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Abstract

A pilot study of predominantly brittle structures, i.e. faults and fractures has been undertaken at Oskarshamn. The main aim of the work is to assess whether or not a more comprehensive investigation of faults may improve the understanding of their kinematic history.

Structural data were obtained in the field along the coast at Simpevarp, along road sections near the Power Plant and in the Äspö tunnel. In addition, we studied selected sections of drill cores from four boreholes. Polished thin sections from samples collected both in the field and from the drill cores were studied using standard petrographic techniques, and in some in some cases also SEM (backscatter). Observations from thin sections combined with data from the field and from drill cores form the basis for the conclusions of the pilot study.

The investigated structures present in the area include low-grade ductile shear zones, several generations of cataclasite, and breccias cemented by diagenetic minerals. The observations are consistent with a sequence of progressively more brittle faulting following plastic deformation.

There are very good exposures of faults in road sections and along the coast in outcrops that were visited near the Power Plant. Distinct populations as well as fault rocks can be identified, which most likely reflect damage zone deformation to the nearby master faults. Since these faults show good slickensides, they can be used in kinematic analyses.

As a general conclusion, it is considered that a more comprehensive structural study may lead to improved understanding of the kinematic pattern in the area of interest. This would require that relevant data can be obtained from a variety of faults and fault populations with different properties and orientations. Based on the conclusions from the pilot study, such data may be derived from detailed fieldwork on surface outcrops in the wider region of interest, combined with data on relative fault chronology obtained from the lower part of the Äspö tunnel. Field and core studies should be supplemented by a general study of the petrography and the micro-structural history of the faults.

Sammanfattning

En pilotundersøkelse av forkastninger og sprekker er utført i Oskarshamn. Hensikten med arbeidet er å vurdere om en mer fullstendig undersøkelse av forkastninger kan gi økt forståelse for forkastningenes kinematiske historie.

Strukturdata ble innhentet fra blotninger langs kysten ved Simpevarp, langs vegskjæringer nær kraftverket og i Äspö-tunnelen. I tillegg studerte vi utvalgte seksjoner av borekjerner fra fem borehull. Polerte tynnslip av prøver samlet på overflaten og fra borekjerner ble studert ved hjelp av standard petrografiske teknikker, og i noen tilfeller supplert med SEM (backscatter). Observasjoner fra tynnslip kombinert med data fra felt og fra borekjerner utgjør grunnlaget for konklusjonene fra pilotstudiet.

De undersøkte strukturene som finnes i området omfatter lav-grads, duktile skjærsoner, flere generasjoner med kataklasitt, og breksjer sementert av diagenetiske mineraler. Disse observasjonene er i samsvar med en rekke av hendelser med stadig mer sprø deformasjon som følger etter plastisk deformasjon.

I det undersøkte området nær kraftverket finnes det gode blotninger av forkastninger i vegskjæringer og langs kysten. Distinkte populasjoner og forkastningsbergarter kan identifiseres. Disse strukturene er trolig relatert til bevegelse langs store, regionale forkastninger. Forkastningene har gode slickensides og har dermed potensiell nytte i en kinematisk analyse.

Som en generell konklusjon antas det at en mer omfattende strukturell undersøkelse kan gi en bedre forståelse av det kinematiske mønsteret i området som er av interesse. Dette vil kreve relevante data fra ulike forkastninger og forkastnings-populasjoner med forskjellige egenskaper og orientering. På grunnlag av konklusjonene fra pilotstudiet kan en få slike data ved detaljerte undersøkelser på overflaten innenfor et større område av interesse, kombinert med informasjon om forkastningskronologi fra den undre delen av Äspö-tunnelen. Undersøkelser på overflaten og av borekjerner bør suppleres med en generell undersøkelse av forkastningsbergartenes petrografi og mikroteksturelle utvikling.

Contents

1 Introduction

This document reports the results of a pilot study of the kinematics of a restricted number of deformation zones at the Oskarshamn site. This study forms one of the activities performed within the site investigation at Oskarshamn. The work was carried out in accordance with activity plan AP PS 400-05-036. Controlling documents for performing this activity are listed in Table 1-1. Both activity plan and method descriptions are SKB's internal controlling documents.

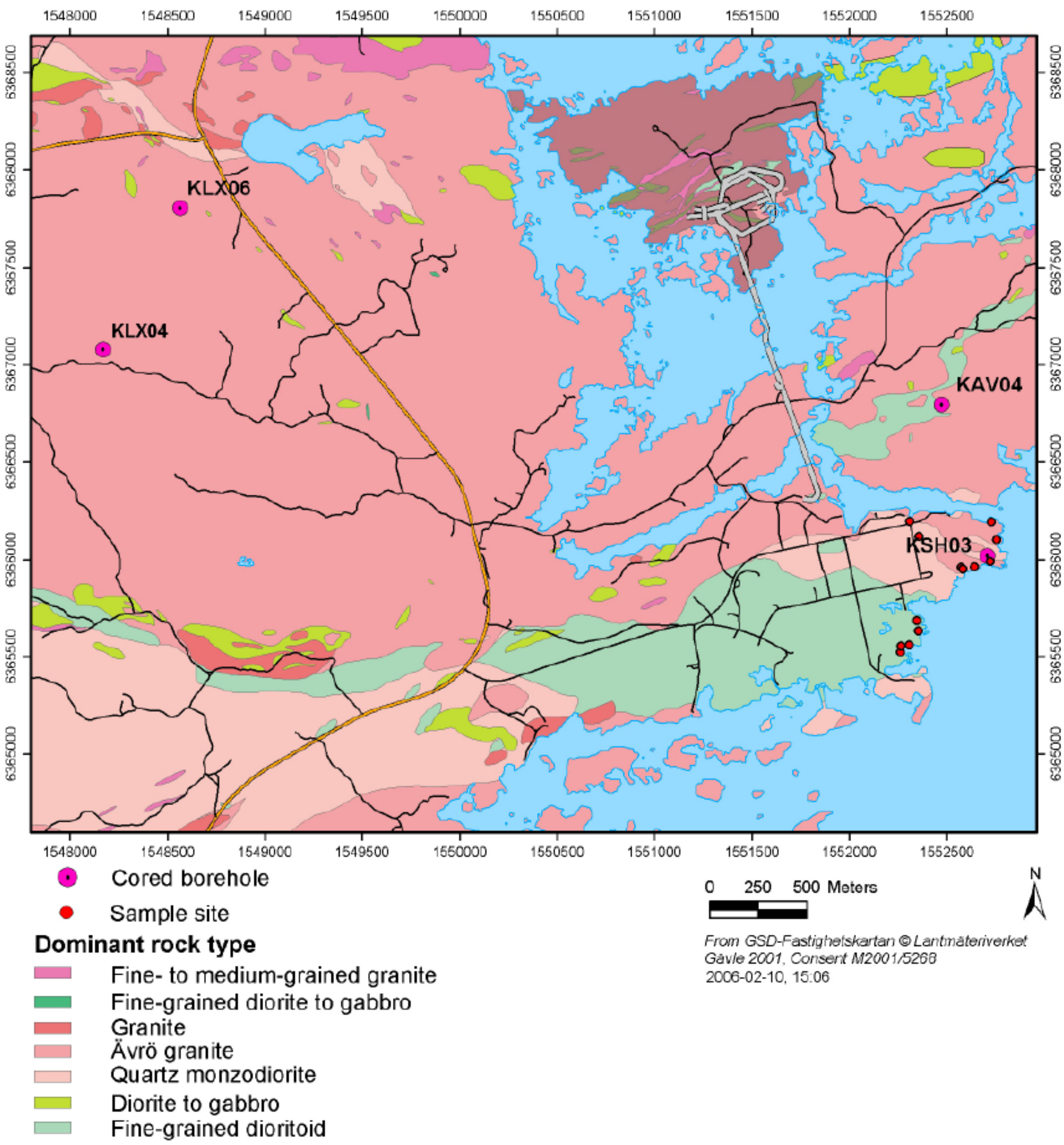

Figure 1-1. *General overview over Oskarshamn site investigation area.*

Table 1-1. Controlling documents for the performance of the activity.

Activity plan	Number	Version
Kinematik i spröda deformationszoner – pilotstudie	AP PS 400-05-036	1.0

2 Objective and scope

The objective of this pilot study is to assess what possibilities exist at the Oskarshamn site to obtain an improved understanding of the kinematics of particularly the brittle deformation zones in the area. The project has not involved detailed and systematic work, but has involved an investigation of some selected localities related to regional deformation zones in the field, in the Äspö Laboratory, and a few deformation zone intersections in boreholes. Observations from thin sections combined with data from the field and from drill cores form the basis for the conclusions of the pilot study.

Given the initial nature of the work, and its limited scope, only preliminary conclusions can be drawn regarding the general pattern and specific properties of faults and fractures. However, the study allows us to address the explicit aim of the project in an adequate manner.

3 Equipment

3.1 Description of equipment/interpretation tools

During field work and core inspection, the standard equipment for structural investigations was used, including hammer, compass, hand lens, diluted HCl, digital camera, and GPS (Garmin etrex) for locating observation points according to SKB standards (Swedish Grid). Samples collected in the field and from drill cores were cut in the core laboratory, and selected chips were correctly marked (felt pen) and sent for preparation of polished thin sections. The thin sections were petrographically analysed and some selected sections were analysed using SEM in backscatter mode.

4 Execution

4.1 General

The project was carried out in conformity with the accepted activity plan AP PS 400-05-036. Literature studies preceded the investigations that were carried out at Oskarshamn on April 26–28, 2005.

Two days were devoted to fieldwork along coastal outcrops at Simpevarp and in the Äspö Laboratory, and the third day involved a brief inspection of selected sections from several drill cores, with a specific aim to study deformation zones with abundant faults and fractures. The following drill holes and sections were inspected: KSH03A (150–275 m), KAV04 (830–910 m), KLX04 (860–980 m) and KLX06 (290–435 m). Samples for thin section preparation were collected in the field, in the Äspö Laboratory and from the drill cores. A total of 15 polished sections were studied at the Geological Survey of Norway (Trondheim) using standard petrographic techniques, and in some in some cases also SEM (backscatter). Observations from thin sections combined with data from the field and from drill cores form the basis for the conclusions of the pilot study.

4.2 Data handling and processing

At the Geological Survey of Norway (NGU) in Trondheim, structural data were analysed and plotted using standard techniques. The thin sections were analysed in several steps:

1) Scanning at high resolution of the entire section using a standard slide scanner.
2) Printing of the scanned jpg-images as A4 colour prints that greatly aid in establishing general relationships and locating critical features for detailed study.
3) Petrographic analysis and documentation of textural and micro-structural relations using a digital camera attached to the microscope (Leitz).
4) Detailed studies of specific mineralogical and textural details using SEM in backscatter mode.

4.3 Analysis and interpretation

The methods employed from fieldwork through structural data analysis and petrographic work are based on those described in /Braathen 1999, Braathen et al. 2002, Nordgulen et al. 2002, Osmundsen et al. 2003/. In this report, definition of fault rocks is according to the classification in /Braathen et al. 2004/. Criteria for identifying the slip-direction on slickenside surfaces is presented in /Petit 1987/.

4.4 Nonconformities

No nonconformities have been noted.

5 Results

5.1 Description of sites and cores

The Oskarshamn site is located to an area of mainly felsic intrusive complexes, characterised by fairly massive granitoids, and subordinate bodies of gabbro /Persson et al. 2003, Wahlgren et al. 2004/. These intrusive rocks are truncated by several sets of faults, of which the more prominent strike NE-SW, E-W, N-S and NW-SE (see Figure 1-1). In the following we describe the outcrops as observed on selected sites along these faults.

Coastline near the Power Plant

This area is located along the coastline south and east of the Power Plant, towards the port facilities of Oskarshamn. The site description relates to localities PSM 007065 to PSM 007070 and PSM 007071 to PSM 007074 (see Figure 1-1).

The host rock south of the Power Plant is a fine- grained dioritoid. Northeastward, the area is dominated by Ävrö granite. Both rocks host numerous dykes of medium- to coarse-grained and pegmatitic granite. Several fracture and fault trends are present, with N-S and E-W structures as the most prominent ones. NE-SW and NNE-SSW fractures are subordinate.

In this area, most N-S structures are fractures without fault rocks or definite displacement. In some cases, the structures are faults that host thin bands and lenses of epidote-rich protocataclasite, and that locally are overprinted by calcite-cemented breccia. Slickensides on some fault surfaces indicate mainly dip-slip displacement with a minor component of sinistral shear.

A well exposed, approximately E-W striking and moderately south-dipping fault (Figures 5-1 and 5-2) show two generations of cataclasites. The most prominent is a yellow-green, epidote-rich cataclasite to ultracataclasite, with two types of cm-sized clasts. Clasts are either of the host diorite, or of a black fault rock. The latter rock is present as a separate layer in the fault. It is a black cataclasite to ultracataclasite (or psedotachylyte?) with cm to mm size host rock clasts. The matrix is extremely fine-grained and few grains are distinguishable in the exposure. Abundant slickensides in and around the fault show mainly down-south displacement with a minor sinistral component (Figure 5-3). Some metres farther south, a WSW-ENE striking and steeply dipping fault reveals a similar green cataclasite (Figure 5-4). Contrary to the gently-dipping fault, this structure has been reactivated, as documented by a lens-shaped, up to 25 cm wide zone of carbonate-cemented breccia. Clasts are of cataclasite and diorite, and are up to 10 cm in size. The abundant calcite cement in a considerable pore volume is consistent with significant dilation. This, and the chaotic nature of the breccia, indicates formation by hydraulic fracturing, supporting a classification as hydraulic breccia /e.g. Braathen et al. 2004/.

Figure 5-1. *Green cataclasite in fault in coastal outcrop (locality PSM 007066). Two fault rocks are seen; the yellow-green, epidote rich cataclasite on the photograph, and a thin layer of ultracataclasite(?) that also appears as clast in the green cataclasite.*

Figure 5-2. *Details of fault rocks at locality PSM 007066, described in Figure 5-1. The yellow-green, epidote rich cataclasite hosts clasts of ultracataclasite(?).*

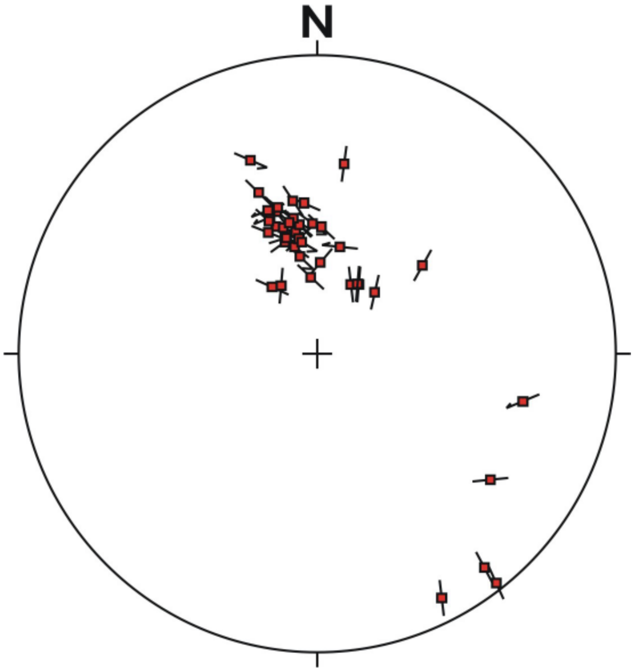

Figure 5-3. *Simpevarp field data. Slip-linear plot of mesocopic faults (N = 29) along the shore close to power plant (localities PSM007065 and PSM007069). The slip-linear plot shows the pole to the fault plane decorated by a line/arrow that indicates the direction (line orientation) and sense of slip (arrow) of the hanging wall. Lower hemisphere, equal area projection (Schmidt net). The plot shows that the main fault population is oriented E-W with gentle to intermediate dips to the north. Slickensides in and around the fault show mainly down-south displacement with a minor sinistral component.*

Figure 5-4. *Photograph of WSW-ENE striking and steeply dipping fault with a green cataclasite. This fault has been reactivated, as documented by a carbonate-cemented breccia (not visible on the photograph).*

NNE-SSW to NE-SW fractures dominates the coastline northeast of the Power Plant. They are sub-vertical, and dip both to the west and east. Many of the structures contain lenses and thin pockets of protobreccia, and the fracture surfaces reveal slickenlines, providing evidence that the structures are faults. The slip-lines plunge sub-horizontally, consistent with strike-slip movement (Figure 5-5a). On some surfaces the slip direction can be predicted; these surfaces consistently suggest dextral movement. However, some of the slickensides reveal more than one slip-line, indicating several events of slip.

Road sections around the Power Plant

Around the northeast side of the Power Plant, there are numerous, excellent exposures of small faults in road cuts. Most faults have a coating of epidote, some also contain lenses of calcite. Slickensides are abundant, and appear both as fibrous epidote and as groves in the fault surfaces. The most prominent population of the recorded faults strike ENE-WSW with moderately south and subordinate north dip. Slip-lines show them to be dip-slip faults with an oblique component. In cases where the direction of movement can be established, the slip-criteria /Petit 1997/ indicate they are mainly normal faults, however, there are also some reverse faults (Figure 5-5b). The road sections also contain a population of steep, N-S oriented faults. Slickensides on these faults suggest they are basically strike-slip faults.

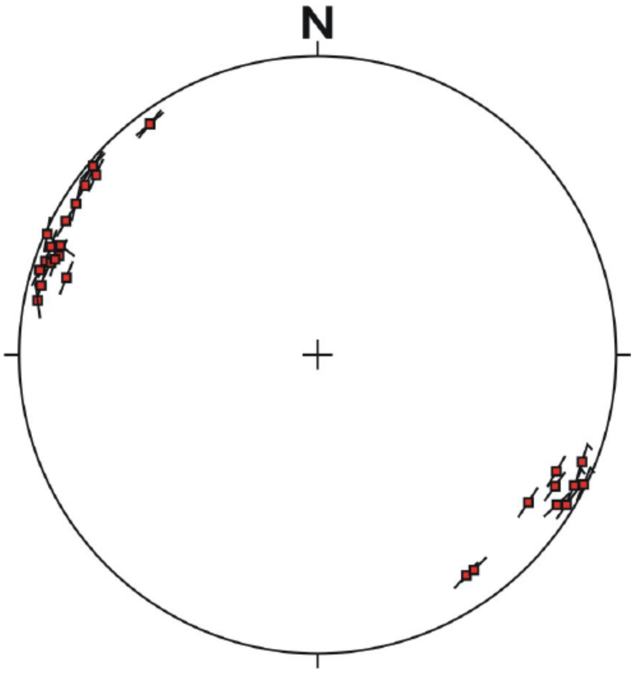

Figure 5-5a. *Simpevarp field data. Slip-linear plot of mesocopic faults (N = 29) along the shore close to and northeast of the power plant (localities PSM007071 to PSM007074). The slip-linear plot shows the pole to the fault plane decorated by a line/arrow that indicates the direction (line orientation) and sense of slip (arrow) of the hanging wall. Lower hemisphere, equal area projection (Schmidt net). The plot shows one NE-SW oriented fault population with steep dips, and slickenlines and striations showing mainly strike-slip motion.*

Figure 5-5b. *Simpevarp field data. Slip-linear plot of mesocopic faults (N = 38) along roadcuts close to power plant (localities PSM007075 and PSM007078). The slip-linear plot shows the pole to the fault plane decorated by a line/arrow that indicates the direction (line orientation) and sense of slip (arrow) of the hanging wall. Lower hemisphere, equal area projection (Schmidt net). The plot shows that there are two main populations among the observed faults; one oriented approximately NNW-SSE with steep dips, and another with steep to intermediate dips towards the south to southeast. Slickenlines and striations on the NE-SW oriented faults are consistent with mainly strike-slip motion. In contrast, dip slip and oblique slip dominate the other fault set, with both normal and reverse motion.*

Äspö Laboratory

Visited sites in the Äspö tunnel and underground laboratory show similar structures to those encountered in surface outcrops, and in addition several dm to m wide shear zones of low-grade mylonites. The latter were encountered at –220 m and –450 m. There, the mylonites have a very fine-grained matrix. Clasts of feldspar show fracturing and are locally totally shattered into a fine-grained, elongated aggregate of small clasts. Quartz forms a platy fabric, characteristic for dynamic recrystallization. Although the strain in the rocks seems high, no clear indication of shear sense could be found. A stretching lineation was not detected in the mylonites. Hence, assessment of the shear-sense in the rock will require more extensive and careful studies.

In the lower, full profile-drilled tunnel, there are excellent exposures of small faults in the walls (Figures 5-6a and 5-6b). The faults host green cataclasites with abundant epidote. Deformation is seen as protocataclasite to isolated smaller fractures with associated red staining of feldspar (intercrystalline fractures) in the fault damage zones. The fault cores contain cataclasites and locally ultracataclasite with cm-size feldspar clasts in a very fine grained epidote(?) matrix.

Figure 5-6a and b. *Photographs from the full profiled tunnel, exemplifying deformation encountered in the lower part of the Äspö tunnel. Small faults are well displayed in the clean-cut tunnel walls. The faults host green cataclasites with abundant epidote. Deformation is seen as protocataclasite along faults with associated red staining of feldspar (intercrystalline fractures) in the fault damage zones. Locally, there are zones of ultracataclasite with cm-size feldspar clasts in a very fine grained epiodote(?) matrix. Cross-cutting relationships between various faults can easily be studied in this part of the tunnel.*

Drill cores

Several drill core sections were examined, with the intention to ascertain that data from the outcrops and the Äspö tunnel covered the main type of structures. In core KSH03A, from 155 to 160 m, there are many small epidote-coated fractures, some of which are stained by iron oxide. At 160 m, these fractures are truncated by a c 10 cm wide fault with red-brown, calcite-cemented breccia. Cm-size clasts contain fragments of the epidote-fractures. Farther down, at 199 m, there is a porous protobreccia (Figure 5-7). Even deeper, at 213 m, a 5 cm wide fault shows several faulting events. An 3–4 cm thick zone of epidote-quartz(?) rich cataclasite is cut by a less than 1 cm wide zone of dark red carbonate-cemented breccia, in which the former fault rock appears as mm-size clasts. There are also calcite-filled veins outside the fault (Figure 5-8). Deeper in the drill hole (260 to 275 m) there are several up to 10 cm wide zones of both low-grade mylonites and cataclasites. In places, a gradual transition between these rocks can be seen.

In core KAV04, between 830 and 910 m, there are several low-angle shear zones with green, epidote-bearing mylonites and cataclasites similar to those encountered in the Äspö tunnel. Here as well, there are transitions between the cataclasites and mylonites. At 863 m, an iron-stained calcite-cemented breccia truncates the green fault rocks (Figure 5-9).

At depths between 290 and 435 m, core KLX06 intersects an approximately E-W striking and steeply south-dipping fault. Between 315 and 389 m, the rock is a proto- to ultramylonite of the surrounding medium- to coarse-grained granite. In this case, the feldspar appears to be recrystallised along the fabric and hence have deformed plastically, contrary to observations in other mylonitic fault rocks. From 389 to 396 m, the mylonites are shattered into a protobreccia to breccia that is cemented by laumontite (Figure 5-10).

Core KLX04 intersects an approximately E-W-striking and gently north-dipping fault. A zone of low-grade mylonites appears at 879 to 876 m, characterised by red staining of feldspar in host rock lenses and fracturing and crushing of feldspars within the fault rock. The very fine-grained matrix seems to consist mainly of green epidote. At 929 and 957 m, there are several-cm thick zones of green cataclasites. Some calcite-filled fractures were also present in the studied core section.

Table 5-1. Overview of drill cores inspected in the project.

Drill core	Inspected section	Reference
KSH03	150–275 m	/Ehrenborg and Stejskal 2004, Mattson 2004a/
KAV04	830–910 m	/Mattson 2004b, Ask et al. 2005/
KLX04	860–980 m	/Mattson et al. 2005/
KLX06	290–435 m	/Mattson 2005/

Figure 5-7. *Photograph from drill core KSH03A at 199 m, showing a porous protobreccia with cm-size clasts between two zones of finer-grained breccia.*

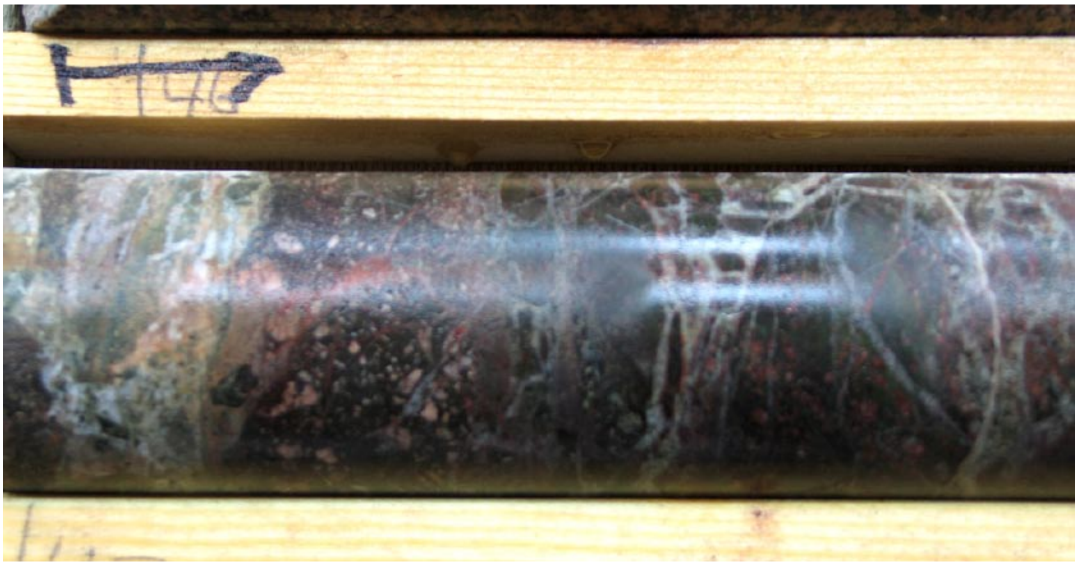

Figure 5-8. *Photograph from drill core KSH03A, at 213 m. There, a 5 cm wide fault shows several faulting events. An 3–4 cm thick zone of epidote-quartz(?) bearing cataclasite locally stained pink, is cut by a narrow zone of dark red carbonate-cemented breccia, in which the former fault rock appears as mm-size clasts. The cataclasite is also cut by a calcite filled veining network.*

Figure 5-9. *Photograph from drill core KAV 04, at 863 m, showing an iron-stained calcite-cemented breccia that truncates a green zone consisting of epidote-bearing cataclasite.*

Figure 5-10. *Photograph from drill core KLX06, at 395 m, showing a protobreccia to breccia that is cemented by laumontite zeolite.*

5.2 Microtexture of fault rocks

A complete list of the high-quality, polished thin section prepared from samples collected in the field, in the Äspö tunnel and from drill cores is presented in Appendix 1. Prior to petrographic analysis, the thin sections were scanned at high resolution, providing a useful image that greatly aids in establishing general relationships and locating critical features for detailed study. Following initial examination of the thin sections, a set of six representative sections, as stated in the contract, were selected for more detailed study and presented in this report. Samples of mylonites and associated cataclasites were mainly collected in the field, whereas core samples provide examples of small-scale faults and fractures as well as associated mineral growth.

In this section, examples of the various microtextures encountered will be presented. The thin sections are all from faults and shear zones in the Oskarshamn area. Of the fifteen thin-sections in the database, only a few will be presented in more detail.

Low-grade mylonites

Thin section A3370A from the Äspö tunnel (–450 m) represents a good example of low-grade mylonite (Figure 5-11), characterised by ductile deformation. The rock has a well-developed planar fabric of pink feldspar and white quartz appearing in lenses surrounded by a very fine-grained, dark green matrix. The matrix mineralogy seems to be chlorite, epidote, white mica and opaques. Quartz clasts show polygonal grain shapes in mosaics that are stringed out as lenses. The quartz mosaics also appear in pressure shadows around feldspars. In contrast, the feldspar appears to be broken down by micro-fracturing into trails of angular sub-grains. Hence, the ductile style of the fault rock is a result of both frictional flow of feldspar, and plastic flow of quartz. Breakdown of feldspar and metamorphic replacement by the fine-grained matrix adds to the ductile style of deformation.

The dark green layers in the thin section represent extremely fine-grained chlorite, epidote, white mica and opaques. Some small clasts of mainly feldspar, sometimes with quartz wings, have an appearance similar to that in the rest of the thin section. Therefore the rock is most likely an ultramylonite. Since no clear cross-cutting relationships have been observed for the mylonites, the differences in grain size probably reflect the intensity of deformation.

Figure 5-11. *Scanned thin section (A3370A) of mylonites encountered in thin section the Äspö tunnel (–450 m). The fault rock has a well-developed planar fabric of pink feldspar and white quartz, which appear in lenses surrounded by a very fine grained, dark green matrix of chlorite, epidote, white mica and opaque. Quartz mosaics are seen in stringed out as lenses and in pressure shadows around feldspars. Feldspar appears to be broken down by fracturing into trails of angular sub-grains. Other places, feldspar seems to be basically entirely replaced by the matrix minerals. The long axis of the thin section is approximately 50 mm.*

Careful examination of the thin section reveals indications of some shear-sense indicators. There are mm-scale extensional shear bands and asymmetric porphyroclasts that can be applied in kinematic analysis: However, this thin section is not oriented, and these observations therefore only show the potential for such analyses.

Cataclasites

An excellent example of this type of fault rock is found in thin section PSM007074 that is from a layered, green cataclasite observed in coastal outcrops near the Power Plant. The host rock has distinct red feldspar, likely related to intergranular fracturing, aggregates of quartz mosaics, and some green amphibole, chlorite and epidote. The dominant fault rock is a dark green cataclasite with angular fragments of quartz and feldspar embedded in a dark matrix (Figure 5-12). The matrix has a grain size of 1–3 μm. Locally, chlorite and white mica can also be identified as clasts. Clasts are angular to sub-rounded and range in size from some mm to c 10 μm. This fault rock is cut by several thin zones of light greyish-green ultracataclasite(?) hosting some 100–10 μm clasts of quartz, K-feldspar and subordinate zircon (Figure 5-13). These clasts are sub-rounded to rounded. SEM studies indicate the matrix of this fault rock to consist of zeolite and/or clinozoisite with a grain size of around 3 μm.

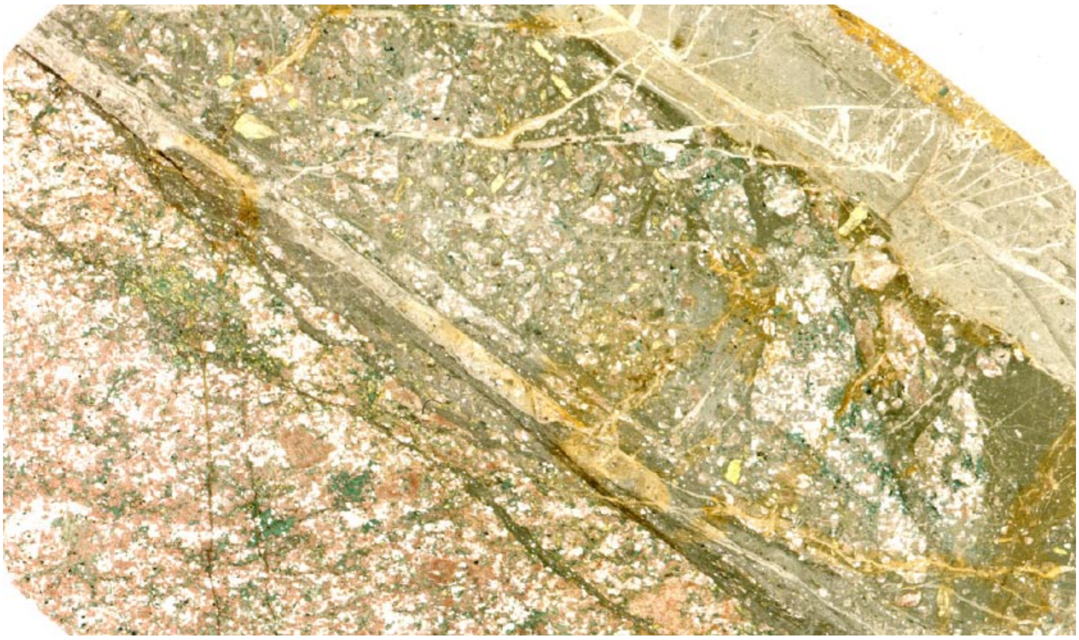

Figure 5-12. *Scan of thin section PSM007074. The rock is a layered, green cataclasite sampled in coastal outcrops near the Power Station. The host rock has distinct red feldspar, related to intergranular fracturing, aggregates of quartz mosaics, and some green amphibole, chlorite and epidote. The dominant fault rock is a dark green cataclasite with angular fragments of quartz and feldspar floating in a dark matrix. The matrix has a grain size of 1–3 μm. Locally, chlorite and white mica can also be identified as clasts. Clasts are angular to subrounded and range in size from some mm to c 10 μm. This fault rock is cut be several thin zones of light greyish-green ultracataclasite(?), as shown in Figure 5-13. Both cataclasites are cut by single fractures or fracture networks of pale veins, illustrated in Figure 5-14. The long axis of the thin section is approximately 50 mm.*

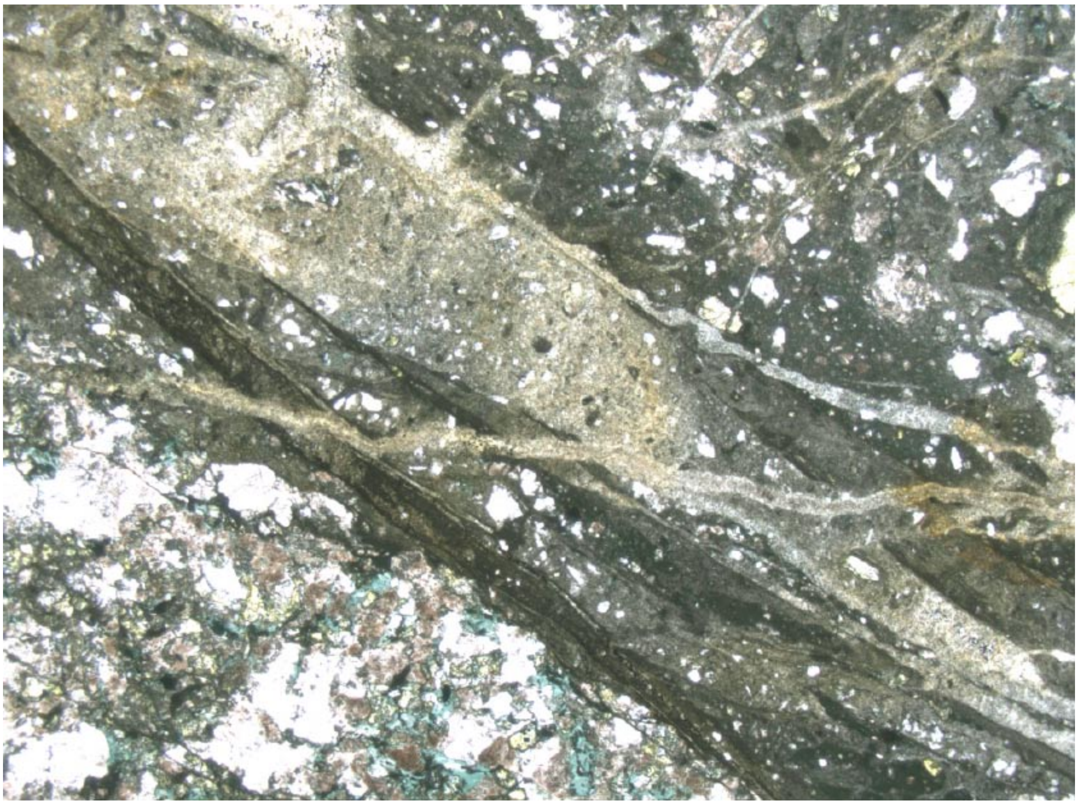

Figure 5-13. *Photomicrograph (PSM007074) of light greyish-green ultracataclasite(?) that cut the darker, surrounding cataclasite. The ultracataclasite hosts some 100–10 µm clasts of quartz, K-feldspar and subordinate zircon. These clasts are sub-rounded to rounded. SEM studies indicate the matrix of this fault rock to consist of zeolite or clinozoisite with a grain size around 3 µm. The picture is 4.36×5.4 mm in the thin section.*

Both types of cataclasite are cut by single fractures or fracture networks with a pale mineral fill (Figure 5-14). They fractures contain small clasts of K-feldspar, which together with chlorite may also be a component of the fine vein-filling material. The chaotic appearance and dilation represented by the fracture networks indicate the rock should classify as a hydraulic breccia.

Thin section KAV04-863 is of special interest. It contains a cataclasite similar to the one described above, and in addition an ultra-fine grained, black to brown-red fault rock with laminae defined by colour variations (Figure 5-15). Clasts in this rock are aggregates of the cataclasite (Figure 5-16), plus sub-rounded small grains of feldspar and quartz. The black fault rock is also found in fracture networks of the host cataclasite (Figure 5-17), suggesting that the rock was mobile. When studied in SEM, fragments down to 2–3 µm can be identified, however, the bulk of the matrix has a grain size below resolution in 1,000 times magnification (Figure 5-18). The sum of observations makes us conclude that the fault rock is a psedotachylyte that is devitrified in the brown-red laminae.

Figure 5-14. *Photomicrograph (PSM007074) of a fracture network, as shown in Figure 5-12. The fractures are filled with clasts of K-feldspar, and a fine matrix of chlorite and K-feldspar(?). The chaotic appearance and dilation represented by the fracture network represent the fundamental observations for classifying the rock as hydraulic breccias. The picture is 4.36×5.4 mm in the thin section.*

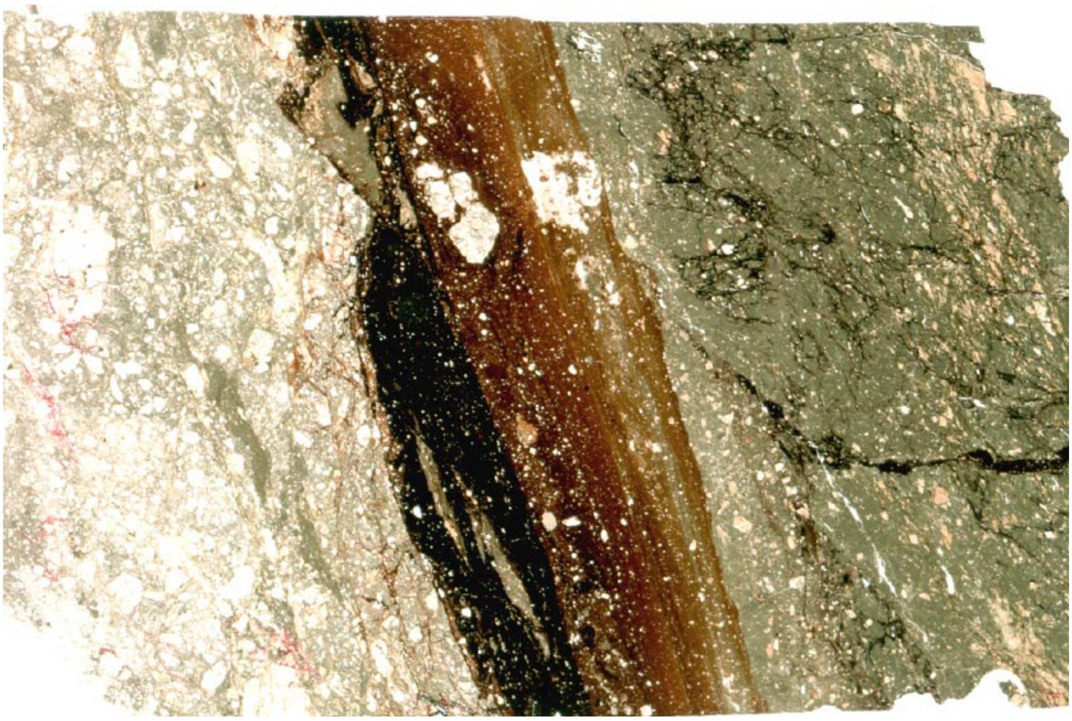

Figure 5-15. *Scan of thin section KAV04-863, showing a cataclasite similar to the one described in other photographs. In addition, there is an ultra-fine grained, black to brown-red fault rock with laminae defined by colour variations. The rock is likely a psedotachylyte, since it injects into the wall rocks, and has a minimum grain size that is exceeds the resolution of the SEM. This matrix could therefore be glass. The long axis of the thin section is approximately 50 mm.*

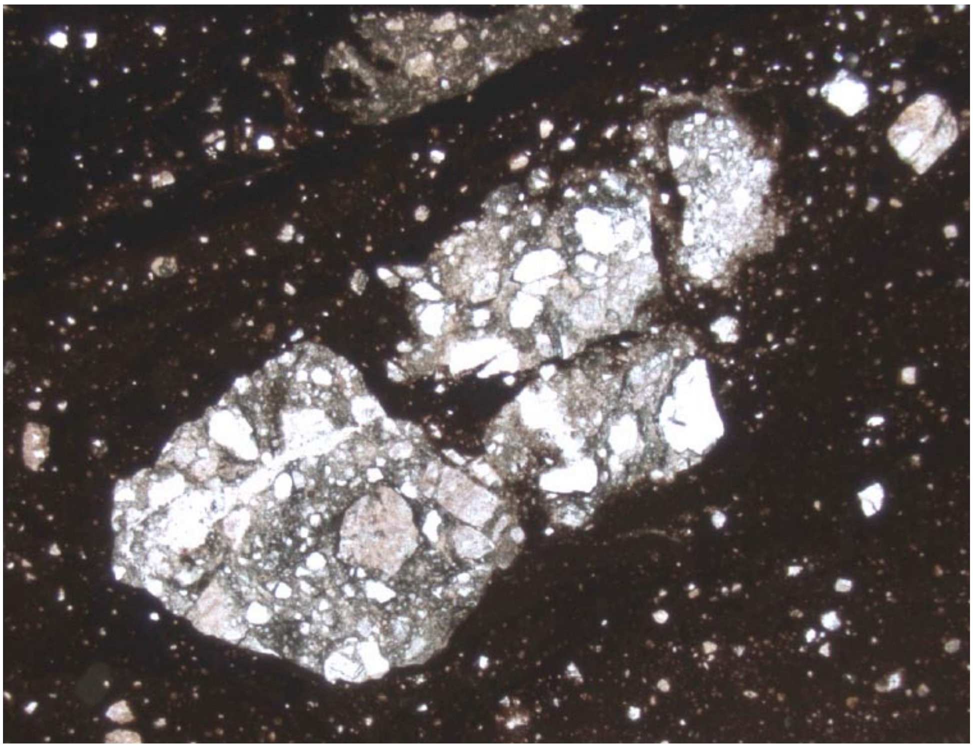

Figure 5-16. *Photomicrograph showing an enlargement of cataclasite clasts in the psedotachylyte described in Figure 5-15. Note sub-rounded small grains of feldspar and quartz and colour shadings along laminae, likely related to devitrification of glass by shear reactivation of the rock. The picture is 4.36×5.4 mm in the thin section.*

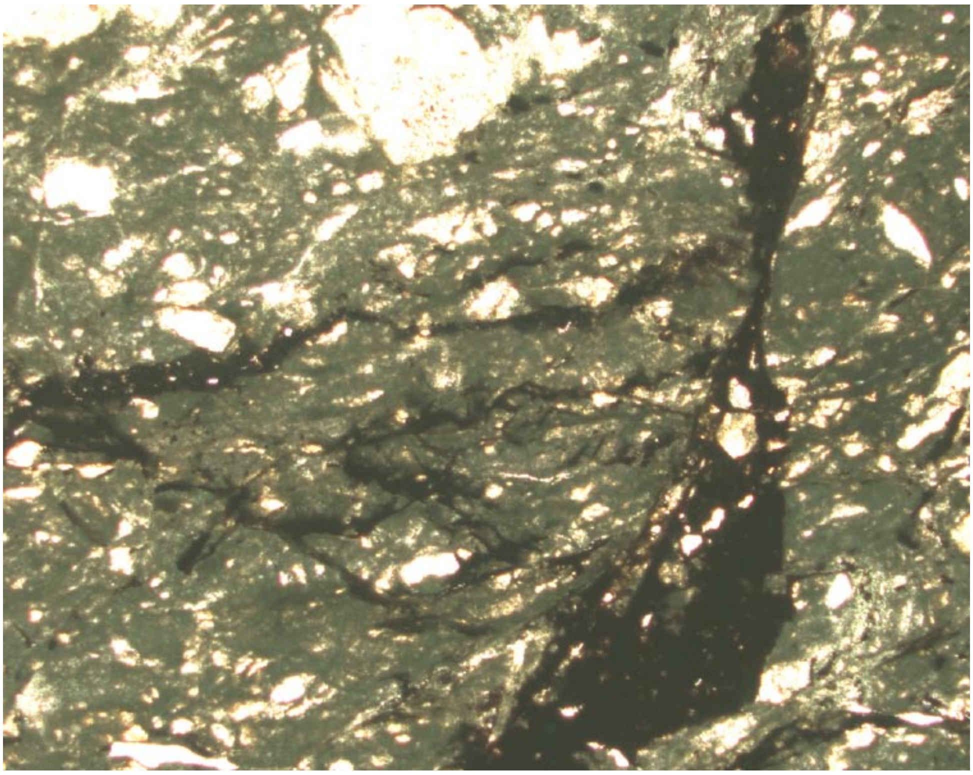

Figure 5-17. *Photomicrograph showing the black fault rock in fracture networks of the host cataclasite (see Figure 5-15). The material seems to have injected into small fractures and voids. The picture is 4.36×5.4 mm in the thin section.*

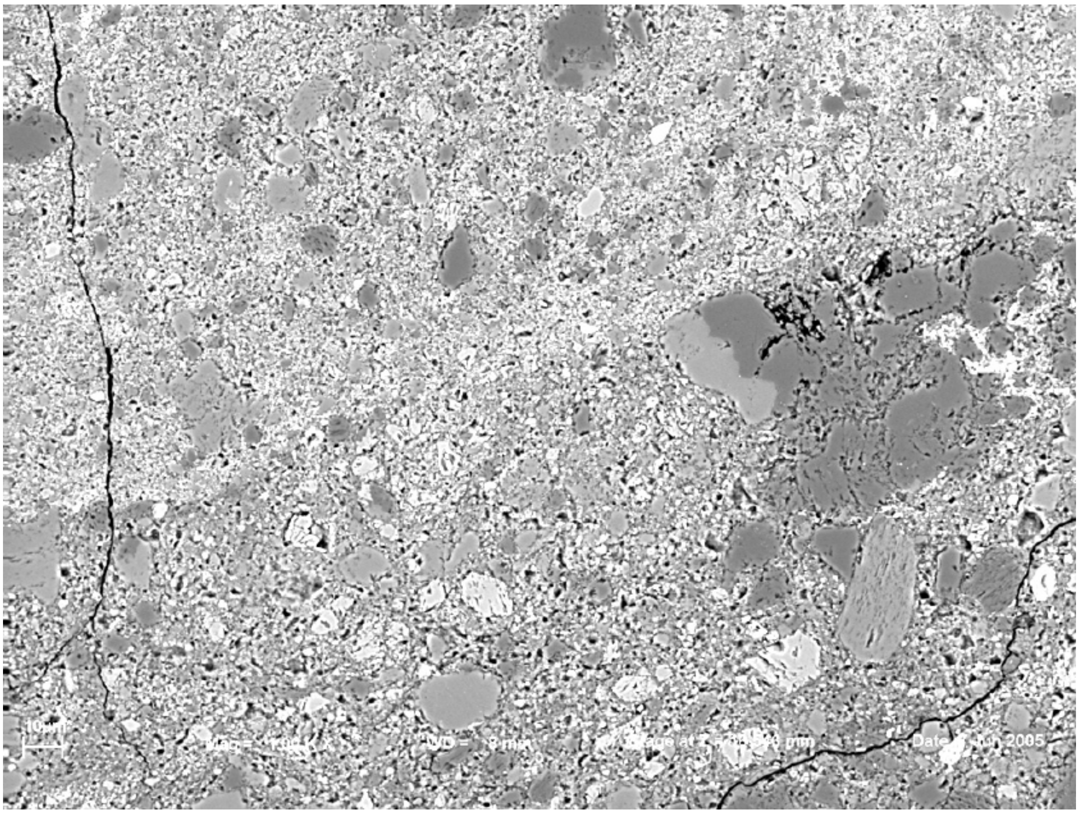

Figure 5-18. *Scan of psedotachylyte from SEM, showing grain fragments down to 2–3 μm. The bulk of the matrix has a grain size below the resolution of 1,000×. Note scale bar in the lower left corner.*

Breccias

This section KSH03-A213 is from a drill core. It reveals several phases of fault rocks, starting with the green cataclasites. These cataclasites are cut white quartz veins (Figures 5-19 and 5-20), which further are cut by brown-pink layers of cataclasite to ultracataclasite. The latter rock has sub-rounded clasts of feldspar and quartz, and a matrix of the mentioned minerals plus likely some zeolite or clinozoizite. Grains in the matrix have sizes between 5 and 2–3 μm.

Thin section KLX06-395 from a drill core is presented as an example of cemented breccia. This rock contains more or less shattered fragments of feldspar and quartz in a pinkish-red matrix (Figure 5-21). The latter is made up of very fine grained Laumontite(?), which likely have filled in the pore volume of the initially porous fault rock and thereby created a secondary cohesion in the rock.

Figure 5-19. *Scan of thin section KSH03-A213, showing several types of fault rocks. The more voluminous is a green cataclasites, which is cut by white quartz veins. These veins are cut by brown-pink layers of cataclasite to ultracataclasite. The latter rock has sub-rounded clasts of feldspar and quartz, and a matrix of the two mentioned minerals plus some zeolite or clinosoizite. Grains in the matrix have sizes between 5 and 2–3 µm. Long axis of the thin section is approximately 50 mm.*

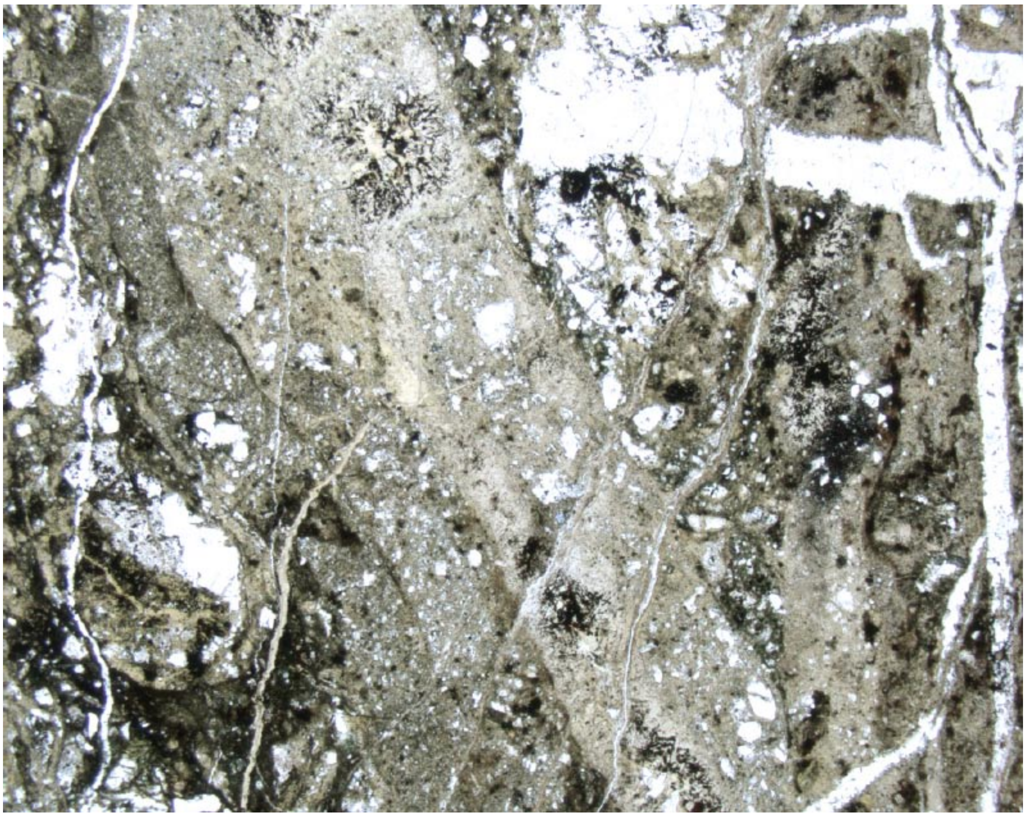

Figure 5-20. *Photomicrograph showing an enlargement of Figure 5-19. The structural chronology is well displayed, with the thicker layer of cataclasite being ut by the quartz vein. The thick vein is truncated by a thin cataclastic shear zone. The picture is 4.36×5.4 mm in the thin section.*

Figure 5-21. *Scan of thin section KLX06-395, showing an example of cemented breccia. This rock contains more or less shattered fragments of feldspar and quartz in a pinkish-red matrix of very fine grained laumontite(?). The long axis of the thin section is approximately 50 mm.*

6 Summary and conclusion

The purpose of the investigation is to carry out a pilot study of the primarily brittle structures at Simpevarp, Äspö and adjoining areas, and to assess the potential of more extensive kinematic studies. The report should also recommend further investigations in order to achieve an improved understanding of the kinematic pattern of faults in the area of interest. The summary and conclusions are therefore related to possible studies that can be conducted in the area, seen in the light of the brief results presented above.

The main conclusions are:

1. The low-grade mylonites represent a challenge when it comes to establishing sense-of-shear. This is so because no stretching lineation or shear bands were observed in outcrops or cores. However, there are microscopic extensional shear bands in the thin sections.
2. Low-grade mylonites show transitions towards cataclasites in that the competing processes of plastic and frictional flow varies. In general, this depends on strain rate, mineral behaviour and metamorphic reactions following breakdown of feldspar.
3. The sequence of fault rocks observed in this study is compatible with deformation events occurring at gradually decreasing crustal depth, i.e. they follow an expected unroofing succession. Progressively more brittle faulting, ending in breccias cemented by diagenetic minerals, followed dominant plastic deformation under low-grade metamorphic conditions.
4. There are very good exposures of faults in road sections and along the coast in outcrops that were visited near the Power Plant. Distinct populations as well as fault rocks can be identified, which most likely reflect damage zone deformation to the nearby master faults. Since these faults show good slickensides, they can be used in kinematic analyses. For a more comprehensive kinematic analysis, it is likely that a similar study of road (and coastal) outcrops in the wider region of interest would yield important data
5. The nature of fault rocks and their patterns of cross-cutting relationships are important in structural analysis. Based on in their overall geometry and matrix mineralogy, brittle fault rocks can in many cases be separated into categories that most likely formed during separate events. As an example, in this study, five distinct events can be identified in one thin section. In the lower part of the Äspö tunnel, the chronology of faulting can be worked out on the basis of cross-cutting faults exposed in clean tunnel walls. Combined with data from different fault populations exposed on the surface, such information would also be of considerable value to a kinematic study.
6. As a general conclusion, it is considered that a more comprehensive structural study may lead to improved understanding of the kinematic pattern in the area of interest. This would require that relevant data can be obtained from a variety faults and fault populations with different properties and orientations. Based on the conclusions from the pilot study, such data may be derived from detailed fieldwork on surface outcrops combined with data on relative fault chronology the lower part of the Äspö tunnel. Field and core studies should be supplemented by a general study of the petrography and the micro-structural history of the faults.

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Appendix 1

List of localities and samples

Locality_ID	North	East	Samples
Simpevarp field localities			
PSM007065	6365524	1552260	
PSM007066	6365686	1552346	
PSM007067	6365633	1552353	
PSM007068	6365555	1552263	
PSM007069	6365562	1552305	
PSM007070	6365959	1552572	Cataclasite
PSM007071	6366102	1552754	
PSM007072	6365990	1552720	
PSM007073	6365963	1552640	
PSM007074	6365952	1552583	Layered cataclasite
PSM007075	6366198	1552308	
PSM007076	6366119	1552356	
PSM007077	6366195	1552728	
Äspö Laboratory			
	Approx depth		
A1180–1181			Fault in gran gneiss
A1650			Fault rock
A3084			Granite mylonite/cataclasite
A3370_A	450 m		Mylonite
A3370_B	450 m		Fault rock
B3420_A			Fault rock
B3420_B			Myl/cataclasite
Drill cores	**Depth**		
KSH03A	198 m		Breccia
	213 m		Polyphase shear zone
KAV04	863 m		Cataclasite/pseudotachylyte(?)
	893 m		Calcite breccia
KLX06	380.3 m		Protomyl/mylonite
	394.9 m		Laumontite-breccia