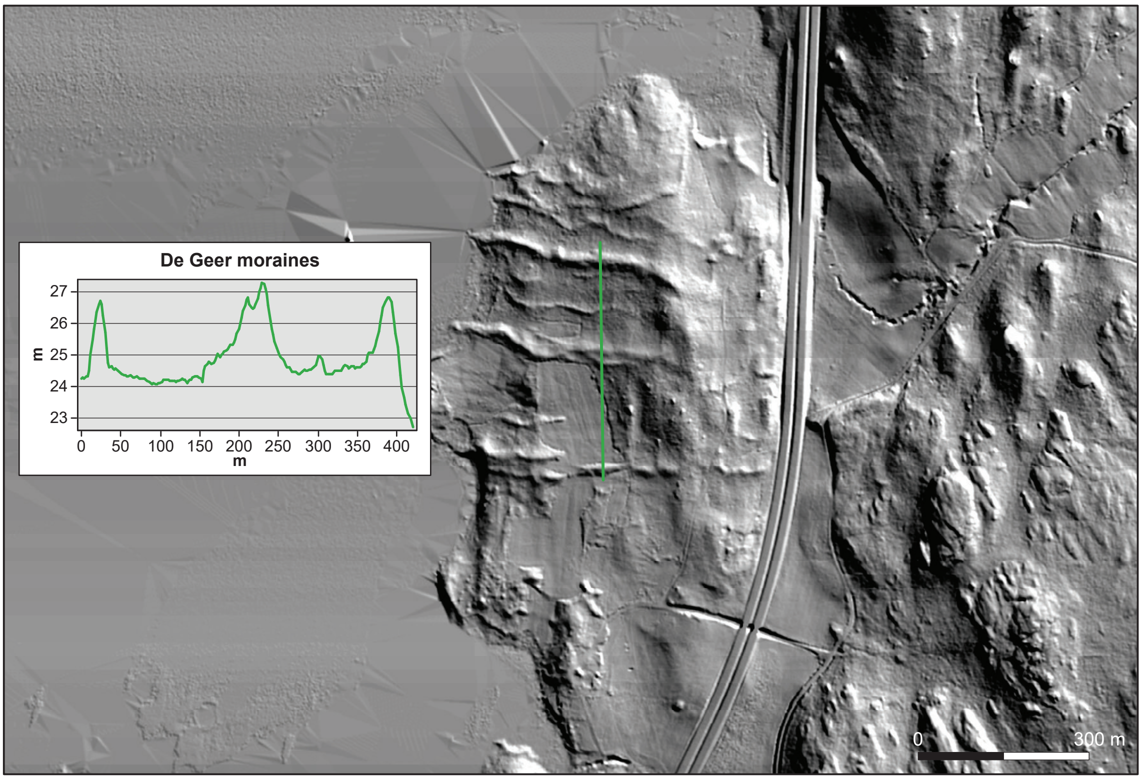


Figure 33. Profile across three De Geer moraines. The distance between them is about 200 m and they rise 2 to 3 m above the surrounding terrain.

Eskers

The lowlands of south-central Sweden are characterised by large eskers, deposited in a subaquatic environment and trending parallel with the direction of the ice retreat. The main eskers in the Stockholm area are shown in Figure 34. Sediment thickness in the ridges can be over 50 m. Their internal structure is often complex and reflects the supply of meltwater and sediment from the ice sheet, as well as the extensive reworking of the ridges as they were raised above sea level. As a rule, there is a core of coarser cobbly gravel material over which more sandy gravely material is draped (Lundqvist 1979). These glaciofluvial materials have subsequently been affected by beach and stream processes. The reworked sediments that often cover the sides of the ridges are underlain by clay covering the sides of the ridge. Where the eskers are less well developed, they may be completely covered by clay, and the landform may not be visible at all. In the Stockholm area in particular, there are the *'malmarna'*, which are large, well-developed delta-like formations. Pålamalm at Södertörn is the last remaining example where their character and morphology can be observed. *Malmarna* are highly complex and represent a period when the ice retreat began to increase as the climate warmed during the transition from the Pleistocene (Younger Dryas) to the Holocene (Lundqvist & Vilborg 1998). Sediment supply increased but the ice front did not retreat so quickly northwards, which caused material to accumulate in large delta-like deposits. South of *malmarna*, the deposits are much smaller. In the north of the Stockholm area, where the ice retreated much more quickly (Fig. 29), certain eskers vary in how they were formed; broader parts appear as hills, with smaller narrower sections between them. These are known as "esker trains" (Lundqvist 1999). This may reflect some cyclicity in the supply of meltwater and sediments due to climatic variations (Lundqvist 1999).

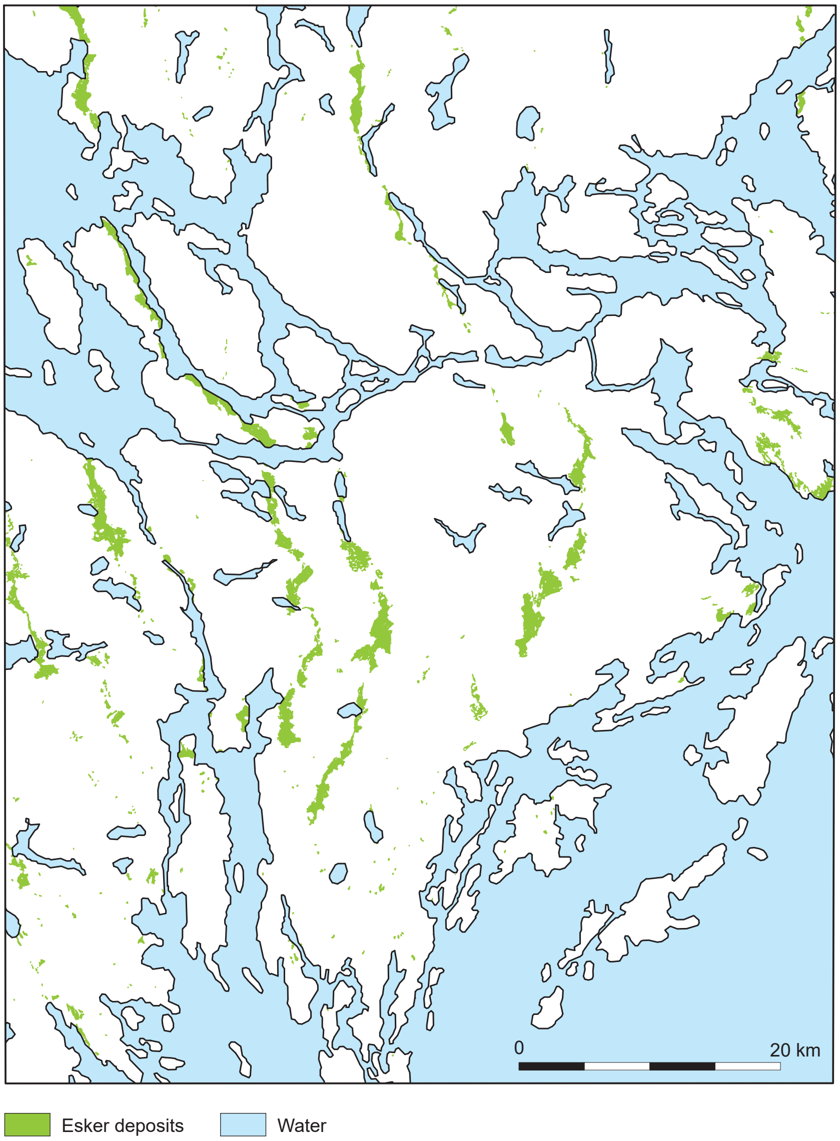


Figure 34. Esker deposits in the Stockholm area.

Glacial fine-grained sediments

Glacial clay covers large areas of the region and is also the predominant type of clay deposit (Fig. 31). A typical thickness in more extensive clay areas in the Stockholm area is 10–20 m, but in some places it is over 30 m. In smaller clay areas and in mosaic bedrock and till terrain, the clay is usually no more than 5 m thick. Glacial clays in the area are varved; sandy and silty layers are common in the lowermost layers of glacial clay. The varves become thinner higher up in the sequence, and the clay content is usually higher. Glacial clay in the area is calcareous, but the carbonate content is lower in the clays deposited in the southern parts of Södertörn. The properties of glacial clays vary across the area depending on the changing character of the ice sheet retreat, with associated changes in the depositional environment (Fig. 28). During the Baltic Ice Lake stage, glacial clay was deposited in a freshwater environment and is clearly varved. During the subsequent Yoldia Sea stage, clay was deposited under brackish-marine conditions, and the varves are more diffuse (Fig. 35). There is also some variation in clay content between glaciolacustrine and the glaciomarine clays, clay content being higher in the latter (Brunnberg 1995). In the glaciolacustrine deposited clays

Figure 35. Diffusely varved clay deposited during the Yoldia Sea brackish-marine phase. The light layers were deposited at the beginning of the year, transitioning into brownish layers during summer and autumn. The end of the annual varve is marked by a darker brown to black layer, representing winter sedimentation. Photo: Stefan Wastegård.

there is also a clear difference in clay content between summer and winter varves, whereby the clay content for the summer varves is about 25% and in the winter part more than 70% (Brunnberg 1995). This difference in clay content between summer and winter parts of the varves is largely absent in the brackish-marine deposited glacial clay. If glacial clays are exposed to loads, for example in the form of buildings or road embankments, they may become consolidated, giving rise to subsidence. Subsidence in clay areas may also occur if the water table is lowered.

Postglacial fine-grained sediments

At lower elevations and in larger sedimentation areas that have been open bays with greater water depth, postglacial clays occur that are grey in colour and not usually calcareous. Postglacial clays are not as thick as glacially deposited sediments; they are usually no more than one to a few metres thick. Postglacial clays were mainly deposited during the Ancylus Lake stage. Organic clays have been deposited in the bays of the Littorina Sea and the younger stages of Baltic Sea evolution. These clays have an organic content of 1–6%. Organic clays contain sulphides, and so may give rise to acidic sulphate-rich soils following oxidation, which may be triggered by trenching or other excavation. Oxidation lowers pH and leaching of heavy metals may occur (Sohlenius 2011). Organic clay occurs in the Stockholm area primarily at elevations close to the current sea level (Fig. 36), mainly adjacent to Lake Mälaren and shallow bays of the Baltic Sea. At elevations above 25 m above sea level there is only a very limited amount of organic clay. Organic clay is commonly no more than one metre thick, but at lower elevations it may reach a few metres. As with fine-grained glacial clays, loading by buildings or road embankments may cause the clay to consolidate and give rise to subsidence. Subsidence in clay areas may also occur if the water table is lowered.

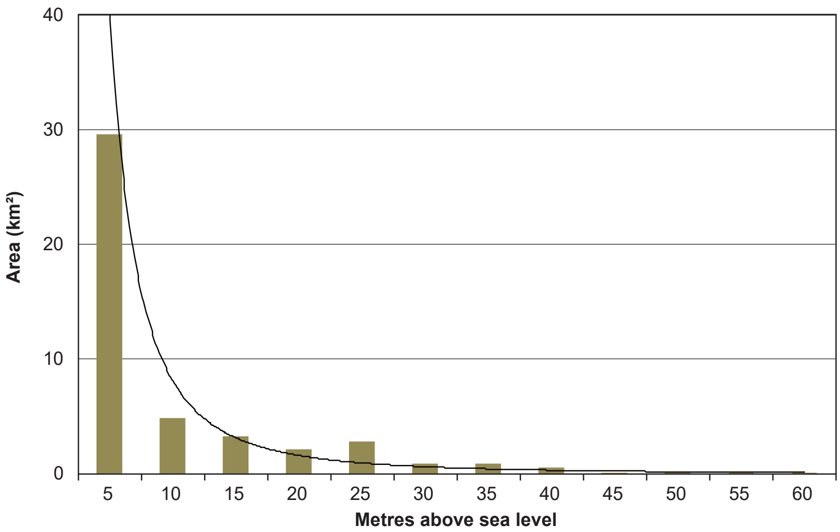


Figure 36. Distribution of organic clays at 5-metre intervals in the Stockholm area. Most organic clays occur at elevations near to the current sea level.

Landslides and ravines

There are very few areas with traces of landslides or development of ravines. The slide-scars and ravines that exist in the Stockholm area are mainly found at Södertörn, and there are none north of Lake Mälaren (see map viewer "Landslides and gullies" at www.sgu.se). The slide-scars and ravines that are found are almost exclusively associated with glaciofluvial deposits. This is because there are stratigraphic and hydrogeological conditions that allow slides to be triggered, and ravines can be formed. In conjunction with glaciofluvial deposits, the soil stratigraphy is often complex, with alternating clay and sandy layers, with the clay on the slopes. These deposits constitute significant aquifers, and conditions therefore exist for the development of high pore water pressures, which can trigger landslides. The ravine formation associated with glaciofluvial deposits is developed in distal silt-rich clays, and is also linked to groundwater movement within the deposits. Scars and slides are absent in the glaciofluvial deposits north of Lake Mälaren because the ice retreated much more quickly here. This, in combination with lower relief terrain, means that conditions have not allowed the formation of complex sediment sequences. The glacial clays here are more homogeneous in their clay content and the occurrence of sand and silt layers.

Postglacial reworked sediments

Since the entire Stockholm area is below the highest coastline, soils and the landscape have to some extent been affected by the waves and currents of the sea. In conjunction with large eskers, with large quantities of sand and gravel for the water to rework, reworked sediments can be thick and extensive. In other parts of the Stockholm area, reworked sediments occur generally, but are not usually thicker than 2 m. In higher terrain, the reworked sand and gravel commonly lie on till or directly on the bedrock. Close to clay areas and eskers, it is not uncommon that clay to underlies the reworked sand or occurs as layers within the sand.

Peat

Peat deposits in the region are usually fairly small, covering 5–10% of the land area. The lowest percentage is in the southern parts of Södertörn and along the coast. This area is part of *"Svealands lägre fornsjöområde"* (von Post & Granlund 1928), and the peat deposits here are mainly overgrown lakes. Hence, the peat is mostly underlain by organic lake and sea sediments in the form of organic mud and organic clay. Fens and bogs occur, with fens predominating over bogs, particularly in the northern parts of the Stockholm area. Thus, the peat mass is largely composed of different types of fen peat, mainly *Carex-Sphagnum* peat. The landscape is young, so the depth of peat in many fen peatlands is no more than 1 to 2 m. But in bog peat areas, the peat may be deeper, particularly at higher levels in the landscape. Here the peat may be between 3 and 4 m deep.

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APPENDIX 1. ENGINEERING GEOLOGICAL EXPERIENCE FROM STOCKHOLM INFRASTRUCTURE PROJECTS

This appendix describes the experiences of infrastructure projects in the Stockholm area. For further reading on engineering geology related to Stockholm, see for example Morfeldt & Persson (1997) and Persson (1998).

Engineering geological experience from Stockholm infrastructure projects

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Moderately dipping fractures at the tunnel portal for a de-icing facility in Älvsjö.

Contents

INTRODUCTION

This report is based on maintenance inspections of more than 100 km tunnels for traffic, energy, pipelines, cables and sewage and about 25 rock caverns for storing oil, coal, ice cream and alcohol, along with those for waste management, parking, train de-icing and public shelters. In addition, experience from geological site investigations and tunnelling, as well as from excavation and inspection of road cuts, railway cuttings and foundations are presented. Examples are also given of the importance of understanding the rock mass for the successful planning and execution of new underground facilities, for slope stability and foundations. The text covers the author's own experience as well as events and circumstances that are judged relevant for future work in the Stockholm area.

The experience is mainly based on objects in central Stockholm and its suburbs, along with water tunnels in Märsta-Stocksundet-Lidingö and Botkyrka-Himmerfjärden, railway tunnels in Kallhäll-Kungsängen, rock caverns in Södertälje, underground hangars in Tullinge as well as Finnberg tunnel in Nacka.

BACKGROUND

The bedrock in Stockholm which consists of gneiss, granite and mixed rocks of different types, with few thick weakness zones of altered poorer rock quality has, with few exceptions, been found to be stable with sufficiently high in situ stresses for the relatively straight forward construction of tunnels, rock slopes and foundations.

The rock mass is relatively 'tight' (low to moderate permeability) with a limited amount of groundwater in the fracture systems. However, this means that even small inflows into underground facilities in the bedrock have caused a local lowering of groundwater levels, with extensive settlements in overlying soil layers. This has been particularly clear and significant in areas with locally thick clay deposits, such as Mariatorget and Karlaplan, where extensive damage to buildings, pipelines and sidewalks has occurred.

All types of underground facilities in the urban area require extensive sealing work with regard to the limited groundwater resources. Exceptions to this may be facilities near to the water-bearing Stockholm esker (Stockholmsåsen) although here sealing is needed for other reasons, such as to reduce pumping costs.

LONG-TERM STABILITY

Infrastructure facilities excavated in the bedrock have been constructed in Stockholm since the mid 19th century, with a sharp rise in the mid 1940's with subway, cable and pipeline tunnels; caverns for coal or oil storage and for public shelters. In general, all facilities have been carried out conventionally by drilling and blasting. The old SJ tunnel at Slussen was the first tunnel excavated with a drilling machine and nitroglycerin in the 1870's. Some tunnels have a circular profile and have been excavated using a so called TBM (full face Tunnel Boring Machine), such as the Saltsjö tunnel in the 1980's, from Huvudstabron to Kastellholmen, with a length of about 7 km. Similarly, in the 1990's the Ormen tunnel from Roslagstull to Karlavägen, with a total length of about 4 km after taking into account some large curves. Around 2000, the Södra länken road tunnels were excavated; around 2010 the Norra länken road tunnels and recently the Citybanan railway tunnels, all by conventional drilling and blasting. At the time of writing, the excavation of one of Sweden's most ambitious tunnel projects, Förbifart Stockholm, a road bypass tunnel system, has commenced from Kungens kurva, south of Stockholm, to Häggvik in the north.

An interesting study of long-term stability was made in 2006 in the underground rock cavern aircraft hangars in Tullinge. There is an older part, probably from the 1950's, with brick walls, concrete floors, vaulted heavy concrete roofs and with two access tunnels to the surface. In the middle of the space there are large, supportive rock pillars. From the 1960's, adjacent to the older part, but about 10m deeper, there is an approximately 500m long central access tunnel with six side rooms and an additional 200m long access tunnel. All tunnels are about 15 m wide and about 6 m high. The rock support consisted of isolated rock bolts and a concrete arch under a weakness zone. Thus, the roof and walls are generally bare with no additional rock support since the 1960's. Leakage into the tunnel has always been dealt with by pumping. In addition to the tunnels mentioned, space was also excavated to provide for staff. The bedrock is made up of grey veined gneiss with some amphibolites and micaeous bands. At the inspection it was noted that the tunnels had a well maintained profile with only rare indications of block fall-outs. Some significant groundwater leakage sites were noted.

In general, it can be concluded from inspections that after excavation and reinforcement tunnels and rock caverns in the Stockholm area show long term stability. In some cases, ventilation in built-in shelters and/or district heating tunnels has resulted in drying out of the rock leading to locally unstable surface blocks as a result, as can happen in metro and railway tunnels, with their heavy ventilation generated by the passing trains. In wet sewer/water tunnels, such unstable surface blocks are very rare. Trapped groundwater, built up behind shotcrete, has occasionally caused block fallouts.

Inspections have most often been performed physically by using a steel rod or hammer to identify loose sitting rock or shotcrete by sound or less often more visually with sample strikes. Most time-consuming are tunnels without shotcrete that require careful inspection of all surfaces, whereas damage/moisture on shotcrete often highlights the need for special control. Depending on the standard of application, material quality and adhesion of shotcrete, visual inspection supported by occasional physical checks may be sufficient in shotcrete sprayed tunnels in many cases. Experience has shown that the encountered rock types provide adequate adhesion for shotcrete use. Exceptions are weakness zones with altered rock or large fracture surfaces coated with mica or graphite. These types of surfaces in tunnel walls, or as flat surfaces in the roof, can usually be identified behind the shotcrete during inspections.

GEOLOGICAL MAPPING

Requirements for geological mapping of tunnels and caverns were introduced during the 1960's, so many earlier facilities were unfortunately not mapped. Few older energy and sewage tunnels are mapped, whereas cable and pipeline tunnels have more often been mapped. TBM bored tunnels such as the Saltsjö tunnel and the Ormen tunnel are mapped as are the Södra länken, Norra länken and Citybanan transport tunnels.

TBM bored tunnels and wire-sawn rock faces that result in smooth rock surfaces have been found to be more difficult to map than uneven, blasted surfaces. Mapping of the bedrock behind the walls of installed facilities, such as underground shelters, is generally difficult or impossible due to the limited space.

During tunnelling, mapping of the rock is preferably done as close as possible to the excavation front as soon as the rock is cleaned and good lighting is available. It is particularly important to perform mapping as soon as possible if poor rock conditions have been encountered that may require temporary support by shotcrete that will conceal the excavated surface. In some cases, with good rock conditions and no shotcrete, long tunnel sections may be reviewed and remapped. If this procedure is possible, a better geological continuity is often obtained, but it requires that the rock is cleaned along the extended tunnel section.

SITE INVESTIGATIONS AND PRELIMINARY DESIGN

Preliminary investigations should be designed and carried out according to the foreseen geological conditions, but many times the client's financial planning dominates the outcome. Some consultant's ambition to achieve an ideal site investigation and cover all design parameters can also lead to high costs. Most of the time, there is a balance between cost and ambition, and although geological or other surprises are rare in the Stockholm area, they do occur.

Some examples of geological conditions that have had negative consequences should be mentioned. For example, the double track train tunnel, south of Kungsängen on the Kallhäll-Kungsängen line, where the presence of very blocky terrain complicated drilling and precluded seismic surveys (fig.1). The project consultant suggested a deeper tunnel, while the client decided upon a shallower depth to achieve a better track geometry. The actual bedrock surface proved to be very irregular during the construction phase and resulted in the costly necessity of part of the tunnel being cast wholly in concrete after extensive excavation from the ground surface.

Figure 1. Railway tunnel south of Kungsängen. Blocky till on top of an irregular bedrock surface.

In Södertälje, underground rock silos for coal were excavated with a height of 70 m, a diameter of 31 m with a circular cross section and tapered upwards in the roof. This geometry is more challenging and technically difficult than excavating vertical walls. Data from nearby oil storage caverns suggested that the rock conditions were good. During the actual rock excavation extensive graphite covered fracture surfaces were encountered in the upper part of the caverns. This resulted in a more complicated and costly excavation sequence than was expected, with more extensive rock support including pre-stressed anchors.

In the early 1970's in the Hästen district next to the NK-building in Stockholm, a 24 m deep excavation was made into the Stockholm esker (Stockholmsåsen). Soil and rock conditions deviated greatly from those indicated by the site investigation, which significantly complicated the foundation design and site work, leading to almost a doubling of the initial estimated foundation cost. The project is further discussed under section *Building foundations* below.

Preliminary investigation and design includes the inspection of any nearby existing underground facilities excavated in the bedrock. As many such facilities are subject to varying levels of security restrictions, it is often difficult and very time-consuming to get relevant information. However, mistakes or incorrect assumptions can have troublesome and expensive consequences. Some examples are listed below.

On plan maps, the same designation may occur for shaft or a building, i.e. a square with a cross. During the excavation of a tunnel between Bromma and Huvudsta probe drilling from the tunnel front was performed and one time a void was detected. The drilling had reached a large pump shaft. The tunnel, fortunately only intended as a sewer, could be backed a short distance and re-routed in a curve around the shaft. What the design had assumed to be an insignificant building turned out to be a critically located shaft.

In Beckomberga a smaller drainage tunnel was to be excavated in the bedrock. The drawings showed a dense array of probe holes for some hundred metres along the tunnel, indicating 3-5 m of rock cover. However, a check on the profile drawings showed different horizontal and vertical scales which had been incorrectly used. What appeared to be a dense drilling array with a maximum of 10 m bore spacing had in fact a spacing of 25 m between the holes with significant risk of depressions being missed in the rock between. Additional drilling was performed and showed, after all, that the tunnel could be carried out as planned.

The Saltsjö tunnel was planned to cross another tunnel at an elevation of about -50 m with a minimum of about 9 m of rock between the tunnels. The existing tunnel, from Sergels Torg/Brunkebergstorg down to Norrström, was assumed to have an even gradient. However, in reality, it had been carried out near Sergels Torg with a steep stepped profile and then a much gentler slope towards Norrström. This, in the combination with the Saltsjö tunnel being placed about 1.5 m too high, led to the actual distance between the two tunnels being 3 m. Remedial measures required the Saltsjö tunnel, that fortunately was in good rock, to locally have extra reinforcement installed as well as grouting to seal it as it was going to be water-filled and at atmospheric pressure.

In connection with the expansion of the Royal Library in the 1980's, consisting of two new rock caverns under existing buildings, next to an existing library in a concrete building constructed in a cavern, drilling investigations were carried out from the ground surface. The client set out the boreholes and drilling commenced. In one of the boreholes the rock was found a few metres down, but after about 50 cm of further drilling the drill-string dropped into a void, accompanied by a complete loss of circulation water. In reality, the 50 cm of "hard rock" was of course the concrete roof of the existing library.

ROCK STABILITY

The bedrock in the Stockholm area generally has a high bearing capacity and can withstand large vertical loads. Problems can occur when unfavourably oriented fractures result in reduced stability in a rock wall, a rock corner or a tunnel roof. Particularly if the fracture surfaces are coated with mica or graphite and if the fractures are water bearing.

A good example of the risk for instability was encountered in the foundation for the Åhléns building in Södermalm near Johanneshovbron. Here a space for a large garage was excavated by blasting down to a level about 5 m below the old Åhléns building that had about 6 floors and was built with a steel frame and plates on bedrock. During an inspection, on a Friday, of other rock works on the site, a 45-degree fracture was discovered in the base of the new excavation that passed up under an outlying rock corner supporting the building. At the time there remained a few smaller blasting rounds that were loaded near the corner. The blasting work was stopped but caused major protests. Late in the evening a very powerful steel beam support was mounted and anchored between the new excavation base and the rock corner. Once in place, the blasting could resume and the site could be closed for the weekend with a clear conscience.

Södra länken road tunnel has many crossing tunnels between ramps and main tunnels with bridges constructed in concrete. The standard bridge design drawing, approved by Vägverket, was a traditional frame bridge in concrete with concrete walls down to the underlying tunnel floor. The contractor quickly realized that the bridge ends could be laid directly on rock foundations instead, to save money. Already at the first bridge, the geological conditions were unfavourable and half the rock foundations failed along a fracture, this led to about 30 concrete workers, who were ready to work with the bridge, suddenly having nothing to do for several weeks. The bridges were subsequently constructed according to the traditional standard.

IN SITU ROCK STRESS AND DEFORMATION MEASUREMENTS

In the Stockholm area, problems with rock stress have rarely been noted during construction work. The existence of a favourable stress field is also supported by in situ stress measurements.

Situations where the stress field has been unfavourable have occurred, for example, for the excavation for the metro station Fridhemsplan at Kungsholmen performed in the 1950's. The station consists of two single-track tunnels in rock with approximately 10 m of rock cover above the tunnels. At the time of the excavation, cracking sounds, suggesting the occurrence of minor rock bursts and explosive stress release, were repeatedly heard after clean up of the rock surfaces. The rock was therefore supported with reinforced concrete arches throughout the station. The bedrock in the area is gneiss with subordinate granite. The gneissic fabric is steeply dipping with a strike at right angles to the station long axis. In the 1970's, a crossing metro tunnel, line 3, was then excavated with a new deeper part to the station, placed under but to the side of the existing tunnels. When a connecting tunnel was blasted between the old and new parts, it was found that the concrete arches in the older station were severely damaged. The concrete arches had fractures with up to 1 cm wide cracks and the rock above the arches had failed. It was found that planar fractures with chlorite and sometimes clay coatings occurred between the upper parts of the older station and the connecting tunnel. Further investigation determined that recoil from the blasting of the connecting tunnel had caused movements in flat rock slabs, which were pushed away and caused the damage. Extensive continuous measurements were performed of cracks in the arches and the distance between the walls of the old station. The measurements showed ongoing movements that gradually stopped. The rock roof and the rock walls of the older station and the rock towards the new station were reinforced with pre-stressed rock bolts and cable anchors. Grouting was also carried out targeting the fractures in the rock forming the tunnel roof.

Near Hälsingehöjden, Vasastaden, in a shallow lying ventilation tunnel to the metro, 'peeling' of thin rock slabs was noted and also clear block fall out behind a reinforcement net in the roof (fig.2). The rock consists of relatively fine-grained granite.

Figure 2. Ventilation tunnel at Hälsingehöjden. Failing of thin rock slabs and even evidence of rock bursts behind a reinforcement grid in the roof.

Deformation measurements are performed to assess stability in tunnels and rock cuts. In Älvsjö, deformation measurements using a special measurement tape and fixed measuring points were made in a shallow sewer tunnel, while the excavation proceeded through three depressions that had been reinforced with jet-grouted piles. Only a few millimetres of deformation were measured and bus traffic above could continue. The tunnel was later reinforced with a concrete lining along the relevant sections.

Södra länken tunnel to Hammarby Sjöstad has a large portal with a 30 m span and next to it another portal with a 20 m span. The rock cover is 5-8 m. Prior to blasting, the smaller portal position was first reinforced with long rock bolts, then a pilot tunnel was driven, followed by cautious blasting and intermediate reinforcement with bolts and shotcrete. Stability control was carried out mainly by looking for cracks in the applied shotcrete. For the larger portal, rock mechanical stability calculations were performed. Two parallel pilot tunnels were driven for a distance of 20 m with a spacing of 10 m and leaving 3 m of rock remaining to reach the final excavation contour, prior to the full excavation of the portal. Before any excavation, reinforcement was installed around the planned portal consisting of two rows of 6-8 m long rockbolts with plates and a 70mm thick layer of fibre reinforced shotcrete. Above the portal, rows of vertical grouted rock bolts were installed to within 0.5m of the tunnel crown. For control, prior to the excavation of the main portal, extensometers and reflectors were installed to allow convergence measurements to be made. Prior to excavation, the rock was horizontally drilled and grouted, around the portal face, to a distance of about 20 m into the rock mass. The excavation followed with pilot tunnels widened to the final contour for approximately 10 m in and then in 5-meter stages with reinforcement of the outer walls. Subsequently, the roof of each pilot tunnel was excavated in a similar way to the final contour and reinforced with 400 mm of fibre reinforced shotcrete and bolts. The middle pillar was then blasted in short stages. Reinforcement was subsequently installed consisting of 400 mm of shotcrete for the first 10 m from the entrance, after which 200 mm was installed, along with bolting. The pillar nose to the connecting 20 m wide tunnel was strongly reinforced, before excavating the lower bench in the main tunnel floor to achieve the final design contour.

The deformation measurements were difficult to interpret, but it has been estimated that the rock at the portal has sunk by 5-6 mm while the rock moved outwards by 15-17 mm. The rock above the tunnel fractured in connection with the excavation work and has been grouted several times due to water leakage. Fracturing has been observed in the overlying outcrops and in the shotcrete in the tunnel roof. The final construction solution for leakage and ice control was that the roof and walls were completely covered with an insulating material in to the pillar nose, about 20 m in from the portal (fig. 3).

Figure 3. The so-called Örsta vault in the Södra länken tunnel.

The existing Käppala water treatment facility was significantly expanded in 1994-1998. The works consisted of seven new rock caverns, connecting tunnels and other ancillary excavations with a total excavation volume of approximately 450,000 m^3. The bedrock consists of veined gneiss with a near east-west strike with subordinate granite and amphibolites. Five of the caverns are parallel to previous caverns in the facility with an approximate northeast-southwest orientation, while two caverns are located along the short ends of the new and old caverns. The rock conditions in the earlier plant and for the new is generally excellent, but in one of the differently oriented rooms, closest to Gåshagaleden, worse rock conditions were seen in the roof, requiring temporary reinforcement and stronger permanent rock support. Soon after commissioning of the plant, instabilities were observed in the cavern roof. Additional reinforcement was installed above the filter basins and equipment for deformation monitoring was installed. No further deformation was noted. The cause of the instability may have been due to the fact that the cavern roof is at a relatively shallow depth, towards the edge of a larger overlying rock mass block, with perhaps a reduced horizontal stress component in the poorer rock volume.

When the Söderleden road cut was built-over in the 1990s, heavy loading resulted from the new concrete cover slab and new overlying buildings. Convergence measurements were carried out in an underlying existing railway tunnel, constructed in the 1870s, where additional reinforced shotcrete arches had been installed. A few millimetres settlement was recorded.

ROAD AND RAILWAY CUTS

Older rock cuts (road or railway cuttings) are interesting, for example, the one from 1914 along Millesgården on Lidingö. During the restoration of Lidingöbanan in 1986, inspection, scaling and rockbolting of the rock was carried out in the usual way. High up in the cutting, above the track, there was a columnar rock block with a height of 5-6 m and a diameter of 1-5 m. Its stability was measured regularly, but the process was both risky and difficult since it involved climbing down from above. A golden opportunity to remove this constant threat to traffic occurred during the restoration, which also included removal of the electrical cables and track. A large and dramatic rock fall was deliberately triggered and the resulting mass transported away. What was not known was that the track area along just this stretch had been involved in a slope failure a long time ago. Knowledge of the earlier slope failure probably would have not changed the decision to take down the block, but of course it would have been carried out in smaller, more carefully controlled, stages.

The rock cuts along Söder Mälarstrand and Stadsgården have been excavated over very many years, the work often handed over from father to son. Much was performed in the 19th century by hand-held drilling with one man holding the drill and two or three men hitting the drill with sledgehammers. Although parts of the cuts are close to one of Stockholm's largest faults, with heavily altered rock and high fracture frequency, the cuts are surprisingly stable, partly due to the careful method of excavation, but maybe also due the very high density of rock bolts installed!

In Årstadal, Liljeholmen, three large rock caverns were excavated for storing packaged ice cream, and food in the 1960's. Access to the rooms was through straight, approximately 30m long, tunnels. In the early 1970's, the rock around the tunnels was blasted in two benches, up to about 8 m from the cavern ends. The new rock cutting, with a height of about 15m, had the same orientation as the strike direction of the vertical gneissic fabric, in principle east-west, which resulted in large, unstable rock slabs in the cutting walls. The rock excavation had followed the planned time schedule, but no rock reinforcements had been installed! All the drilling for rockbolting over a height of 5 m had to be carried out from a sky-lift because drilling with a larger machine had not been performed during the upper bench stage. The temperature in the ice cream storage cavern was minus 26ºC, and after about 10 years the 0ºC isotherm had spread into the rock for about 6 m from the room wall. This meant that the temperature in parts of the surface of the new rock slope was close to zero degrees but was sub zero farther in. Consequently rockbolting in this area of the cutting was carried out by filling the bolt holes with hot cement, after which power was connected to inserted steel reinforcement bolts for heating during the hardening period.

At Värmdöleden, a rock slide occurred onto the roadway in the 1970's. The cause of the slide was considered to be water in the rock fractures in combination with freezing. To improve drainage in the rock behind the cutting, a niche was blasted into the face from ground level, after which long holes were drilled from the niche upwards to a few meters below the surface. When contact with water bearing fractures was achieved the niche was insulated to minimize the risk of freezing.

Rock cuts for roads and foundation excavations have in some cases become unstable due to incorrect drilling and blasting, which has resulted in high maintenance costs and unnecessary safety risks. Sometimes the contract has specified closely spaced drilling in the contour and perhaps in a secondary auxiliary line, while the distance to the next hole line series can be several metres. Often it has been so specified for cost reasons. In reality this leads to the costly, closely spaced contour drilling, losing its intended effect, and the remaining bedrock is fractured and potentially unstable, resulting in the need for additional reinforcement and increased future maintenance work. The contract may also have only allowed for a single price per cubic metre of rock excavation, with minimum regard to the environment, inevitably leading to less carefully controlled blasting and unnecessary fracture damage to the remaining rock. The contract specification and site inspection should therefore be performed by an experienced blasting engineer.

FOUNDATIONS

Buildings in central Stockholm have since the late 1940's often been constructed with one or more basements down to or below the natural bedrock surface. In order to avoid risk of water leakage or settlements in the surrounding area, the rock is grouted and sealed before, during or after excavation. Sealed concrete outer walls are cast from the rock floor and up to above the groundwater level. Depending on the quality of the rock, there is a lot of variation in the need for grouting and the in situ groundwater pressure also plays an important role. Compare, for example, the department store Åhléns, in Gripen district, on Klarabergsgatan with a foundation level of about -5 m and the nearby, former PUB department store, in Skotten district, with a blasted bedrock foundation level of -19 m.

In the 1970's, perhaps the most exciting foundation in Stockholm so far was carried out, with diaphragm slurry walls in the Hästen district next to the NK building. The depth to bedrock varies between 12 and 24 m below the street level and the groundwater level is 3-4 m below the same level. The diaphragm wall method was new to Sweden and involved a deep narrow slot or trench being excavated in the soil down to the rock surface. The rock surface was then chiselled horizontally. The trench was kept open during the whole process by keeping it full with a thixotropic liquid of heavy bentonite to prevent collapse and so that a reinforcement cage could be lowered to the chiselled surface. Subsequently, concrete was poured via a pipe from the bottom upwards. The slit wall was cast in 4.5-7.5 m wide panels with lengths up to about 24 m. 59 panels with a total area of 5500 m^2 were made with an 80 cm thickness. According to the documents, the soil layers included fill as well as distal deposits from the Stockholm esker with, from the top, clay, silty sand and sandy gravel against the rock surface, along with occasional single rock blocks. The bedrock was described as granite, gneiss and pegmatite of fairly good quality. Diagonally over the plot the bedrock was assumed to form a depression where the rock would be of lower quality.

From the beginning it was found that the excavation encountered harder material about 3 m above the assumed bedrock surface that required the use of hydraulic chisel machines. When about half of the 59 panels were in place, contact grouting between the bottom of the wall and the rock commenced, with large amounts of grout injected in some places without achieving a seal. The results from the grouting and tests were first interpreted as indicating that the wall did not stand on bedrock but rather on packed rock blocks. After further investigations, it was assumed that there was a thick layer of altered weaker rock overlying the solid rock. When the large plot was surrounded by diaphragm walls, excavation commenced but was interrupted when increasing amounts of water came into the excavation. Since it was suspected that there was leakage past the grout seal, a decision was made to suspend excavation and pumping and instead freeze the soil outside the suspected sections to stop the leakage. The pumping was interrupted so as not to have flowing water during the freezing process. This meant that for a few months the whole plot was flooded. After freezing, additional grouting was carried out and then excavation down to the bedrock across the entire plot proceeded with backward anchoring of the diaphragm concrete walls using 650 temporary anchors. Approximately 9 months after the initial leakage issue at the base of the original diaphragm wall, it was found after excavation that all the panels stood on or in bedrock but that the rock itself was locally strongly altered. No till was found on the plot. Supplementary walls were cast on the inside of the existing ones, grouted and designed for the expected uplift pressures.

After finishing work in the Hästen district, it was noted that the layer closest to the bedrock surface mainly consisted of a gravely, rocky soil with a thickness of up to 10 m. The amount of blocks varied between 2 to 15 per m^3. According to the SGU mapping, the material represents a branch of the Stockholm esker. Large portions of the plot are covered by so-called "rösberg", fractured and weathered rock with a thickness of up to several metres.

The Stockholm esker is connected to Saltsjön so there is a ready access to groundwater in Hästen district. The water leakage into the plot was monitored with piezometers during 1971 when most of the curtain grouting and a minor part of the contact grouting were carried out. The leakage into the 6000 m^2 plot was measured after 2 months of test pumping with steady state conditions to be approximately 150 l/min, with the water surface being lowered to a level of -10 m. After further grouting, the leakage was measured as being about 70 l/min, and without lowering of the groundwater level outside of the plot. After a subsequent increase in leakage during 1974 to 1975, it was decided to undertake supplementary grouting, mainly at the panels' contact with the rock. Afterwards leakage was then measured at about 40 l/min, which is approximately 10 l/min less than what was then specified for this type of construction design, namely 0.008 $l/min/m^2$.

Some additional practical experiences from constructing foundations on rock that can be mentioned are the importance of horizontal fractures. During rock excavation at Lidingö, the contractor drilled the charge holes across the entire plot before blasting. Then, probably at the very first round, the rock moved on-mass slightly laterally slightly, above a sub-horizontal fracture, so that the other vertical charge holes were offset over the fracture and could not be loaded. All the holes had to be re-drilled.

Another example is from rock excavation near and above an underground metro cavern at Hornstull. The excavation was designed with expanding cement, so called 'snail dynamite', to avoid vibrations. The area was drilled with vertical blast holes filled with liquid 'expansion cement'. The entire area, plus a newly renovated neighbouring house, was subsequently lifted as the cement had spread into sub-horizontal fractures and expanded.

Any remaining reinforcement bolts left in rock after the excavation for a neighbouring area, can cause both vibration and excavation problems in a subsequent rock excavation of a new site. Temporary rockbolts may need to be installed in excavation walls, but should be removed when the building is complete. Temporarily bolted sections may need to be permanently supported, but non-essential bolts, if left, can cause extra costs for a new site.

ROCK SLOPE AND TUNNEL FAILURES

In general, rock falls along cuttings and tunnels have been rare in the Stockholm area, largely due to the mostly good rock conditions. However, several cases have occurred.

One of the most discussed failures occurred in November 1965 when excavating a tunnel perpendicular to and under Södra Hammarbyhamnen near Skanstull. There was a tunnel collapse and two workers were trapped, but managed to reach an air pocket at the tunnel front at Ringvägen. There was a lot of publicity and a special drilling machine from Germany was brought in. They drilled down into the tunnel and managed to supply food and set up telephone contact with the trapped workers. They were later rescued by excavating from an associated shaft on Södermalm. It was first assumed that soil and water from Södra Hammarbyhamnen had penetrated the tunnel, but it turned out that the failure occurred in the tunnel's second excavation front on the other side of Södra Hammarbyhamnen at Mårtensdal. An extensive crater formed at the surface where large transformers and minor buildings had toppled over (fig.4). The evening before the collapse, the tunnel had little or no bedrock cover and penetrated a soil mass at about -22 m. After extensive excavation at the collapse point from the Södermalm site, a concrete plug was cast in the tunnel about 160 m away from the point of collapse, and a new tunnel was driven, following a steep down gradient to a level 10 m below the initially planned level, where the tunnel continued below and to the side of the collapse site.

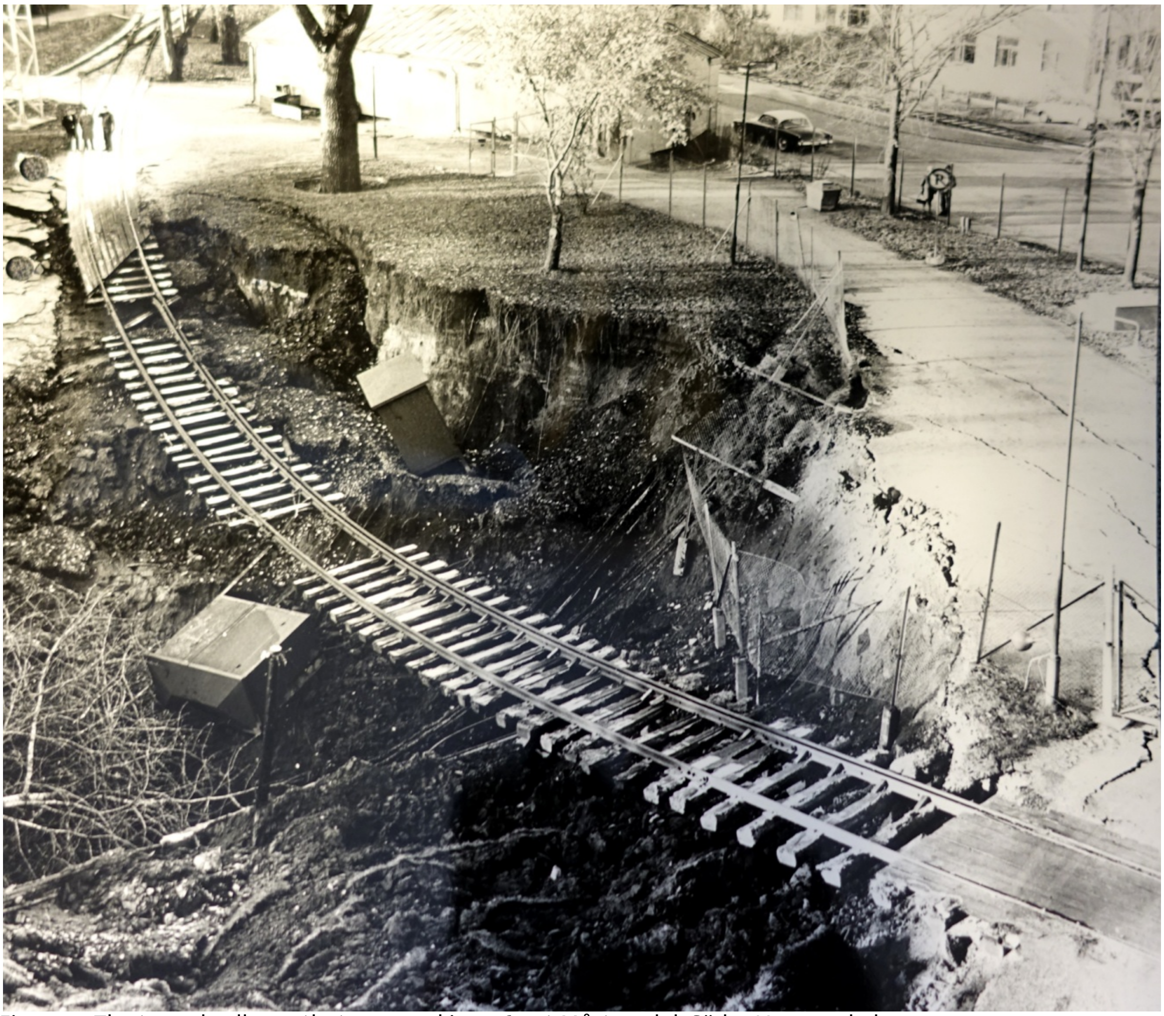

Figure 4. The tunnel collapse that occurred in 1965 at Mårtensdal, Södra Hammarbyhamnen.

From Södra Hammarbyhamnen and southwards, soil and rock probing was carried out as far as southern Hammarbyvägen. Then a stretch of about 400 m had been assumed to have sufficient rock cover and it was after about 250 m that the collapse occurred in a deep depression in the bedrock. The depression was oriented east-west and was judged to have been encountered in the foundation of the southern part of Johanneshov's bridge, where bedrock was found 15-20 m below the water surface and piles were drilled 5-6 m down into poorer quality rock, before sufficient bearing capacity was obtained.

In Masmo a collapse occurred in an existing, smaller sewage tunnel due to poor rock conditions.

A collapse occurred in 1959 in a conduit tunnel under the Hammarby canal, opposite Danviksklippan, generating a small crater rising on the north side of the canal and the tunnel was reportedly filled with glacial clay.

Minor failures have occurred a few times in tunnels due to water being trapped with increasing pressure behind applied shotcrete. Mostly, only the shotcrete has failed and fallen away.

At Kungens kurva, next to the present Heron City, a larger failure occurred at the excavation of a rock cut before the construction of Heron City. The failure occurred along a sloping fracture plane from the rock surface and into the blasted excavation area.

In Årstadal, near Liljeholmen, a failure occurred in 1972 when excavating rock to improve access to existing rock caverns (fig.5). An approximately 2 m thick and 6 m wide vertical slab of rock detached from the rock slope and slid down in front of the tunnel portal completely blocking it.

Before the failure, distribution vehicles drove frequently in and out of the tunnel through the portal. The reason for the failure was partly the presence of a vertical fracture coated with graphite and partly that the horizontal pressure in the rock had been removed by the new rock excavation.

Figure 5. The rock slope failure at Glace Bolaget AB in Årstadal 1972.

In a 30,000 m^3 storage cavern in Fittja for heated oil, a failure occurred in and near the vertical shaft down to the cavern in 1972, with the rock detaching from the lower shaft edge and blocking the inlet and outlet pipes. After reinforcement of the shaft from a suspended platform and pumping of all heated oil, the rock roof could be inspected from a raft out on the water filled room. It was noted that most of the rockbolts were inserted in too large holes, since the perfobolts and grout system available at the time could not fill the holes. Therefore the reinforcement effect was low. Many blocks hung on the bolts or sat loose in the cavern roof. In the area where the larger failure occurred, the stability sensitive part where the shaft enters the cavern, there were very few bolts installed. It was decided to change the heating system in the cavern from base water heating to preheated oil, as the entire rock roof would otherwise have had to be strengthened and in the midst of the oil crisis, a ship with an oil delivery was also expected. In a scaled and newly reinforced 6 m wide strip along the middle of the roof, a delivery pipeline was suspended from long pre-stressed anchors and two vertical pipes were led to the bottom of the cavern and anchored.

GROUNDWATER, TUNNEL GROUTING AND GEOENERGY DRILLING

In Stockholm there are extensive clay deposits with confined groundwater within sandy layers near the rock surface. Examples are Karlaplan, Mariatorget and Lindhagensplan.

When two different tunnels, with different owners, were being excavated at Karlaplan, a 6 m fall in the groundwater level occurred within approximately one week. Water stopped leaking into the tunnels but ground settlements were rapidly developing. The sidewalks were disrupted and boilers hung from their pipes in cellars. The tunnels were sealed and artificial infiltration was started. However, there were lengthy legal negotiations and extensive restoration work was required (fig.6 and 7, from Byggnadsgeoligi, Staden och grundvattnet).

Figure 6. Karlaplan area 1964. Subsidence of the street adjacent to a building supported on wooden piles.

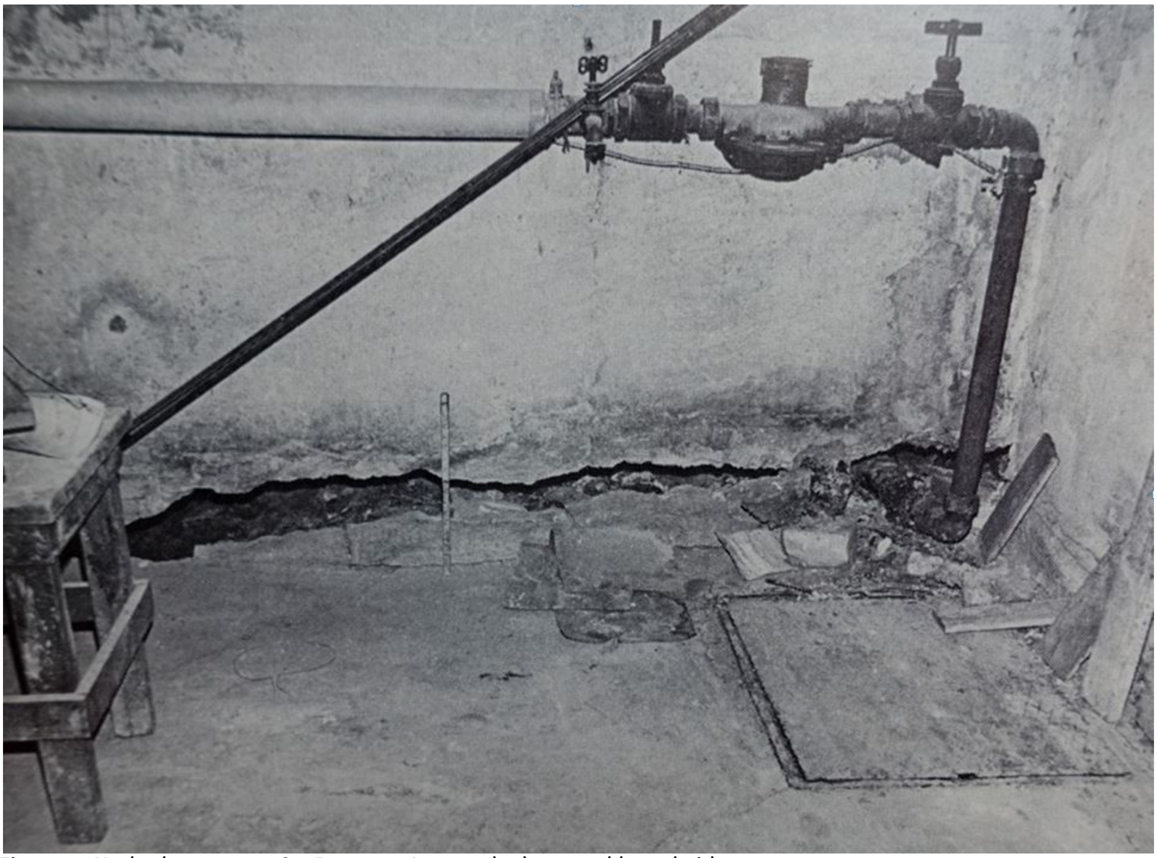

Figure 7. Karlaplan area 1964. Basement severely damaged by subsidence.

At Mariatorget there was a metro tunnel in the rock which, with its associated leakage, lowered the groundwater level, so that the ends of wooden piles used in the foundations to older buildings were above the groundwater surface and the piles began to rot. Repairs due to the settlements were carried out but some properties had to be demolished.

In tunneling in urban areas, the inclusion of control measurement ponds are specified during excavation to see whether the sealing efforts are sufficient or need to be increased in order to meet the specified leakage restrictions. The leakage specifications themselves maybe misjudged so that surrounding groundwater levels drop despite meeting the required criteria. Remedial work may require temporary infiltration, often from the tunnel, until the sealing has been improved or if it is not successful, infiltration may need to be permanent. Both the timely installation of control ponds and sufficient grouting can be challenging to implement in a project due to time and economic reasons. They need to be given a high priority in the contract documents and associated penalties if they are not performed.

Geoenergy boreholes are being carried out more and more often and now not only for individual houses but also for larger residential buildings. By law, such wells must be registered with SGU, but this does not always happen. Wells shall be drilled within their owners plot and may be several hundred metres long. They are always dependent on groundwater, so groundwater lowering associated with the construction of a tunnel can be very costly. As it is difficult to get tunnels sufficiently sealed, areas with geoenergy boreholes should be avoided if possible.

ICE PROBLEMS IN TUNNELS AND ROCK CUTS

Problems with ice occur anywhere where water exits the rock during the winter period (fig.8). An old misconception is that ice build up ceases when the ice has sealed the leak, which it does not. Depending on the location of ice formation, it implies greater or lesser risks and associated maintenance work. Particularly sensitive are railway and road tunnels or rock cuts adjacent to traffic routes.

Many attempts have been made to reduce ice formation, of which one of course is to seal the leak by grouting. Often this does not completely succeed and minor leaks remain, which in time can give rise to large ice build up. If the seal is successful locally, the result will often be that the water seeks new paths and new ice build up points develop as a consequence. In Stockholm, hot air curtains have been tested at a shorter rock tunnel, but traffic brings with it large amounts of cold air and too much disruption for it to work. Electrically heated drains have been tried as well as flushable drains. In some places, where it has been possible, gates have been fitted, so that the air is still and the in situ temperature of the rock will reduce or eliminate ice formation.

During the 1960-1990's, drainage was often installed with a thin, narrow mineral wool strip covered with shotcrete. Mostly, the construction worked poorly, froze and cracked sometimes generating its own fallouts. Nowadays, at least 1 m wide vertical strips of extruded polyethylene, like a foam blanket or mattress, are set up against the rock, where the water can flow behind to the ground. The thickness of the drainage protection is determined by the expected temperature and length of cold periods. In traffic tunnels the air flow due to the traffic must also be taken into account. In some tunnels air is taken for cooling and they are more sensitive to ice build up and can almost be completely blocked by ice.

Figure 8. Ice build up in a tunnel.

In the Finnberg tunnel there was major ice formation especially at the upper tunnel portal (fig.9). To solve the ice problems, flexible insulating sheets of extruded polyethylene were mounted in the roof and walls at the portal and for a distance into the tunnel (fig.10).

Figure 9. Ice formation in the Finnberg tunnel before remedial measures.

Figure 10. Sheets of extruded polyethylene being installed in the roof and walls at the portal and for a distance into the Finnberg tunnel.

SPECIAL EXCAVATION METHODS AND SOUND TRANSMISSION IN ROCK

In different contexts new methods of rock excavation are tested. Large-scale examples in Stockholm have been full-face tunnel drilling, carried out with the same TBM (Tunnel Boring Machine) namely the Saltsjö tunnel and the Ormen tunnel in the late 1980s and early 1990s.

In the case of the Ormen tunnel, the machine had been modified so that pre-excavation grouting of the rock could also be carried out at the tunnel floor. Both the Saltsjö (fig.11) and Ormen tunnels have a diameter of 3.5 m and a length of 7 km and 4 km, respectively. The tunnels have been drilled under Stockholm at levels between about -20 and -50 m. The Saltsjö tunnel is filled with water at atmospheric pressure, while the Ormen tunnel is for short-term wastewater storage and is therefore relatively empty for long periods. TBM excavation was tested with a few shorter tunnels in the 1970's in Stockholm, but with too weak machines for the hard rock. In the Saltsjö tunnel, no major weakness zones in the bedrock were intercepted, while the Ormen tunnel penetrated deformation zones under Humlegården, a part of the fault under Birger Jarlsgatan. The rock reinforcement requirements in the tunnels were extremely small and the pre-grouting was not very extensive. One problem with the Saltsjö tunnel was steering the machine, which caused unplanned lateral deviations of 25-30 m and sometimes vertical deviations of 1-2 m. The noise level was low compared to blasting, but still meant that the machine was stopped a few minutes before a performance at the Operan when the machine was 45m below the theatre.

Figure 11. The Saltsjö tunnel

In the past, slit drilling was sometimes used along the outermost contour of an open excavation in rock in order to reduce vibrations affecting the neighbouring property. It required that the slit be made completely open to reduce vibrations, but often there was water or stones in the slot which made the difficult and expensive drilling work more or less worthless. Recently, wire sawing of rock as an excavation method has been used more and more with good results and generates minimal disturbance (fig.12). The method is used for all possible applications such as shafts, walls, etc.

Figure 12. Wire sawing is used more often to prevent vibrations propagating and adversely affecting existing buildings.

Raise-boring as an excavation technique is used quite frequently for ventilation and other vertical shafts. The method involves a borehole (pilot hole) being drilled down to an underlying space, for example a tunnel, thereafter a much larger borehole crown (a reamer-head suitable for the required shaft diameter) is placed on the drill rod, after which the drilling direction is reversed being raised back towards the machine, with the waste rock falling downwards (fig.13). It is important to consider the need for any pre grouting before excavation and be aware that installation of rock support in a raised bore with poor rock conditions can be problematic.

Figure 13. Raise-bored ventilation shaft.

FIRE IN TUNNELS

Fortunately, fire in tunnels is a rare event, but it has occurred in the Stockholm area.

A fire broke out in an energy tunnel in operation in Akalla. The cause may have been a short circuit in the electrical system. The fire resulted in the shotcrete and thin layers of the underlying rock in the tunnel roof, loosening and partly falling into the tunnel. Scaling was carried out to remove the loose rock and shotcrete and a new layer of reinforced shotcrete was applied. A fire occurred in a smaller underground shelter in Ulvsunda that had no reinforcement in the roof, and here also flaking and peeling of the rock mass occurred. Such a process can also occur if a fire is set on a rock outcrop at the ground surface.

SAFETY AND SECURITY ZONES

Tunnels and caverns in the Stockholm area have safety zones of 50-100 m and protection zones of 2- 10 m depending on the type of tunnel. The purpose of the protection and safety zones is to protect the tunnel from any disturbance due to events such as nearby soil or rock excavation, piling, geoenergy drilling or the like. Contact needs to be established with the respective tunnel owners in the planning stage for new projects.

CONTRACTS, PROCUREMENT AND QUALITY CONTROL

There are several types of construction contract forms. Each has their pros and cons. Experience shows that, regardless of the type of contract, the client must ensure full control over the entire execution of the contract and ensure that all possible eventualities are considered and priced for in the contract; that penalties are sufficiently large to discourage, for example, delays; that the guarantee commitments are realistic and that 'as-built' documents, showing the actual final construction, are always produced and delivered. An item that is often overlooked is winter conditions and the additional costs they may incur. The above sounds straightforward, but since it is always the project economy that governs, despite all the quality control documents, it is a challenging task for the client to constantly maintain full control.

Examples of over interpretation of instructions exist. When the water tunnel from Botkyrka to Himmerfjärden was built in the early 1970's, the client specified that scaling of the rock surface (removal of loose sitting rock) should continue until a solid rock surface was reached and this was applied even in the case when weakness zones or poor rock conditions were encountered. As a consequence, the tunnel at such zones had metre deep side and roof niches, which were then supported with thick reinforced shotcrete. Even completely stable in situ rock slabs at the foot of the tunnel walls that were later to be covered by concrete, were ordered to be removed. In addition to a legal process associated with the significant cost increase, which the contractor lost, the stability of the tunnel was not enhanced.

The significance of the correct design and performance is shown by a contract for hanging heavy pipes from the tunnel roof with bolts in the rock. The contractor claimed that testing of the bolts was unnecessary, since they were installed correctly. Test loading was ordered with regard to what would happen if the pipes fell down during operation. A number of bolts failed and had to be re-installed - they were then approved after a new test run (fig.14).

Figure 14. Heavy pipes suspended from the tunnel roof. Load testing was necessary to ensure the capacity of the rock anchors.

INSPECTIONS AND READING TIPS

For safety reasons, inspection of tunnels and rock caverns should not be performed by a lone individual but in pairs or more. Each tunnel owner can have their safety regulations, which must be checked and followed. In tunnels like the metro system, it is a requirement to have an accompanying qualified safety/security guard. Water and sewer tunnels should be aired and inspection staff should bring oxygen canisters, masks and have waist-high watertight waders. Contact with personnel on the ground surface should be established and an estimated time of inspection must have been agreed. The oxygen level may be low in sewer tunnels. The lighting must consist of at least two completely independent lighting systems to allow for back-up if one should fail. In the case of ongoing projects and site works, contact with the site supervisor must be made before access.

For better knowledge of how the Stockholm metro system has been designed and constructed, reference to the following are suggested: Technical description of the Stockholm subway, Kungl.

Boktrykkeriet P. A. Norstedts Stockholm 1957, Stockholm Tunnelbanan 1964, A Technical Description, SVR's Förlags AB Stockholm, Kristianstads Länstryckeri Kristianstad 1964, and The Stockholm Underground '75, A technical description, issued by Stockholm County Council, August 1976.

GEOLOGICAL CHALLENGES

As noted above, tunnelling in the Stockholm area generally has encountered good rock quality conditions over large areas with only relatively small weakness zones. However, the large east-west weakness zone along Stadsgården and Söder Mälarstrand has not yet been penetrated by a rock tunnel, although drilling has been carried out for the Kungsträdgården-Nacka subway extension, for the Östlig förbindelse ('Eastern Connection') between Kvarnholmen and Djurgården, for an energy tunnel and for any future metro tunnel parallel to Västerbron. A similar or perhaps the same zone has been investigated between Smedslätten, Brommalandet and Hägersten. The survey results show depth to the bedrock of 40-90 m, and poor quality rock to an extent not previously encountered by infrastructure projects in the Stockholm area.

APPENDIX 2. ENGINEERING GEOLOGICAL EXPERIENCE FROM STOCKHOLM INFRASTRUCTURE PROJECTS

This appendix describes the experiences of infrastructure projects in the Stockholm area. For further reading on engineering geology related to Stockholm, see for example Morfeldt & Persson (1997) and Persson (1998).

Engineering geological experience from Stockholm infrastructure projects

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November, 2017

Comparison of a wire-sawn and blasted rock mass.
Photo: Jörgen Theander, Golder Ass.

Contents

INTRODUCTION

Geological conditions in general, and in particular geological brittle structures, such as faults and fractures, but also foliation planes, where mica has been completely or partially altered to clay, can affect the stability of rock excavations and result in extensive costly reinforcement work. Inadequate knowledge concerning the position, orientation, and condition of such structures relative to a designed facility usually results in increased costs. Previous experiences of the impact of geological structures on rock stability can be used to lower the risk of unforeseen slope failures and other undesirable events.

The following is a summary of experiences, partly the author's own, partly from current and former employees at the consultancy firm Golder Associates AB. The projects mainly comprise open rock excavations with a slope height of up to about 10 m. Most of the projects are located within or near the city of Stockholm with the exception of the train tunnel at Arlanda airport.

STRESS RELIEF (SHEET) JOINTS

Fractures, whose orientation follows the rock surface, and which are believed to have been formed due to stress release associated with the latest deglaciation, can often be seen in open rock cuts, which in most cases are less than about 10 m deep.

In areas north of Stockholm, e.g. Täby and Ulvsunda, there are stress relief fractures filled with some centimetres of sand or clay. In connection with blasting in Täby, unforeseen damage occurred to the Vallentuna granite when explosive gases penetrated a planar stress relief joint located above the groundwater surface, lifting a metre thick sheet of surface rock. In this way the rock was completely broken up (Figure 1), which meant that several blasting holes had to be re-drilled.

Stress relief joints with a much more irregular shape and clay infillings (Figure 2) were also found in sedimentary gneiss in Ulvsunda, as well as in gneiss at Liljeholmen, where the flat-lying fractures have an irregular shape and even partially follow the steep gneissic foliation (Figure 3). On the other hand, in a sedimentary gneiss at Smista Allé' there are persistent stress relief fractures that crosscut the most dominant foliation without being significantly affected by it (Figure 6).

Figure 1. Täby. Left: drilling of contour holes next to a sheet pile wall. Right: in the upper half of the photo, bedrock unintentionally shattered by blasting gases from a round 4m away can be seen. Photo: Lars M Hansen, Golder.

Figure 2. Ulvsunda. Sedimentary gneiss with irregular stress relief joints at 10 m depth below the rock surface, filled with some cm of sediment. Photo: Lars Bergkvist, Golder.

FRACTURED BEDROCK SUFACE

A heavily fractured bedrock surface occurs here and there in the Stockholm area, often under several metres of soil cover, as is the case in for example around the Stockholm Central Station. Fractured, blocky bedrock of this type is rarely found in areas where the bedrock is exposed at the ground surface or where there is only thin soil cover since the inland ice has eroded away any loose rock material. When excavating bedrock it is necessary to consider the need to remove any loose rock (scaling) as well as anchoring and grouting. When sealing surface rock at the base of a diaphragm wall trench, a packer must be placed in the overlying soil, which is first grouted, and requires carefully specified packer pressures to avoid cracking of the injected soil.

Figure 3. Liljeholmen. Wire sawn rock cut with irregular stress relief joints and steeply dipping gneissic banding/foliation. The rock cut lies above an existing tunnel; both horizontal and vertical wire sawing has been performed to comply with vibration restrictions due to a nearby elevator shaft. Photo: Anja Olsson, Golder.

EXISTING UNDERGROUND FACILITIES

A funicular railway runs in a tunnel from Liljeholmen underground station. Above the tunnel a new road and houses are being constructed. In order that specified vibration limits should not be exceeded and to avoid damage to electrical equipment in the existing elevator shaft, the road cut was wire sawn instead of blasted (Figure 3). The rock, which is micaceous gneiss, is prone to split along the steep foliation of the mica-rich planes.

PLANE FAILURE, WEDGE FAILURE AND TOPPLING

Planar structures, especially fault planes and surfaces with mica or clay minerals, but also foliation in general and planar fractures, can cause extensive slope failures with very serious consequences if their location and orientation are unfavourable relative to a rock cut, especially if the roughness of the fracture surface and mineral coating/filling results in reduced friction.

Plane Failure

A planar structure oriented parallel to a rock cut, or at a slight angle to it, may cause so-called plane failure.

Wedge Failure

Two planes whose line of intersection trends towards an open excavation can lead to so-called wedge failure.

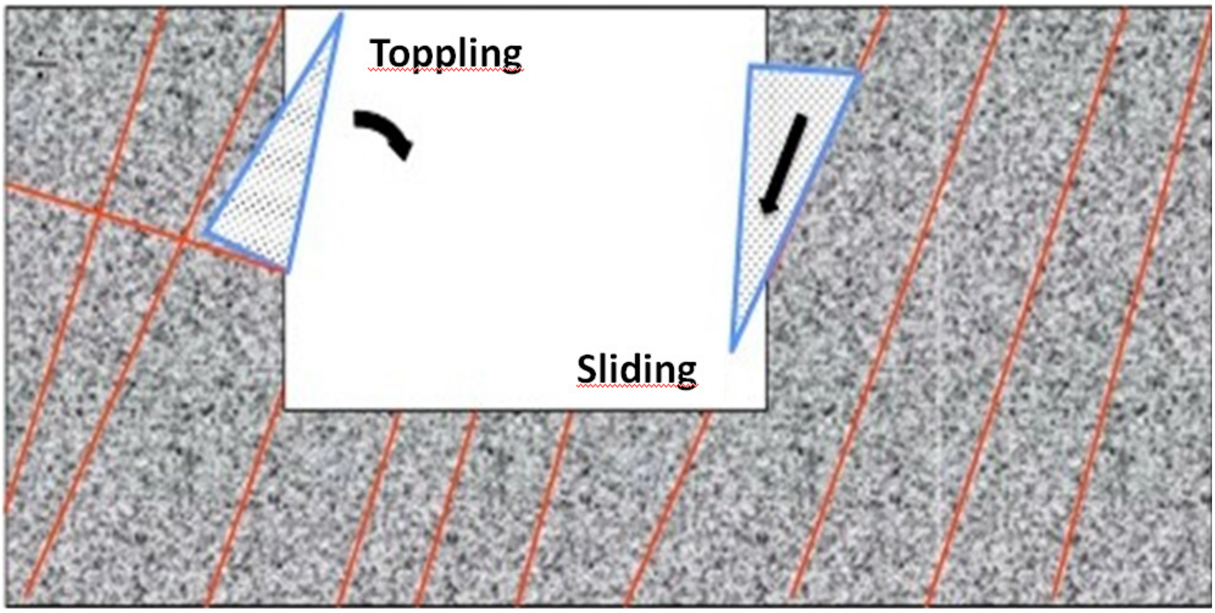

Figure 4. Section of an excavation in rock showing toppling on the left and sliding on the right.

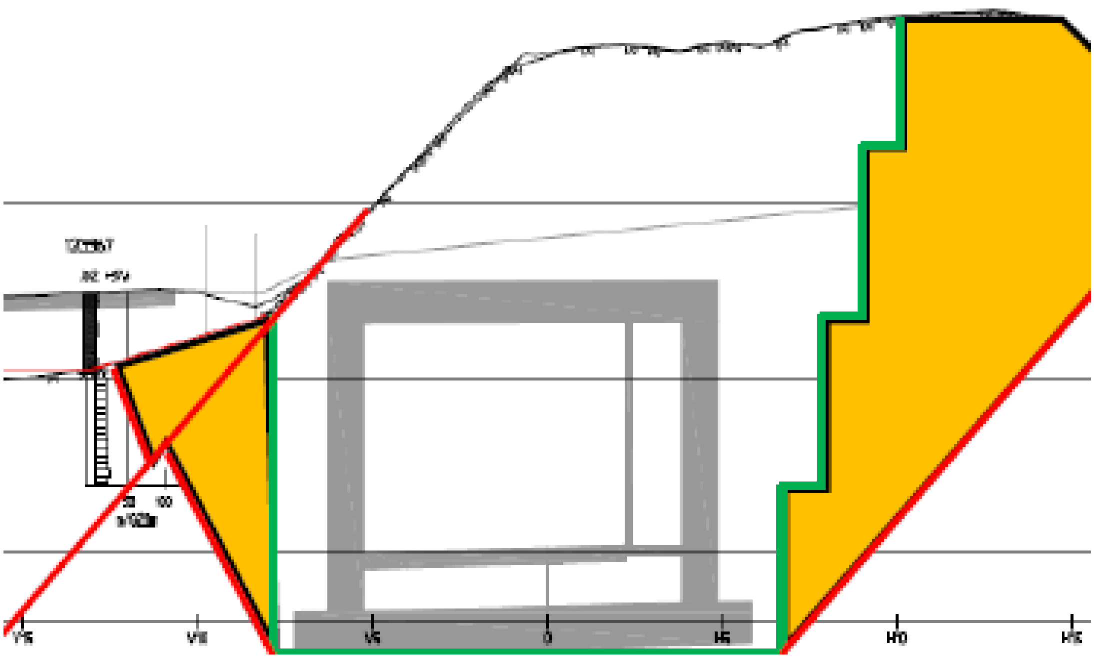

Figure 5. Section of an excavation in rock for a concrete tunnel showing how the potential slide volume rapidly increases with the height/depth of the cut. On the left side, toppling failure may also occur.

Toppling

Plane failure and wedge failure, both forms of slide movement, may occur on one side of an excavation, while on the opposing side there may be toppling failure, even though there are the same planar fractures (Figure 4). The volume of a plane or wedge slide is proportional to the square of the slope height (Figure 5).

The bedrock in the area of the Kungens Kurva, south of Stockholm, consists of folded and faulted metagreywacke, and there are steep folds with dips to the east, an east-west oriented shear zone, as well as foliation surfaces with coatings of illite, chlorite and other clay minerals. The orientation of these structures varies from approximately north-south at Heron City to north-east at Smista Allé, and dip 40-60° to the east and south-east respectively. In the area can be seen several examples of rock slides, one at Smista Allé (Figure 6) and the largest at Heron City, where several planes together form a slide scar, which is clearly visible from Månskärsvägen and from the adjacent multi-storey car park (Figure 7).

Figure 6. Rock cutting at Smista Allé. The rock cutting is about 3 m high. Due to sliding along a foliation surface, the slope of the face has become flatter than the drilled contour design, which was vertical. The limited face height resulted in a manageable outcome, and the slope is now stable as it now is compatible with the existing rock structure. Photo: Lars Bergkvist, Golder.

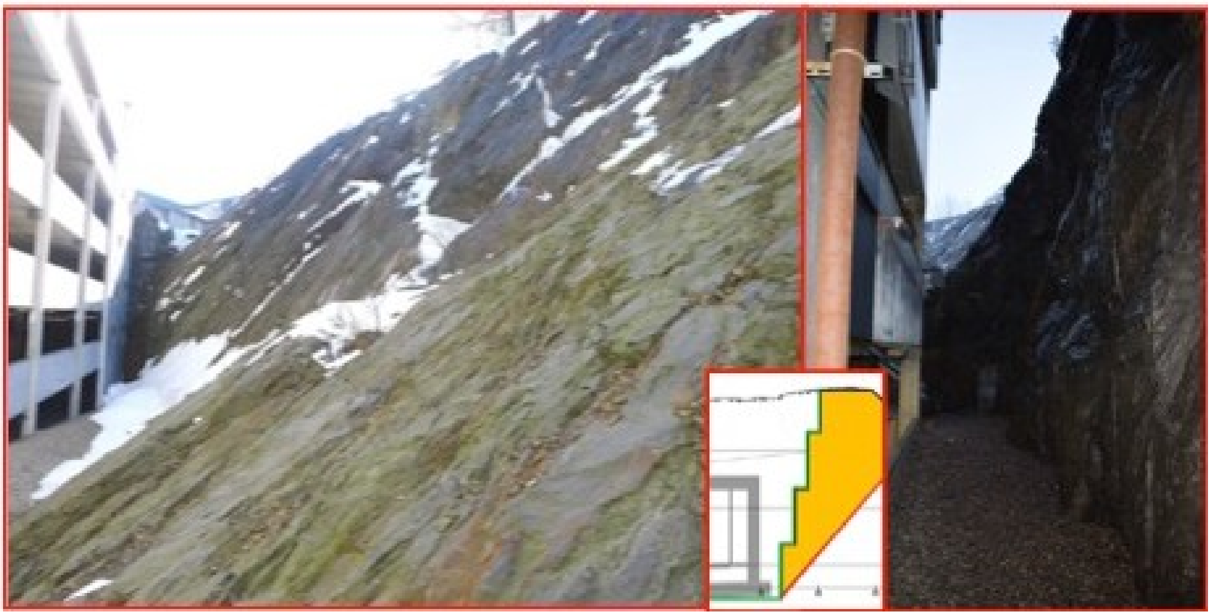

Figure 7. Rock cutting at a multi-storey carpark at Kungens Kurva. The rock slope is about 12 m high and was designed to be vertical as shown by a short section to the right. However, a rock slide along the foliation resulted in a slope of 50 °. The exposure of the planes at the foot of the excavation, together with the height of the slope, resulted in a very large failure of about 7000 cubic metres. The slope is now stable as it conforms to the rock structure that comprised the failure surface. The failure occurred during the construction period and not after the building was completed and put into service. A similar slope failure in Norway destroyed a residential building and took a number of human lives. Photo: Mehdi Bahrekazemi, Golder (left), Lars M Hansen (right).

Figure 8. Rock cutting at E4 / E20 at Kungens Kurva. The rock cutting is about 6 m high. The contour holes have been drilled vertically, but due to rock slides, the upper slope profile has become flatter. The exposure of the failure plane high on the slope limited the slide volume. The lower red line, in the right figure, indicates a structure that is far enough from the shaft to form support for the rock mass. Photo: Lars M Hansen.

In the above examples (Figure 6 and Figure 7), existing facilities are not affected. Figures 9, 10 and 11, on the other hand, show power line supports that are founded on rock near a road that is to be widened. One of these supports stands on rock of poorer quality (Figure 9), another in an area with planar structures that have an unfavourable orientation and undesirable position.

In order to minimize any disturbance during rock excavation, wire sawing (Figure 10) was used to create a slot, in order to facilitate the escape of blasting gases and prevent them from penetrating and opening other fractures that could cause an unacceptably large damage zone. Outside the picture is another mast that may be affected during the widening of the E4 / E20 (Figure 11). Slots have also been generated by wire sawing, but at the time of writing, the rock mass has not yet been excavated, since minor settlements have occurred that indicate the need for the installation of additional reinforcement.

Figure 9. Power line mast near to a road to be widened. The rock mass consists of sedimentary gneiss of less good quality and with weathered sections. Photo: Lars M Hansen.

Figure 10. Same power line as in Figure 9. The planned cut was moved a few metres from the initial position and was sawn in three sections. One of the sawn sections is clearly visible to the left of and below the mast. Photo: Lars M Hansen.

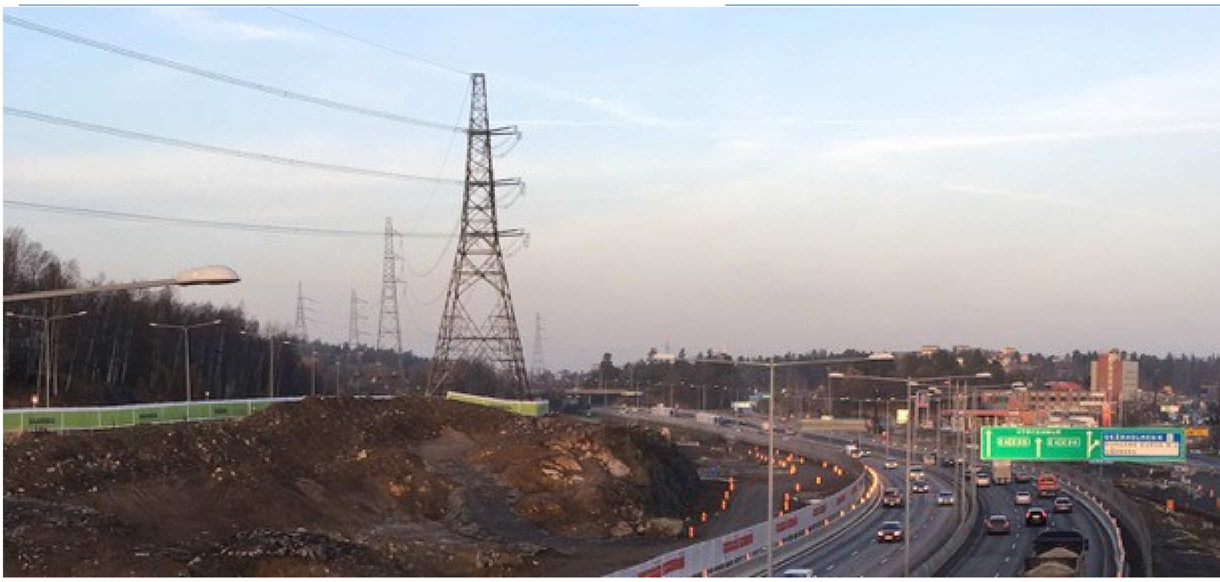

Figure 11. Power cable mast founded on rock. Along the Skärholm road and along the E4 / E20 there are planar structures with unfavourable orientations for stability (see Figure 8) and sliding of the same dimension as shown in Figure 7 can cause major damage. Therefore, rock excavation is carried out very carefully, and continuous measurements are made of the foundations to determine whether movement occurs. Photo: Lars M Hansen.

FRACTURE ZONES AND LINEAMENTS

The topographic lineaments, "fracture zones" and "crush zones" shown on the construction geological map of Stockholm (Stockholm City, Technical Office) do not always mean that there is any major zone with an influence on stability, as has been demonstrated in tunnels and open shafts. At Hjorthagen there is a topographic lineament along Rådjursstigen, which is due to an approximately 1 m wide zone with crushed rock (Figure 12). At Riddarholmen a "crush zone", which also constitutes a topographic lineament, has been found to be a fracture zone of only about 0.5 m width (Figure 13). These two examples show that the indicated fracture zones and crush zones need to be reviewed since a crush zone is usually considered more extensive than a fracture zone by a design engineer or contractor. Suggestions on how this can be done are included in the section on continuous updating.

The influence of zones and single foliation or fracture planes on stability is completely dependent on the interaction between their position and orientation relative to a tunnel or rock slope. For example, a 3 m wide, steeply dipping, crush zone that crosses a tunnel can have a very small impact; while a single foliation surface (or combination) with about 50-60 degree dip and striking parallel to a rock cut (Figure 6) can have devastating consequences for stability, if it is exposed at the foot of the slope (Figure 7 left); while the same type of structure further into the rock mass does not cause any stability problems (Figure 7 right).

Figure 12. Hjorthagen. Fracture zone indicated on the Construction Geology Map. Overview and close-up. Photo: Sofie Eskilander, Golder.

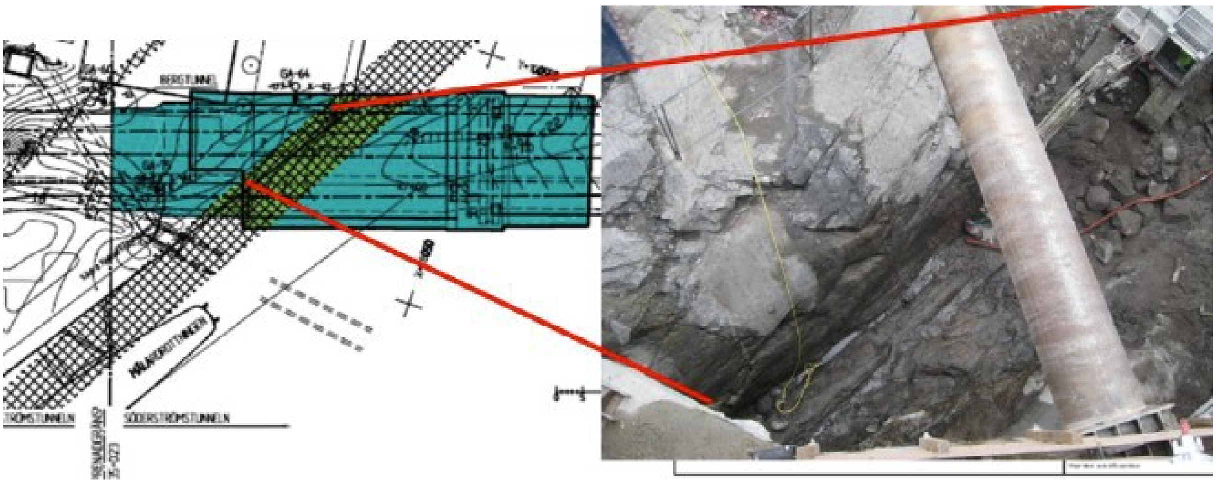

Figure 13. The "crush zone" indicated on the Construction Geological Map corresponding to a fracture zone with a width of about 0.5 m (north is approximately to the left of the figure). Photo: Anja Olsson, Golder.

HIGH ROCK WALLS NEXT TO EXISTING BUILDINGS AND OTHER FACILITIES

For several ongoing projects, construction results in relatively high rock cuttings next to existing facilities (eg. Förbifart Stockholm at Smista-Skärholmen-Kungens Kurva) and several rock cuttings have been generated adjacent to buildings (e.g. Idrottshögskolan, Karolinska sjukhuset and Musikhögskolan) and also water, for example, at Riddarholmen (Figure 14). At

Södersjukhuset excavation is currently underway as well as installation of rock reinforcement and wire sawing for vertical cuttings and tunnels (Figure 15, 16 and 17).

Figure 14. Riddarholmen. Excavation in bedrock, isolated from Riddarfjärden´s water with the help of secant pile walls (concrete diaphragm/concrete bored pile wall) which are seen at the top of the road in the photo. Careful rock excavation is being performed by wire sawing when the rock cover is small. A depression in the rock surface above the concrete tunnel has been filled with concrete. The depression is due to an approximately 0,5 m wide fracture zone (Figure 13), which is oriented NW with a dip to the SW. Photo: Anja Olsson, Golder.

Figure 15. Södersjukhuset. Wire sawn 10 m high rock walls next to existing buildings. Prior to sawing, rock reinforcement has been installed in the form of a long bolt set from the top of the planned cut. Photo: Jörgen Theander, Golder.

Figure 16. Tunnel with limited rock cover. The tunnel is reinforced above the planned roof line before rock excavation and the contour is wire sawn to prevent explosive gases penetrating rock fractures to crack and causing an excessive damage zone in the rock around the tunnel. Photo: Jörgen Theander, Golder.

Figure 17. Comparison of a sawn and blasted rock mass, where the sawn surface also needs to be reinforced. A sawn surface can be treacherous and attention is required since the fractures do not appear as clearly. Photo: Jörgen Theander, Golder.

FAULTING IN SÖDERSTRÖM

A number of planned tunnels (Förbifart Stockholm, a sewage tunnel between Bromma and Sickla, a metro tunnel between Kungsträdgården and Södermalm, a cable tunnel between Danderyd and Södra Hammarbyhamnen and a road tunnel to the east (the Östlig förbindelse) are planned to cross Mälaren-Söderström-Saltsjön, and a large challenge for these projects is the regional fault under Stadsgårdskajen along Söderström (Figure 18). The northern block is downthrown (Stålhös 1969, map), and at Slussen-Stadsgårdskajen, the fault dips approximately 50 ° to the south (Olsson et al. 2014). Consequently, this is a reverse fault with the southern block having moved up and over the northern block.

At Slussen and farther east to Stadsgårdskajen, three cored drill holes have been bored (13GA01 for Stockholm City as well as KB01 and 13VEC06 for the City Link project), which indicate a distance of about 50-100 m with fractured rock, along and under Stadsgårdskajen, with several indicators of movement such as clay alteration, slickensides and crushed rock that get worse northwards with drill core losses that quite abruptly go over to better rock (Figure 19). In connection with the drilling of 13GA01, at the transition from very bad to better rock, under Stadsgårdskajen, more than 2.5m of drill core was flushed away with the drilling water. This material probably consisted of swelling clay, which could be detected from a bit of altered rock from the same core (Clarin & Clark, 2015).

Fractures with slickenlines dipping to the south have been observed at Södersjukhuset (Figure 20), but the direction of movement is not certain. Even in a tunnel for Citybanan at Söder Mälarstrand (Figure 21) there are fractures with clay-altered surfaces and with dips to the south, and outside the quay there is a zone with a width of 50 m (Olsson et al. 2014).

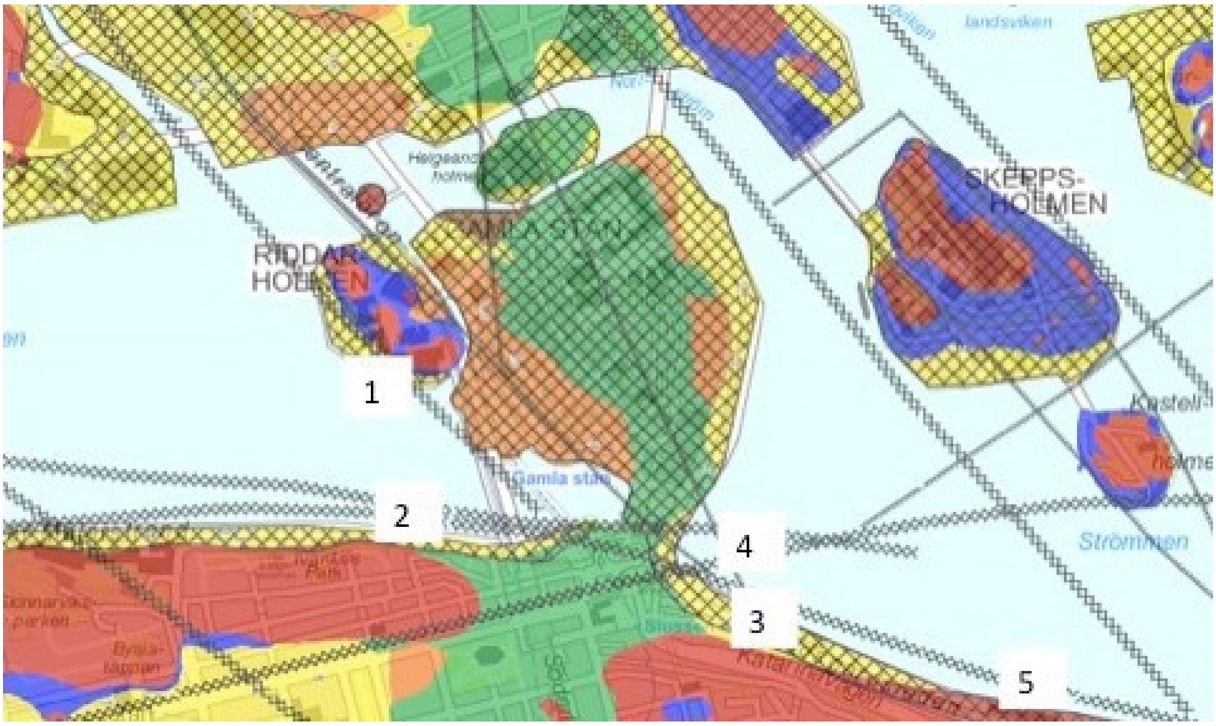

Figure 18. Construction Geological Map around Strömmen. 1: <0.5 m wide fracture zone (see Figure 13 and Figure 14). 2: Depression in the bedrock outside of Lappskon, larger at Söder Mälarstrand. 3: > 50 m wide fracture zone found in cored borehole (13GA01), which in the north borders on good rock but with a 2.5m wide core loss which is believed to be a zone of clay altered rock with swelling clay. 4: These two crush zones have not been found by a cored drill hole, 13GA01, which has been drilled from a tunnel under Katarinavägen to cross them. 5: similar zone as in # 3 has been found in two boreholes.

Figure 19. Drill core from core drilling through the Söderström fault at Slussen. Core-loss of approximately 2.5 m spread over two drill runs is believed to be due to swelling clay. A minor amount of such clay was found in the brown section of altered rock, and exhibited a 150 kPa swelling pressure (Clarin & Clark 2015). The missing clay may be assumed to have a similar swelling capacity.

Figure 20. Southerly dipping fractures at Södersjukhuset. Photo: Lars Bergkvist, Golder.

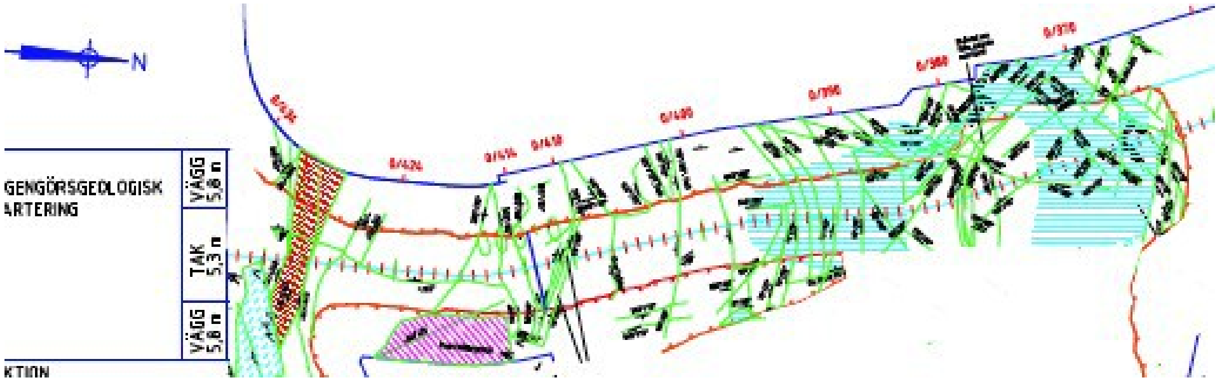

Figure 21. Tunnel mapping at Söder Mälarstrand. The brown line is the tunnel wall. On both sides of the tunnel the walls are folded out (standard for tunnel mapping). Green lines are fractures in the walls and roof. The lines represent a fracture swarm striking approximately east-west with a dip of about 50 ° S.

ASSESSMENT OF FRACTURING IN A ROCK MASS BASED ON DRILLCORE MEASUREMENTS

The ratio between the total number of fractures in a drill core and the number of fractures above a certain diameter (circular fractures) in a rock mass has been expressed as an exponential function (Fox et al. 2008). The constants of the function are site-specific and have been determined, for example, for Forsmark and Oskarshamn. For example, fractures with a diameter of more than 5 m in the rock mass in Forsmark can be estimated to constitute about 10% of the amount of fractures found in a drill core. At Henriksdal this has been tested on a tunnel with a width of 4 m, a length of about 100 m and an equally long drill core. There were 200 fractures in the drill core, and in the tunnel about 20 fractures were mapped that cut through the tunnel, which is correct. The method needs to be checked in several locations to determine if the function from Forsmark can be used generally for Stockholm or needs to be modified for different parts, e.g. younger granites in the north and sedimentary gneiss in the south.

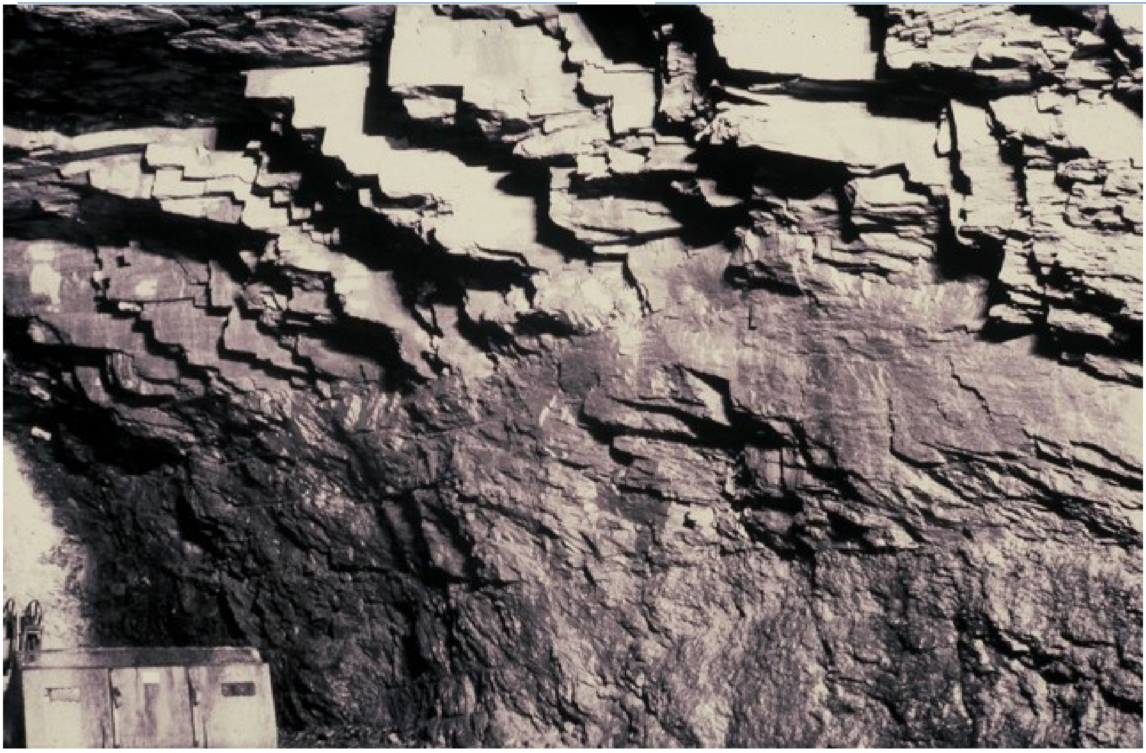

Figure 22. The photo shows how the same fracture system appears differently in terms of the extent of the fractures, due to differences in the deformation properties of the rocks. At the top is mylonitic quartzite, in the middle grey phyllite and under graphitic phyllite. High rock stresses (20-40 MPa) have been measured in the rock mass However, the rock stresses did not generate the fracture system, which was caused by stresses generated during the formation of the mountain chain. From the tunnel at Stora Sjöfallet. Photo: Lars M Hansen.

ROCK STRESSES

In the greater part of the Stockholm area, initial in situ stresses are quite favourable (3-10 MPa) for construction in the bedrock. Rock bursts in tunnels in Stockholm and its surroundings are therefore rare. The effects of the rock stresses depend on the magnitude and direction of the stresses in relation to the size and orientation of the excavation as well as on the deformation properties of the rocks (Figure 22).

Measurements of rock stresses

In the Stockholm area, in situ rock stress measurements have been performed for several projects. The results and evaluation of all these measurements are summarized in a report for Citybanan (Perman & Sjöberg 2007). The directions of the stress are shown in Figure 23. Near to the Söderström fault at Finnboda, the stresses are low and even negative, which is consistent with the regional stress field and the fault's strike direction.

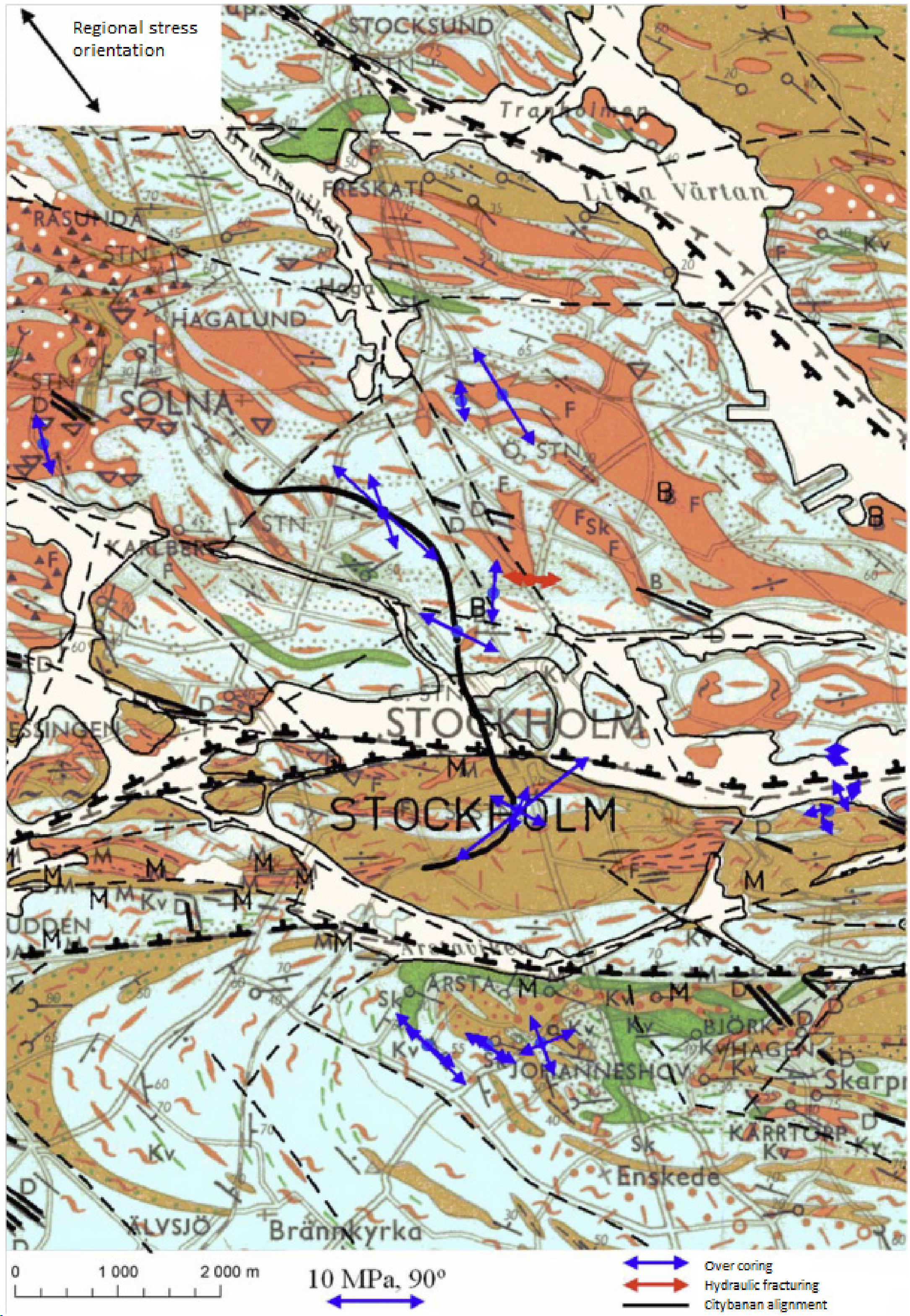

Figure 23. In situ stress magnitude and orientations in central Stockholm. The measurements at Södermalm have been carried out in an area affected by the Söderström fault system and therefore deviate from the regional north-west oriented stress field, which can be seen in, for example, N Djurgården and south of Årstaviken. (from Perman & Sjöberg 2007).

No measurements have been made systematically across the fault at Söderström or elsewhere in Stockholm so that the variation in the stress field around a fault can be studied. However, such measurements have been carried out around a normal fault in a tunnel at the Vietas power station

(Figure 24). This fault is part of a group that forms a rift under the Caledonian front (Hansen 1989)

The results seen in Figure 25 show high (20-30 MPa) nearly two-dimensional rock stresses directed parallel to the fault plane, on the hanging wall side, up to about 5 meters from the fault plane. On the footwall (left in the picture), the stress field next to the fault is almost completely horizontal and directed across the fault, similar to some of the results at Söderström, but after 5-10 m returns to approximately the same orientation as on the hanging wall side, but with significantly lower vertical stress. Future measurements may answer the question if the stress field around the faults in the Stockholm area shows a similar pattern, and what differences exist between different types of faults.

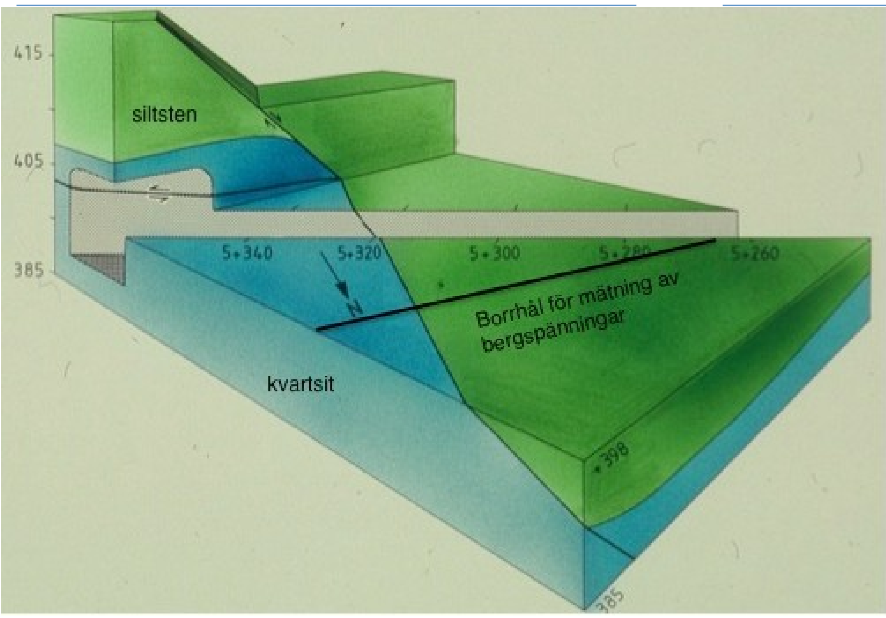

Figure 24. Block model of a rock mass with a fault plane between Precambrian quartzite and overlying layered siltstone. Rock stresses have been measured with over coring in a borehole drilled from a tunnel at Stora Sjöfallet, Lapland (Martna & Hansen 1986).

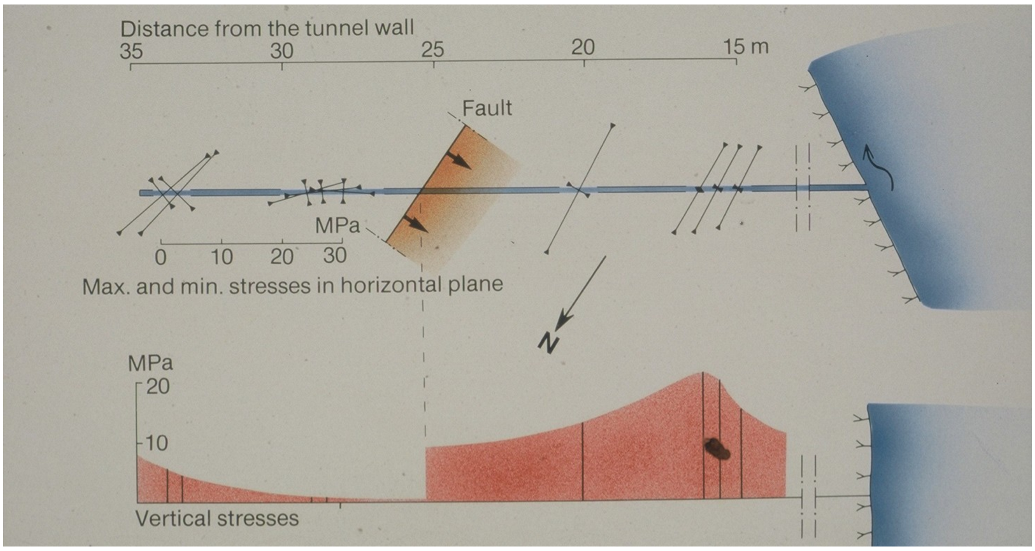

Figure 25. Outcome of rock stress measurements by over coring around a normal fault. (Martna & Hansen 1986).

IN SITU STRESS AT ARLANDA AIRPORT

The Arlanda railway line, built in micaceous gneiss and schist, which in many places appears as phyllite and in the northern section granodiorite, is an example of how rock stress can have a favourable impact on tunnel stability. The largest principle stress in the station area is directed approximately across the tunnels. The stations are located in a 20 m wide rock cavern with a height of about 8 m and a rock cover of about 10 m (figure 26). Between the track tunnels there is a pillar of about 4 m width (Figure 27).

During the rock excavation of the Northern Station at Terminal 5, the rock stresses caused a lifting of the roof, so that at the transition between the station and the track tunnels, a gap of about 5 mm was formed between the rock pillar and roof, which showed that the station rock cavern had favourable stability conditions (Ljunggren & Chang 1998).

Similarly, the wide tunnels of the Citybanan at Tegelbacken and Söder Mälarstrand benefit from the in situ rock stress field.

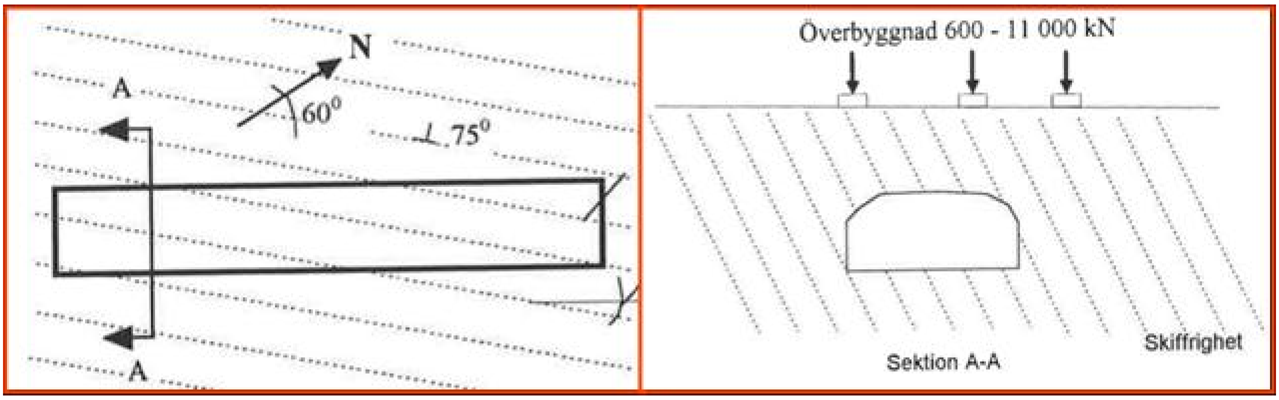

Figure 26. The orientation of the schistosity in the area of Arlanda N. The section AA shows the load from the Terminal building on the rock mass above the station (Ljunggren & Chang 1998)

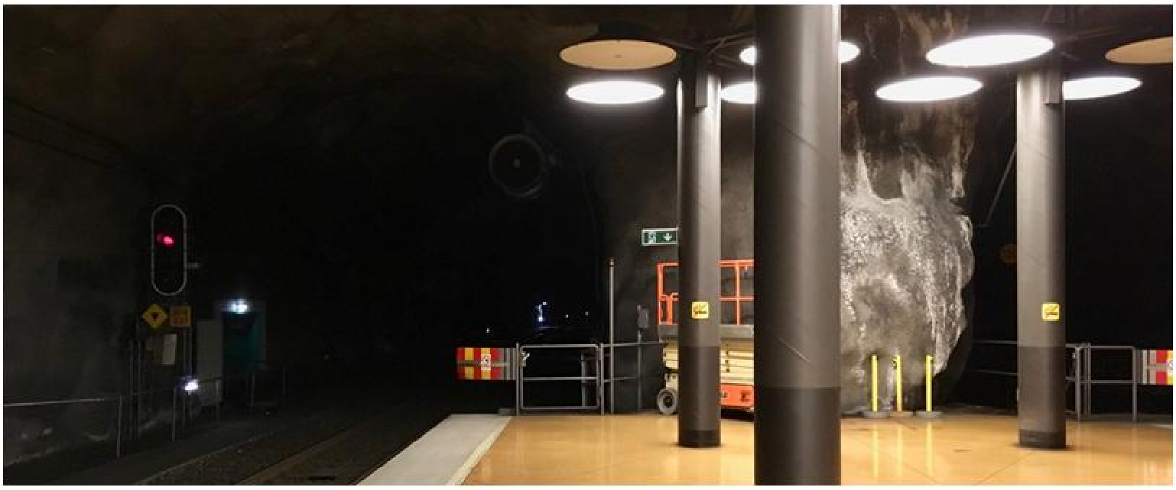

Figure 27. Rock pillar at transition between the station platform cavern and the track tunnels. Photo: Lars M Hansen

Figure 28. Arlandabanan, southern end of Arlanda N station (terminal 5). Here there was a movement,-heave in the roof, in connection with blasting. The crack that occurred between the rock pillar and the overlying rock mass cannot be seen in the picture as it is covered with shotcrete and the cast concrete pillar. Photo: Lars M Hansen.

LOOSE SOIL MASSES ON ROCK

Fall of loose blocks from high rock slopes

In many places in the Stockholm area there are high natural rock slopes in the vicinity of houses (Figure 29). Tyresö is an example where rock falls have occurred. Risk analyses for such events can be performed using software to assess the likelihood of how far from the slope or cliff, blocks of a certain size and shape can travel (Figure 30).

Figure 29. A house below a steep rock slope, and a large block on the slope edge. Photo Anja Olsson, Sofie Eskilander.

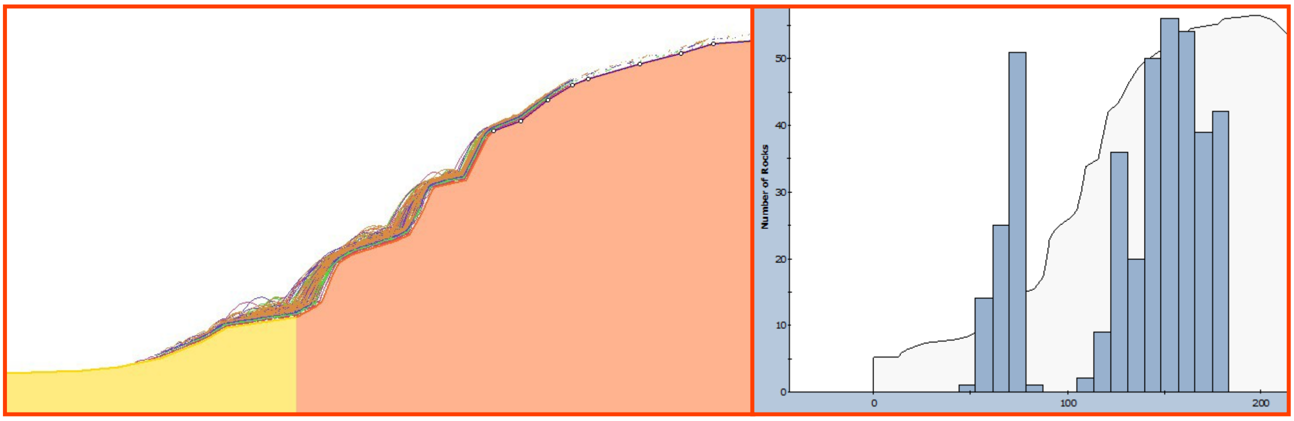

Figure 30. 400 simulations of rolling blocks have been performed. The example shows that 3/4 of these blocks stay high on the slope, while about 1/4 comes all the way down. The simulation is conservative since it deals with cubic blocks, whereas real blocks are more likely to stop earlier. Trees and shrubs also have a braking effect.

Depth to bedrock

When planning and designing construction work, exploration is often performed to investigate the soil's technical properties and the depth to the bedrock. The expected depth controls the spacing of the investigations performed. However, there are always uncertainties: Figure 31 and Figure 32 show examples of this from a building site on Northern Östermalm.

Figure 31. Example of how bedrock probing can give rise to a misleading interpretation. When probing was performed at the arrows (cc about 10 m) the depression was missed. Photo: Edward Runslätt, Golder.

Figure 32. The figure shows the interpreted (white) bedrock profile based on probes and the real (red) bedrock profile, as well as the supporting walls that needed to be built. Photo: Edward Runslätt, Golder.

Diaphragm walls

When rock excavation is to be carried out at depth below the soil, the construction of some kind of diaphragm wall is often required to prevent collapse and inflows of soil and groundwater. In addition, careful sealing may be required to prevent disturbance of surrounding groundwater levels that could lead to settlements in existing buildings. Figure 33 shows the creation of a typical diaphragm wall involving the installation of sheet pile wall in combination with grouting, and how different methods are used in the geological formations. The contact between wall and rock is shown in Figure 34 and Figure 35.

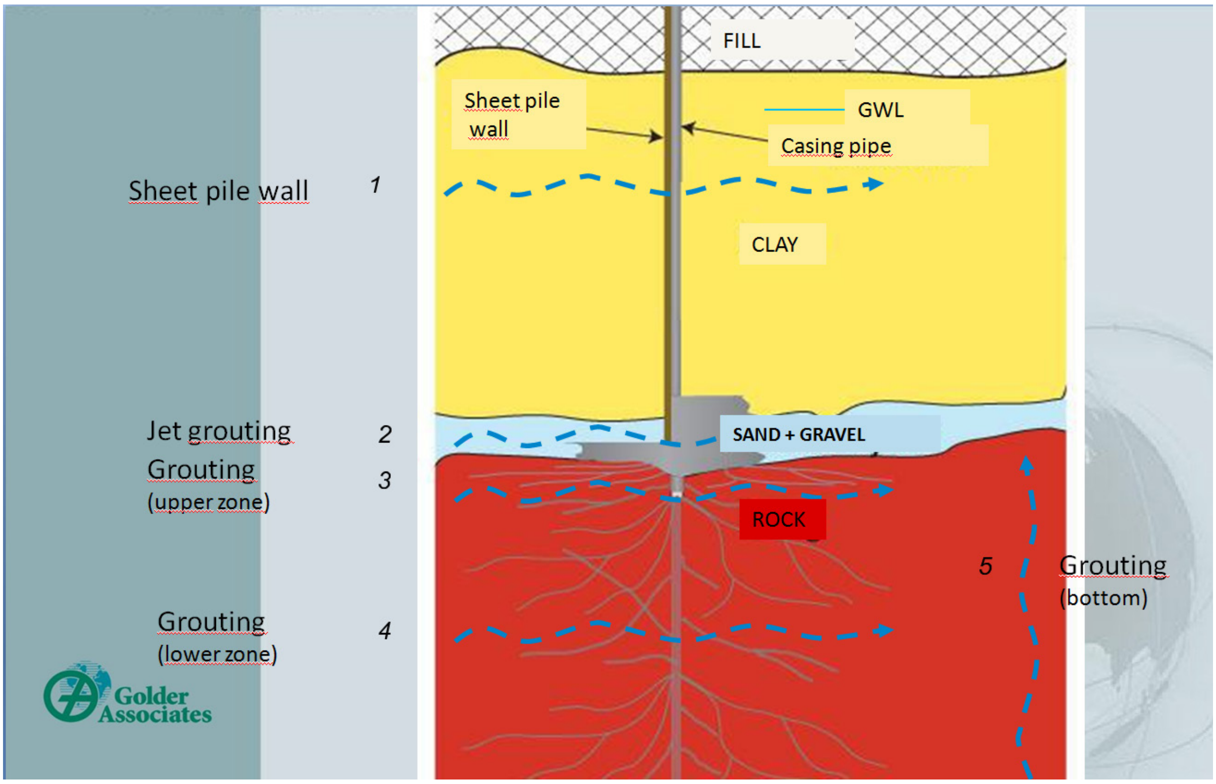

Figure 33. Construction of a diaphragm wall with sheet piles that both seals against water inflow and prevents wall collapse into the pit and grouting that takes place on several levels, and with different methods. In many cases, the wall is secured with reinforced and anchored concrete. 1) The constructed membrane in the fill and clay consists of a sheet pile wall that both seals against water inflow and prevents wall collapse into the pit. In sandy soils over rock and in the rock mass, sealing is achieved by grouting. 2) Jet-grouting is carried out at the soil bedrock boundary. 3-4) Pre-grouting in the rock may need to be done at various levels, and even final bottom grouting may be required (5). The rock surface (3) is often poorly sealed, and can together with any sandy soils form a leakage pathway that may or may not be further connected to any deeper rock aquifer if it exists. (4) Modified after original by Mikael Creütz, Golder.

Figure 34. Grout at the contact between the sheet pile wall and the bedrock. Photo Mikael Creütz, Golder.

Figure 35. Excavation with drilled pile wall consisting of casing and welded plate, where the rock wall to the left has been cut with a wire saw and blasted to the right. Below the foot (dark area to the right of the middle, where the lower end of the feed tube hangs) blocks have slipped out, a slip of the same type as shown in Figure 8. Photo Mikael Creütz, Golder.

PROPOSAL FOR CONTINUOUS UPDATING OF CONSTRUCTION GEOLOGICAL INPUT

• Review of existing tunnel mapping and other material from pre-investigations and follow-up of Citybanan and other completed projects, regarding the detection of deformation zones and mapped lineaments.

• Continuous follow-up of ongoing and planned projects regarding interception of deformation zones that can be linked to an interpreted zone or lineament marked on the construction geological map.

• The above can be done by students as a part of their degree or master's degree work.

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