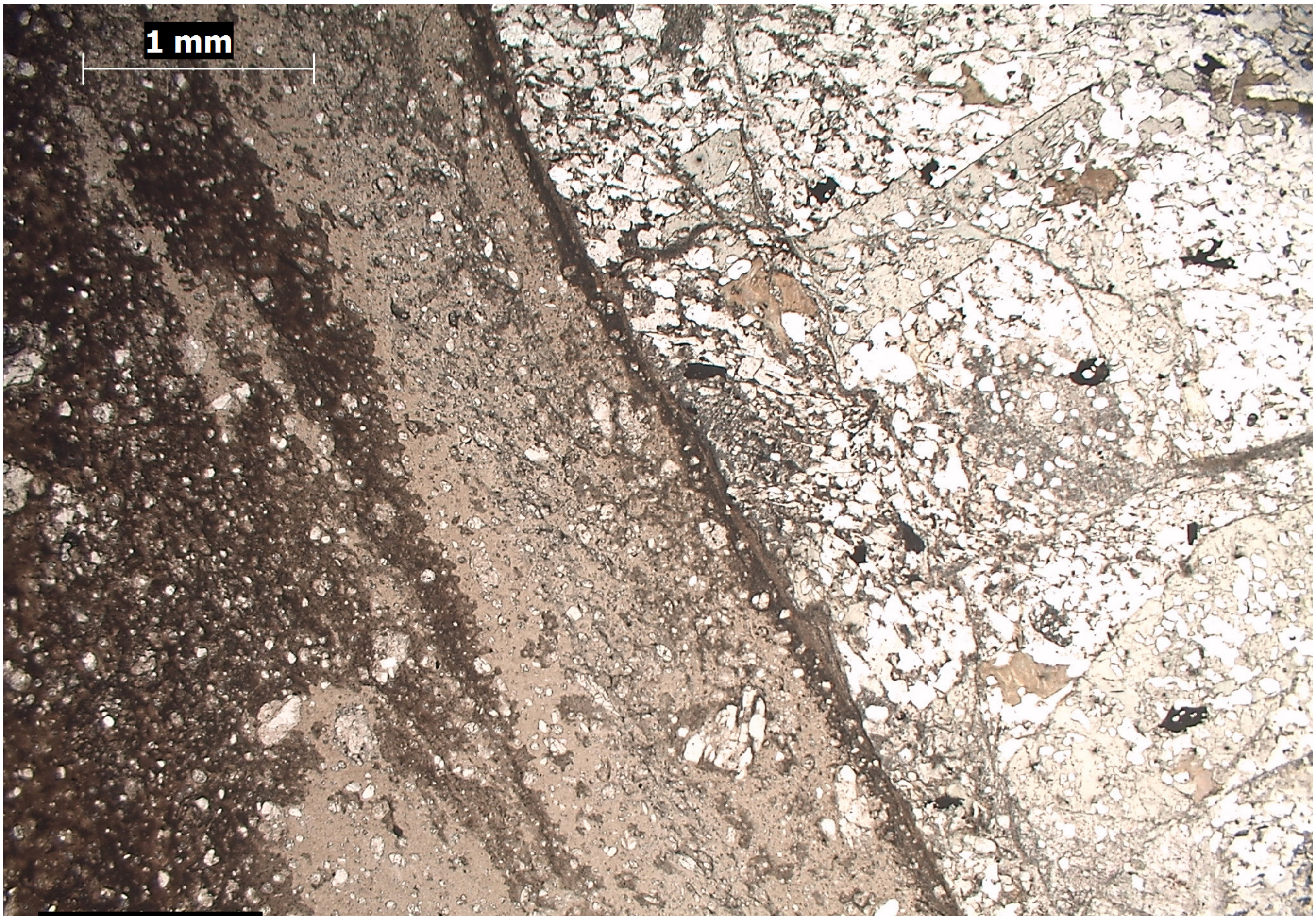
Master Thesis

Degree Project in
Geology 45 hp

The Pseudotachylites of Tännforsfältet, Western Jämtland, Swedish Caledonides

Amanda Bergman



Stockholm 2017

Department of Geological Sciences
Stockholm University
SE-106 91 Stockholm

Abstract

A fine grained, glassy structure occurring in mylonite zones in Tännforsfältet has previously been described as pseudotachylites, thought to have formed during the latest stage of deformation in the Caledonian orogeny (Beckholmen 1984a). The term "pseudotachylite" is to this day a somewhat unclear concept, as it by some researches is used to describe fine grained, glassy looking material on fault planes, and by others is strictly used for fault plane material that at some point has undergone a stage of melting due to high pressure seismicity. In this thesis a detailed study of the pseudotachylite structures from Tännforsfältet has been carried out, with the addition of a previously undescribed, similar structure at Greningen. The main part of the analysis was done on oriented thin sections of these fracture veins, with the aim to assess the presence of a melt phase during the formation event. The observations led to the conclusion that the pseudotachylite structures have a melt origin, except for the Grenignen fracture vein material. Furthermore did the analysis of the samples from Håltbergsudden and Stalltjärnstugan reveal two pseudotachylite forming deformation events, presumably separated by a phase of ductile deformation. This sheds new light on the deformation history of the Caledonian orogeny and confirms current understanding of re-activation of fault planes.

Contents

Introduction

The Scandinavian Caledonides are well known for nappe stacking and thrust tectonics, which covers a region of several hundreds of kilometers of lateral displacement (Törnebohm, 1888). These tectonic thrust sheets have been grouped into different nappe units, which in turn are grouped into four main allochthons, Lower-, Middle, Upper and Uppermost Allochthon. The focus of this thesis is the Köli Nappe Complex (KNC) which belong to the Upper Allochthon. The Köli Nappe Complex's southern most outcrop is found in Tännforsfältet, in the western mountains of Scandinavia (the Scandes). Why this area is of interest in this thesis is due to previous studies which documented mylonite zones with brittle deformation causing pseudotachylite formation (Beckholmen, 1978). The origin of pseudotachylite structures and their definition have been an ambiguous concept since the term was first introduced in 1916 (Shand, 1916). This millimeter to centimeter scale structure caused by melting and crushing of the rock during sudden rupture of the mountain as defined by Jackson (2005) and are expressed in the field as thin planes of fine grained to glassy material on fault planes. The presence of pseudotachylites on fault planes has widely been accepted as a feature indicating palaeoseismic faulting and has in the literature been referred to as "fossil earthquakes".

In the area of Tännforsfältet the brittle-phase structure of pseudotachylite has been inferred to represent a late stage deformation phase in the Caledonian orogeny (Beckholmen, 1982). However, little is known about the pseudotachylites in this area and with an increased understanding of these structures, it has become relevant to conduct a more detailed study of these fracture veins. During this project, five previously described localities of pseudotachylites (Beckholmen, 1982) were revisited, including a sixth newly discovered locality at lake Greningen (fig. 1). At these localities, studies where done on the fault rock that contained fracture veins which fit the description of a pseudotachylite melt. In addition to rock samples, both measurements of the foliation and lineation adjacent to the pseudotachylite structures were taken. At the newly discovered pseudotachylite-locality of Greningen a more detailed study of the fault planes was carried out.

By investigating pseudotachylites in relation to microstructures in the surrounding host rock, up to five different deformation events have been recognized. Shear sense indicators seen both in the host rock and in the pseudotachylite suggest the direction of movement in the Köli Nappe Complex with reoccurring top-W normal faulting. The most interesting finding, however, is that of two pseudotachylite-forming events, separated with a phase of ductile deformation. This sheds new light on the deformation history of the Köli Nappe Complex in the Scandes. Moreover, the occurrence of different pseudotachylite generations confirmed our current understanding of seismically re-activating of fault planes.

Aims for this project

The main aim of this thesis is to verify the presence of pseudotachylites and try to determine whether they are derived from a melt or not. Further aims include attempting to put the pseudotachylite formation in relation to other deformation events.

Geological background

The two continents of Baltica and Laurentia collided in the Silurian to Early Devonian (Gee et al., 2012, 2008) and formed a mountain range with extensive lateral thrust displacement, first suggested to be up to 100 km wide (Törnebohm, 1888). Today the orogeny is inferred to have been comparable in size to that of Himalaya and is exposing a 300 km wide lower to middle crustal section from within the orogeny (Gee et al., 2008). The thrust sheets were emplaced onto the platforms of Baltic and Laurentia with the eastern flanks now exposed in the western Scandinavia and the western flank in eastern Greenland. The thrust sheets on are grouped in four major units, going from the Lower Allochthon with rocks evident to be derived from the Baltioscandian platform, to the Middle Allochthon originating from the outer margin, to the Upper with oceanic driven terranes and Uppermost Allochthon with Laurentia- platform affinities (Gee et al., 2012, 2008, 1985; Robinson, 1995).

The Köli-Nappe-Complex (KNC) belongs to the Upper Allochthon with its southern most outcrop of the Swedish Caledonides found in the Tännforsen Synform (fig. 1). The typical Köli stratigraphy is of variation in metasediment and metavolcanic sequences, in part of Early Palaeozoic age, as determined further north in the northern Jämtland (Beckholmen 1984b; Kulling, 1933). The rock units at Tännforsfältet were previously described by Kulling (1933) to be of Ordovician to lowermost Silurian age, as inferred from the fossiliferious Björkvattnet-Virisen area. The area of Tännforsfältet was mapped in the early eighties by Beckholmen (1984a) who made a thorough study of the rock units and their structural geometry. The metamorphic grade was found to increase from the southeast to the northwest with its biotite-, hornblende-, garnet-bearing grabenschiefer. The rocks at this area mostly consist of calcareous schist, metasandstones and phyllites and of the higher-grade hornblende-garnet schist Garbenschifer. The coarser sandstone beds in the south contained quartz, albite, calcite, white mica and chlorite, with the schistosity defined by the phyllosilicates. Further north, as the metamorphic grade increases, biotite, hornblende and pyrite are present in the form of porphyroblasts, all partly chloritized.

Beckholmen (1984a) also identified five different major tectonic units, divided into two lenses and three nappes. The lenses describe units at the base of the nappe complex in contact with the underlying Seve unit (Middle Allochthon). The nappes themselves are defined as the three main tectonic units going from SE to NW: the Duved, Gevsjön and Middagsfjället Nappes. These major units are divided by two SW-NE trending mylonite zones, one going from Håltbergsudden (Fröding 1922 cited in Beckholmen 1984b) and the other passing Finntjärnen (Beckholmen 1982) through the area of Stalltjärnstugan and upwards above Häggsjön (fig. 1). These three nappes were previously defined as the Gevsjön Formation (Beckholmen, 1978) and have been shown to be derived from different tectonic units, based on the presence of the mylonite zones (Beckholmen, 1984). Six phases of deformation have also been inferred (Beckholmen, 1983). The first deformation, D1, have been inferred by tight-isoclinal pre-schistosity folding F_1. D2 has been inferred to be syn-schistosity folding with axial planes with a gentle westward dip. D3 occurred with large scale, easterly overturned F_3 –folds, giving a steeper westerly dip of S_3 foliation. D4 is represented by folding of S_3 with axial planes close

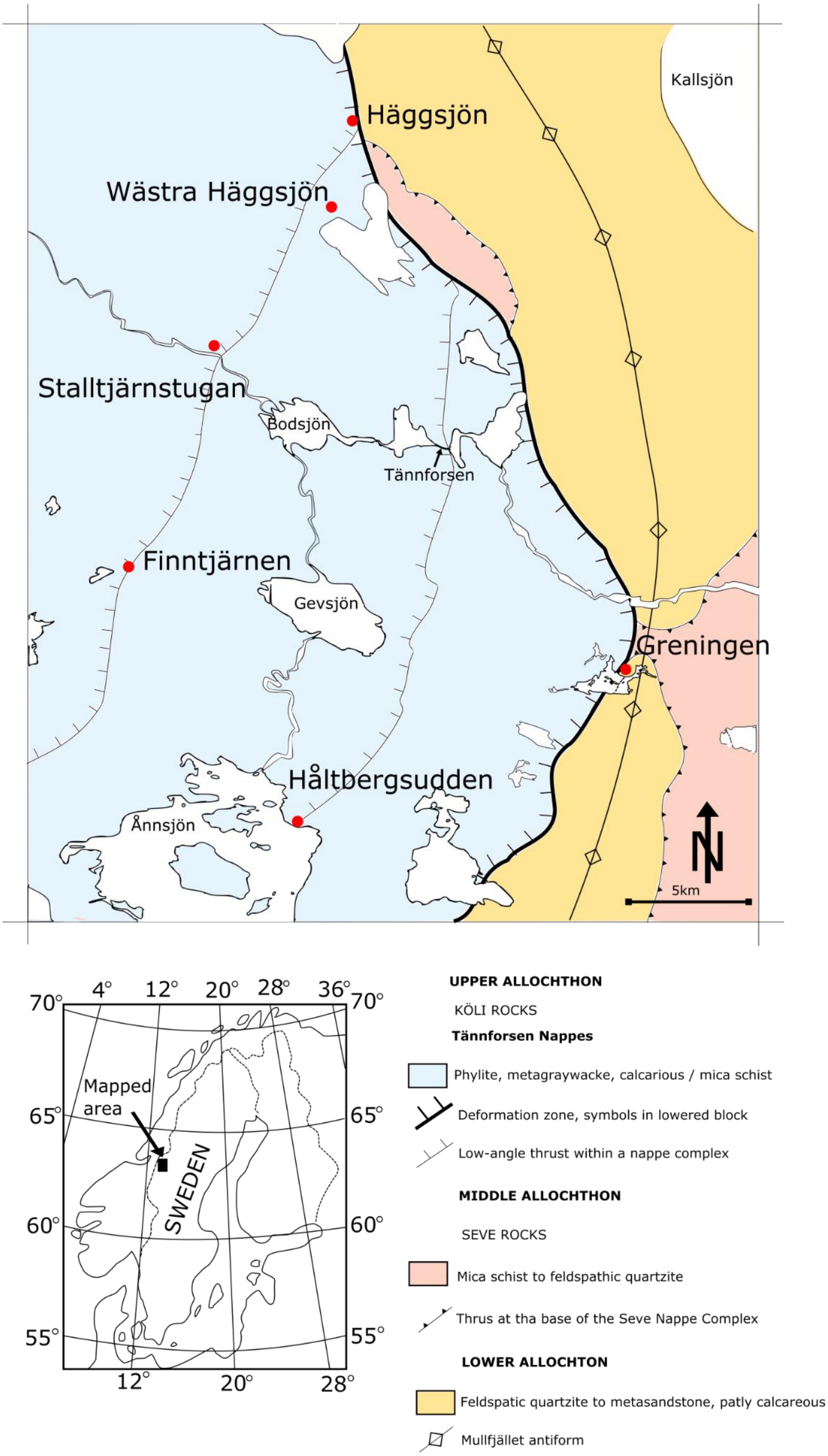


Figure 1 – Map over Tännforsfältet, central Sweden. The area is a synform, with the Riksgränsen Antiform to the west, outside the map area, and the Mullfjället antiform to the east. The two mylonite zones are defining three nappe units and are shown on the map as low-angel thrust within the Köli Nappe Complex. The different studied localities are marked as red dots. The localities belonging to Finntjärnen-Mylonite-zone and to Håltbergsudden-Mylonite-zone have previously been studied by Beckholmen (Beckholmen 1984, 1982, 1978). The new localitiy is that of Greningen, which is located very close to the deformation zone related to Mullfjället antiform. In this calcarious phyllite of the Gevsjön Formation the flat lying, westerly dipping schistosity planes are defined by white mica and chlorite. Biotite, hornblende and pyrite occurs as porphyroblasts. The deformation grade increases upward, to the north-west, from a calcarious phyllite to grabenschiefer (Beckholmen 1982).

to that of F_2. D5 is interpreted as post-schistosity folds with crenulation cleavage visible in S_5, and finally D6 with kink band formation and movements inferred to have caused pseudotachylite formation in the mylonite zones.

The presence of pseudotachylites in the mylonite zones are inferred to represent an early ductile deformation phase followed by brittle deformation event causing brecciation and pseudotachylite formation (Beckholmen, 1982). Five key localities mark the pseudotachylite findings as largely following the mylonite zones (fig. 1) (Beckholmen, 1982). The mylonite zones are described to show grain size reduction, re-crystallization of mineral and elongation of quartz and white mica grains. The Håltbergsudden-Mylonite-zone is a 10 m thick unit of calcareous phyllite with the pseudotachylite occurring as thin layers parallel to the schistosity of the rock (Fröding, 1922 cited in Beckholmen 1982). The glassy layer of pesudotachylite is described as blue-gray in hand sample and yellowish to brown in thin sections. Other features such as off-shots (in this work interpreted as injection veins) flow structures and amygdales were also observed. Further north of this zone, in the area southeast of Häggsjön, pseudotachylite structures were also recognized. The Finntjärnen- Mylonite-zone is not clearly defined further north as different trajectories of movements were recognized (Beckholmen, 1982). In this zone the pseudotachylites were found both within the ductilely foliated deformation zones near Finntjärnen and Stalltjärnstugan as well as in the less-foliated rock in the Häggsjön area. At the locality of Finntjärnen the melts were described to contain larger quartz and calcite aggregates and internally folded layers of the melt. Some bubbly texture of the melt matrix were also described as either vesicles or spherulitic microlites (see definition below). The pseudotachylites, especially in the Häggsjö area, were observed to have developed both parallel and crosscutting to the foliation. Most interesting, however, was the observation of pseudotachylite crosscutting porfyroblastic amphibole crystals. Beckholmen (1982) concluded that this crosscutting relationship of higher grade minerals, such as the amphibole hornblende, are indicative of a brittle pseudotachylite deformation event occurring post peak metamorphism. However, the pseudotachylite deformation event in Tännforsfältet has been interpreted to be partly ductile, as argued by the ductile deformation of breccia and ultra-cataclasite in connection with the pseudotachylites. Nevertheless, Beckholmen (1982) concluded that the pseudotachylites of Tännforsfältet define a brittle phase in the latest stage of deformation.

Classification of pseudotachylite

The term "pseudotachylite" has been, and still is, a somewhat disputed term. It was first used to describe aphanitic, glassy veins and networks in the Vredefort Dome by Shand in 1916 (Shand, 1916). A number of different alternatives have been suggested both prior to, and since Shand, including *crushed rocks* (Clough et al., 1909; Peach et al., 1888) and *microlitic or glassy ultramylonie* (Wallace, 1976). In the Glossary of Geology the term pseudotachylite is defined (Jackson, 2005):

"(a) A dense rock produced in the compression and shear associated with intense fault movements, involving extreme mylonitization or partial melting."

Jackson further define pseudotachylite formation as:” (b) some pseudotachylite have behaved like an intrusive and has no structures obviously related to local crushing.”

As described by Lin (2008), this definition is not clear enough for researchers in the field of fault-tectonics, and some therefore want to restrict the term pseudotachylite strictly to melt originated veins whereas some argue that there is a gradational transition between melt-pseudotachylite and pseudotachylite-like cataclastic veinlets (Kirkpatrick and Rowe, 2013; Wenk et al., 2000). The distinction between a melt origin pseudotachylite and a cataclasite, where the rock is simply crushed, is of great importance since it put distinct constraints on the seismic energy during the fault event (Kirkpatrick and Rowe, 2013). Furthermore, throughout the literature there is also an unclear use of the term as either being generic, e. g. formed from melting or crushing, or descriptive, e. g. a dark, glassy vein (Reimold, 1995). There are also uncertainties in distinguishing between fault-related pseudotachylites and impact-generated melts. A fault-related pseudotachylite occurs within a fault shear zone, where the frictional heat becomes high enough to melt the rock during a seismic rupture (e.g. Dietrichson 1952;Sibson, 1975). The impact-generated melt, however, can be derived from two processes; (1) shock brecciation with melting and (2) from frictional melting at the impact site (Reimold, 1995). The resulting frictional melts, and/or crushed material from both fault-related and impact-related pseudotachylites are shown in the field as planar features. These planar features are sometimes called the generation plane, which can be seen with injection veins branching off into the host rock in co-seismic fractures (Ferré et al., 2015; Lin, 2008).

When describing a fine grained, glassy planar structure in field it is not always evident whether it is a pseudotachylite or not. For this reason, a number of identification features are used to distinguished a pseudotachylite melt from that of other structures, most typically that of cataclasite. Amongst the most common features to classify a pseudotachylite from a cataclasite is the ratio of host rock fragments to melt, the roundness of clasts, flow structures, presents of vesicles, amygdales, microlites and injection veins (Beckholmen, 1984; Fabbri et al., 2000; Lin, 1999; Lin et al., 2005; Ray, 2004, 1999;Berlenbach and Roering, 1992; Magloughlin and Spray, 1992).

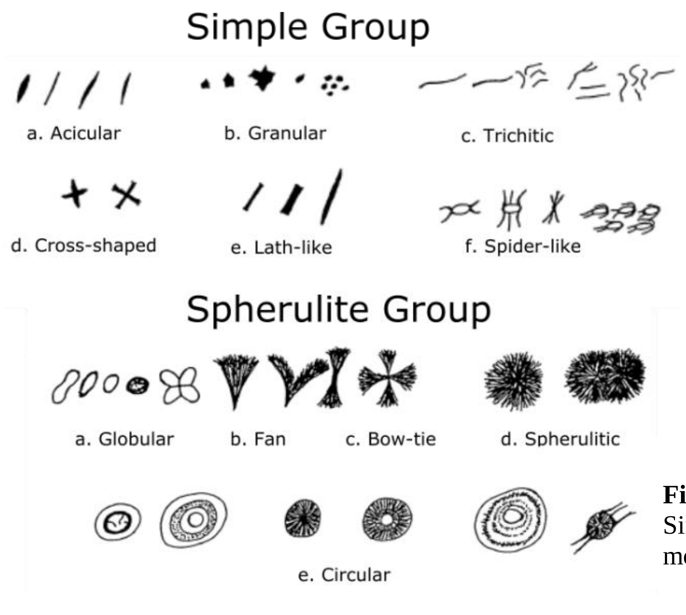


Figure 2 – Microlite shapes from the Simple Group and the Spherulite Group, modified from Lin 2008.

These characteristics features arise in different ways, but all indicating that the material was once in a melt phase. Vesicles and amygdales are thought to arise from gas extrusion from the melt and are two of the features that speaks most strongly of a melt origin (Lin, 2008, 1994a). Microlites are micro-sized crystal, also commonly found in melt-originated pseudotachylites (Lin, 2008). These crystals are generally smaller than 6-7 µm and have a variety of shapes that can be divided into different groups (Lin, 1994a). The first of these are called the Simple group, which comprises the most basic forms (see figure 2). The most common form found in pseudotachylites is that for the Lath-like shape found in the Simple Group (Lin, 2008). The mineralogy of microlites can often be identified in optical microscopes but the chemical composition is most often measured using finer tuned machines such as scanning electron micro (SEM) or by an electron microprobe analyzer (EMPA) (Lin, 2008).

In this study, two distinctly different pseudotachylite-like structures are investigated: one is a fine-gained, glassy structure found on fault planes in the typical Köli -phyllite and –schifer rock, whereas the other occurs as a glassy black network and veins in an un-foliated quartzite at the locality of Greningen. In the text, these pseudotachylite structures are most often referred to as fracture veins and in the thin section descriptions the abbreviation "Pt" is used.

Methods

Measuring and sampling in field

During the fieldwork, the focus was on identifying pseudotachylites on fault planes and to take oriented samples of these. Seventeen samples in total were taken from the locality of Håltbergsudden, Finntjärnen, Stalltjärnstugan, Wästra Häggsjön and Häggsjön. The foliation and the most pronounced lineation of the rock was measured with a compass or with a smartphone using the RockLogger software. Several measurements were taken in close proximity so that a representative mean of the locality could be gained. The measurements was later analyzed using the Stereonet software by Allmendinger (2013). The stereonet plotted the data on a lower hemisphere projection and an analytical tool for mean-calculations was used.

A more detailed mapping was done at the locality of Greningen, where an abundance of dark, glassy looking veins. These vein occurred in the bedrock on fault planes. A total of 67 measurements of this fine grained to glassy structure were taken. The measured fault planes were plotted in a lower hemisphere projection in the Stereonet software by Allmendinger (2013). Five samples containing these dark veins, as well as cataclastic material, were taken and studied in a peterographic microscope.

The sampling was done by the conventional method of using a rock hammer, safety glasses, marker pens and sampling bags. The sample ID, its foliation and lineation were noted together with the coordinates of where it was taken. Each sample was marked with at top-notation and a mark for the foliation plane. If the sample was large enough everything was marked on the rock as shown in figure 3A. If the sample was too small, only the top and the foliation plane were marked.

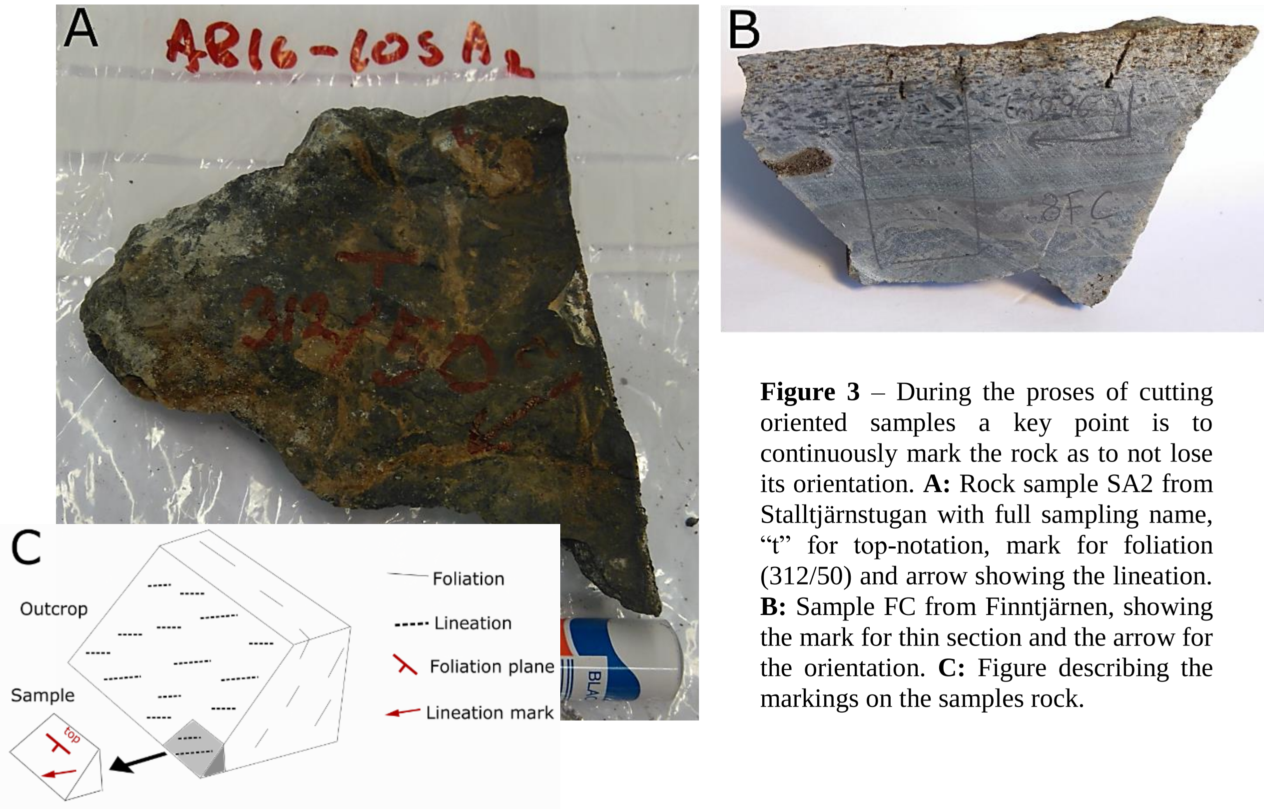


Figure 3 – During the proses of cutting oriented samples a key point is to continuously mark the rock as to not lose its orientation. **A:** Rock sample SA2 from Stalltjärnstugan with full sampling name, "t" for top-notation, mark for foliation (312/50) and arrow showing the lineation. **B:** Sample FC from Finntjärnen, showing the mark for thin section and the arrow for the orientation. **C:** Figure describing the markings on the samples rock.

Thin section preparation

The rock samples were first examined optically at Stockholm University and those that looked most promising were cut into cubes of standard size (10x20x35 mm) in preparation for making thin sections. The cutting was done perpendicular to the foliation and parallel with the lineation, so that the resulting thin section shows a side parallel with the shear sense. This way of cutting also enables mineral identification as the resulting thin section displays the B-surface of the minerals. This crystallographic orientation gives a low interference color of the mineral quartz, which is used to correlate the interference colors of the surrounding minerals (Nesse 2012). During the rock cutting the resulting slabs of rock material were continuously marked (fig. 3B) as to not lose the field orientation, and hence the correlation both to the compass measurements the sear sense indicators observed within the samples themselves. A total of 24 samples were chosen, 5 from Greningen and 17 combined from the other localities. After the cubes were marked and labeled correctly they were sent to Würzburg University, Germany, for thin section manufacturing.

Microstructural analysis

The microstructural analysis were carried out at Stockholm University with a petrographic microscope of the Nikon model. Both plane and crossed polarized light was used, with some additional use of reflecting light for ore mineral identification. The analysis had two focuses: (1) the structures in the mylonitic host rock and (2) identifying pseudotachylite-like features of the fracture vein. The observations made on the mylonitic host rock was primarily concerning crosscutting relationships and shear sense indicators. However, these were noted both within the host rock mass itself and in relation to the fracture vein sampled. In order to determine if the fracture vein contained any evidence of a melt origin, typical identification features such as compositional banding, flow structures and injection veins were noted. Clasts within the fracture vein were also of interest since they are a strong indicator of melt-originated pseudotachylite. In addition to this, observations relating different fracture vein to each other were of great importance, since it enabled correlation between different deformation events.

Results

Field measurements

All the measurement taken in field were plotted on a stereonet using the Stereonet software by Allmendinger (2013). The mean of the compass measurements as calculated by the stereonet program that used a built in tool for weighted mean calculations (Allmendinger, 2013). In the five localities connected to the mylonite zones, the foliation gave a general W-dipping orientation whereas the stretching lineation shows more pronounced S-W direction (fig 4). In the foliated Grabenschiefer rock at Finntjärnen the stretching lineation is especially obvious, with boundins formed in the amphiboles oriented in the stretching direction (fig. 5). The orientation of the sampled fracture veins and cataclastic planes largely follows the W-dipping foliation at each locality. At Stalltjärnstugan the angel between the fracture vein and the foliation is largest. At the locality of Häggsjön, two distinct successions of fracture veins could be measured, one more steeply dipping than the other.

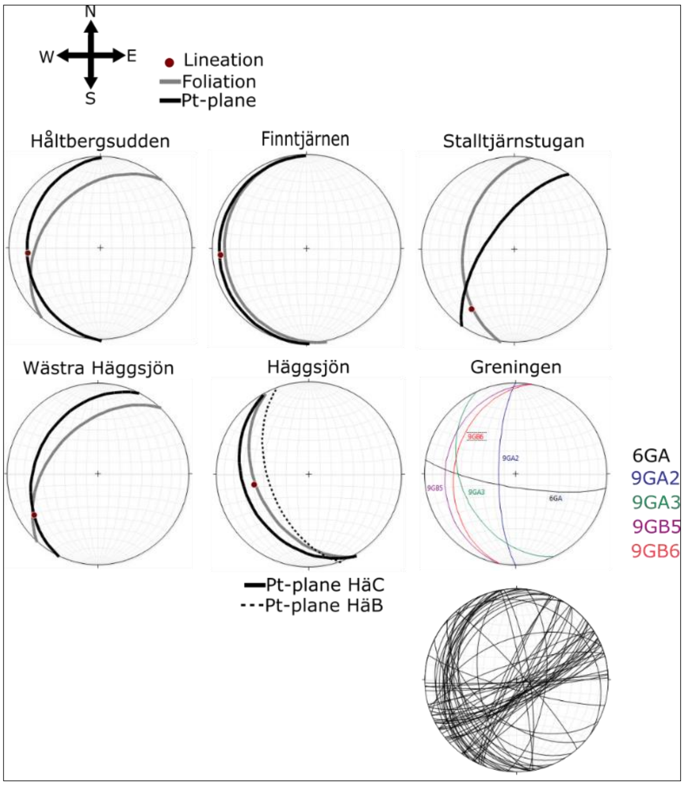


Figure 4 – Stereonet plots of the mean of the filed measurements of foliation and lineation together plotted together with the fracture veins (Pt-planes). The foliation is generally dipping to the W, as does the fracture veins. From Häggsjön two fracture veins were sampled, both showing the same orientation but slightly different dip. From lake Greningen a total of 67 measurements of fracture veins on fault planes were taken. As shown in the lower most stereonet these display the presence of a conjugate fault set. The samples acquired from this location mostly represents the shallow E-dipping set.

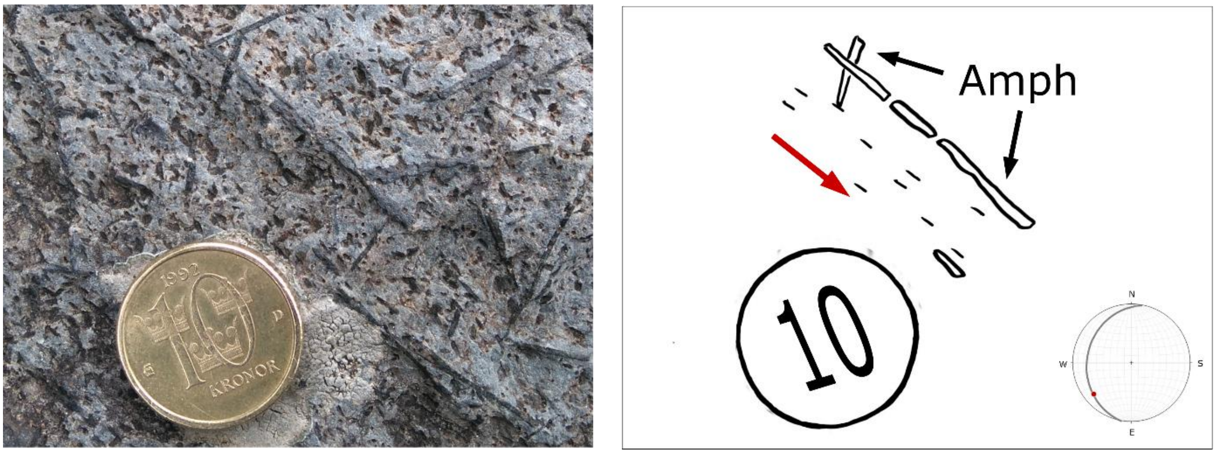


Figure 5 – The typicla Grabenshifer rock unit from the location of Stalltjärnstugan. The amphibole crytsals oriented with the streaching lineation shows boundins. The coin is 1,5 cm in diameter. The red arrow shows the stretching lineation (230/18°). The foliation (280/24) and the lineation are shown on the stereonet plot in the lower right corner. Amph = Amphibole.

At the locality of Greningen where the fracture veins and cataclasite were easy to identify in the quartzite (fig. 6), the measurements were done over a larger area. The result of all measured planes revealed the presence of a conjugate fault set, shown in the lower Greningen plot in figure 4. The dark veins and cataclastic fault material sampled from this locality is shown in the colorful sample lot. This plot reveals that only the W-dipping fault is represented in the acquired samples.

Figure 6 – A cataclastic plane, at location Greningen. The black material to the right is thought to be a melt plane whereas the "pocket" of dark material to the left is more typical for a cataclasite. These two are connected via injection veins.

Thin section analysis

For the thin section analysis both a scanned image and image sketch are presented together with a written description for each sample. For the entire thesis a total of 24 samples were studied from the localities of Håltbergsudden, Finntjärnen, Stalltjärnstugan, Wästra Häggsjön, Häggsjön and Greneing. During the analysis the most targeted structures of interest were shear sense indicators, offsets and crosscutting relations. Typical pseudotachylite features were also noted. From these observations five possible deformation events could be derived (D1 to D5). These are summarized both in table 1 and as a text on page 50. Only a few samples showed all five deformations in succession. Note that since the fracture veins observed at the locality of Greningen appears in an un-foliated quartzite, these samples are not correlated to the deformation events and are treated separately in the section "Detailed Study of Greningen".

D = deformation event, Pt = pseudotachylite

Locality - Håltbergsudden

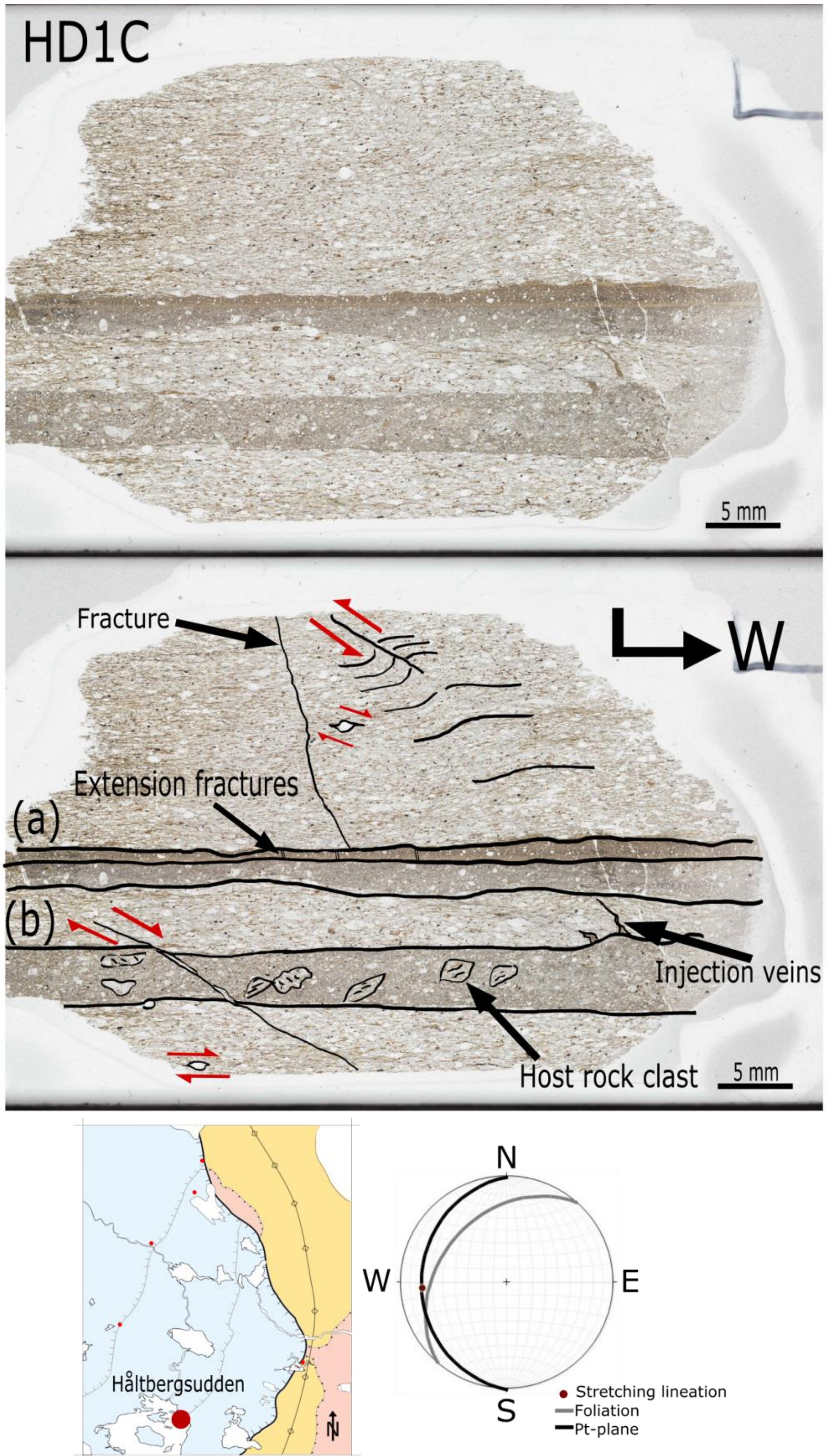


Figure 7, sample HD1C – Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The black arrow in the top right corner give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane).

Sample HD1C

Host rock and Minerals

Mylonitic texture as defined by the preferred orientation of biotite, elongated feldspars and calcites. The foliation is subhorizontal to the fracture vein and show a post foliation positive slip flanking fold with top to the E. The kink in the foliation that can be traced until it gets cut off by the top most Pt. The lower Pt-plane is faulted by a top-W normal fault, and the fault plane have been infilled with calcite. In the lowest and the top most part of the thin section the mylonitic fabric shows sigmoidal feldspar clast which suggests top-to-the-W shear sense.

Feldspar, quartz, biotite, white mica, sericite, calcite, opaque minerals (pyrite), some weathered minerals.

Fracture vein

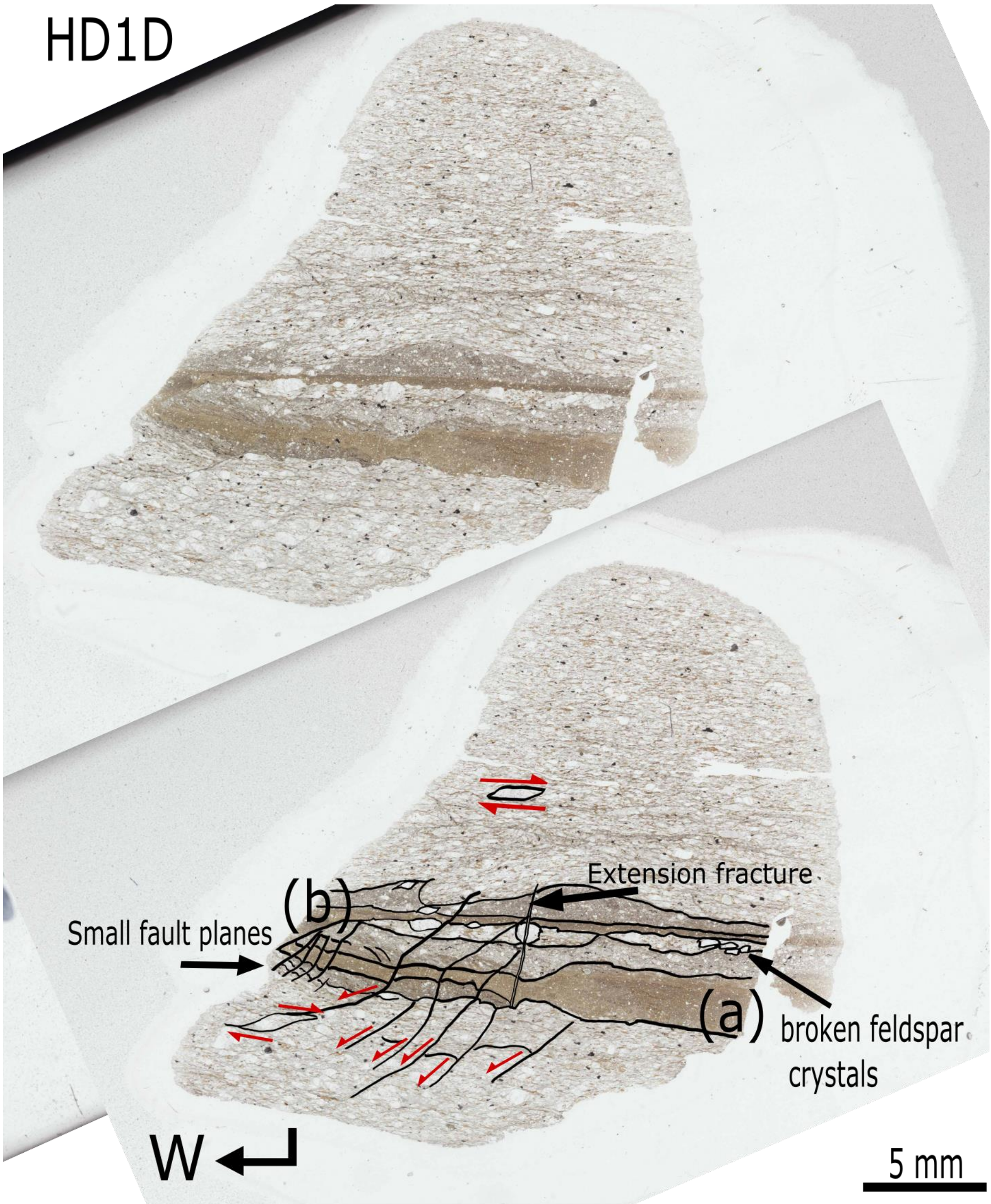
Vein (a) and (b) are parallel with the lineation of the host rock. Vein (a) has yellowish-brown color with compositional banding, a sharp upper boundary to the host rock, and an undulating lower boundary. Extensional fractures are present in the upper half of the fracture vein. They are perpendicular to the vein and the calcite crystal infill suggest E-W extension. Vein (b) has sharp contacts but a more cataclastic matrix with foliated host rock clasts. The matrix also contains biotite, sericite and bigger clasts of sheared out calcite. Two injection veins are seen in connection to vein (b).

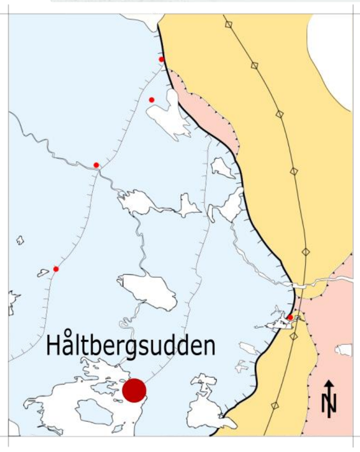
Order of events

First there is ductile shearing forming the mylonitic fabric, later there is a contraction event, leading to the kink and positive slip flanking fold, in E-W direction. Later brittle deformation causes the formation of pseudotachylite. Latest event is an extensional phase in E-W direction, which causes fracturing and faulting of the whole rock.

D1 – Ductile phase, mylonitic foliation, top-W shear.
D2 –Shortening, top-E positive slip-flanking fold.
D3 – Brittle phase, Pt and cataclasite formation
D5- Brittle phase, E-W extension.

Locality - Håltbergsudden





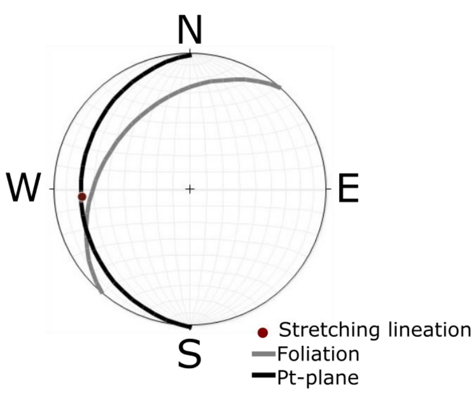
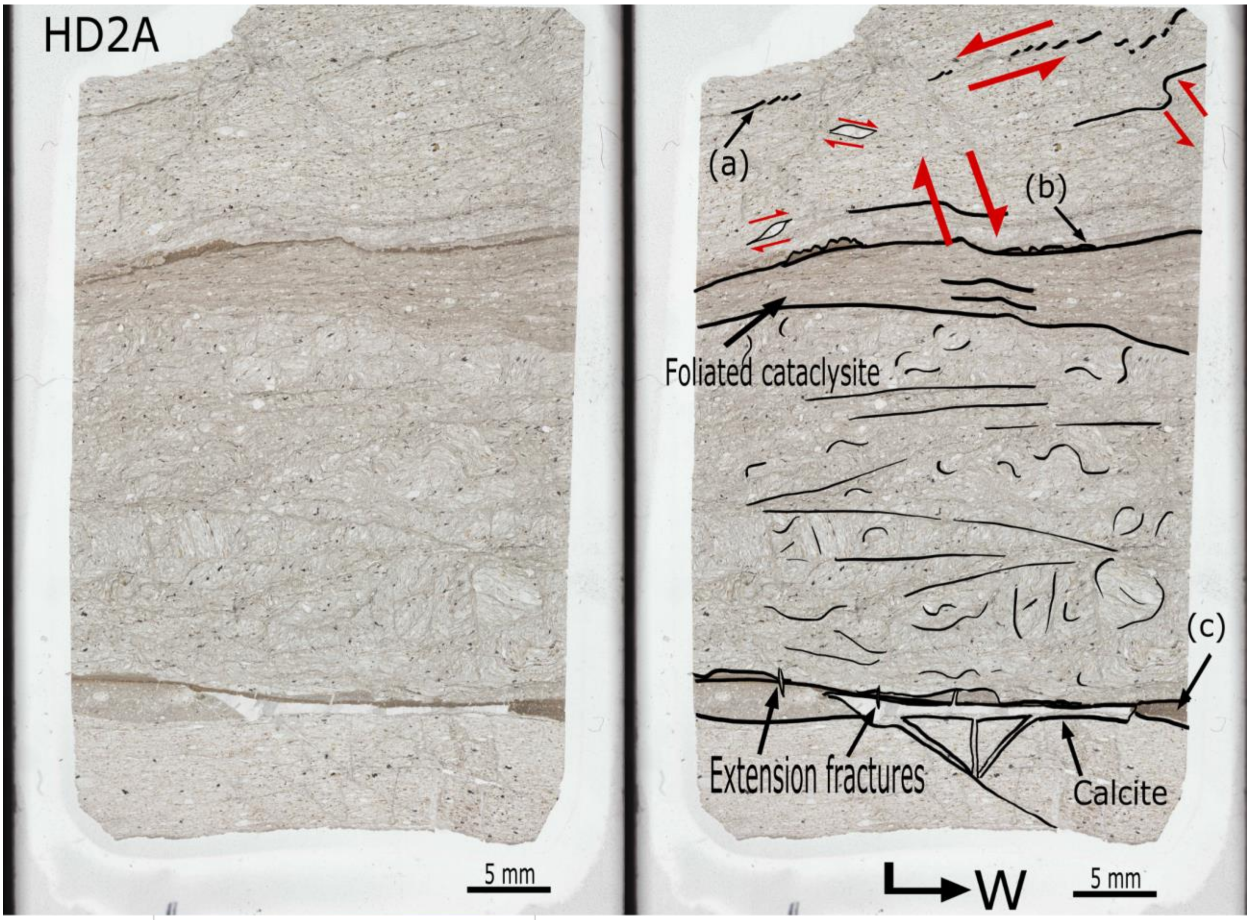
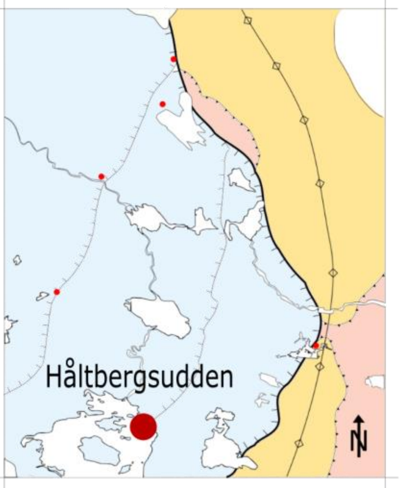


Figure 8, sample HD1D – Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The black arrow in the lower left corner give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane).

Sample HD1D
Host rock and Minerals The host rock display mylonitic texture with subhorizontal foliation. Two shear sense indicator suggest a top-E direction: a mineral fish of a feldspar in the upper part and a sigmoidal type structure formed by a feldspar aggregate in the lower part. Above fracture vein (b) the foliation bends towards the fault plane. Below (b) an offset in a feldspar crystal gives a top to the W shear sense. Small scale faults all show a top-W shear sense. In the foliation below fracture vein (a) some C'-fabric gives a top-W shear sense. The top-E S-C like structure at bottom left is probably coalescing normal faults. Feldspar, quartz, biotite, white mica, sericite, calcite, chlorite, opaque minerals (pyrite), possibly talc.
Fracture vein Fracture vein (a) is parallel to the lineation and is crosscut by fracture vein (b). Vein (a) is also offset by top-W small scale normal faults. One of the faults in (a) can be traced up into fracture vein (b) however an offset is not clearly shown in (b). Both fracture veins have compositional banding, with darker and lighter colors of brown. Cataclastic material surrounds both fracture veins. One extension fracture goes through both veins and into the host rock, suggesting E-W extension.
Order of events First an event of ductile shearing to cause the mylonitisation, then a brittle deformation event causing the formation of fracture vein (a) which then faulted towards the W and the got crosscut by fracture vein (b). Latest event are top-W normal faults and extension fractures as seen in both veins. D1 – Ductile phase, mylonitic foliation, top-W shear. D3 – Brittle phase, Pt formation D4 – Brittle phase, top-W normal faulting of existing Pt (a) and formation of younger Pt (b). D5- Brittle phase, E-W extension.

Locality - Håltbergsudden





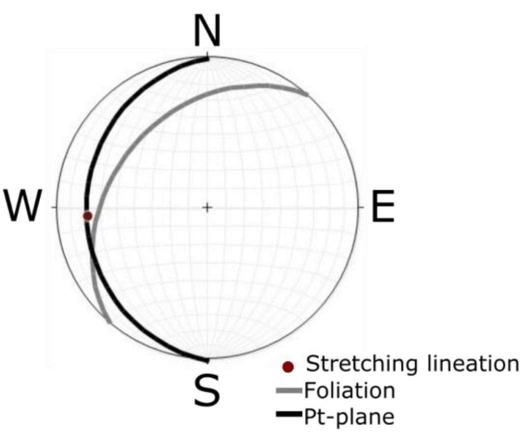


Figure 9, sample HD2A – To the left is the scanned image of the thin section. Important features are enhanced in the sketch to the right. The black arrow in the lower right image give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane).

Sample HD2A
Host rock and Minerals The host rock have a mylonitic texture and a horizontal foliation. In the middle of the thin section the rock appears more cataclasticly deformed. In the upper part of the host rock some shear sense indicators are seen in feldspar clasts, kinks and top-W faulting. The lowermost unit of this rock is crosscut by fractures filed with calcite. Feldspar (some with poikilitic texture), quartz, biotite, white mica, sericite, calcite, chlorite, opaque minerals (pyrite).
Fracture vein Vein (a) is parallel with the lineation and show asymmetric boudinage providing top-W shear sense. Vein (b) has a sharp contact to the host rock and shows compositional banding. This vein has been kinked or faulted in a top-W normal fault. Vein (c) at the bottom of the sample has a sharp crosscutting relations to both the lineated host rock and the more cataclastic unit above it. The top layer of this vein has a darker brown color. In vein (c) a great amount of the fault material has been replaced by large calcite crystals. Calcite-veins are going in different directions but some fractures of the host rock, filled with calcite, suggest an E-W extension.
Order of events First ductile shearing causing mylonitic foliation, then different brittle deformation phases. One cause formation of cataclasite and the upper fracture vein (a) (could possibly have occurred during two different formations phases), this is then faulted to the west as seen in the faults in the upper vein and the lower fracture in the host rock unit. Another brittle phase allow the formation of fracture vein (b) and (c). D1 – Ductile phase, mylonitic foliation, top-W shear. D3 – Brittle phase, Pt (a) formation. D4 – Brittle phase, faulting of Pt (a) ad formation of younger Pt (b) and (c). D5- Brittle phase, E-W extension.

Locality - Håltbergsudden

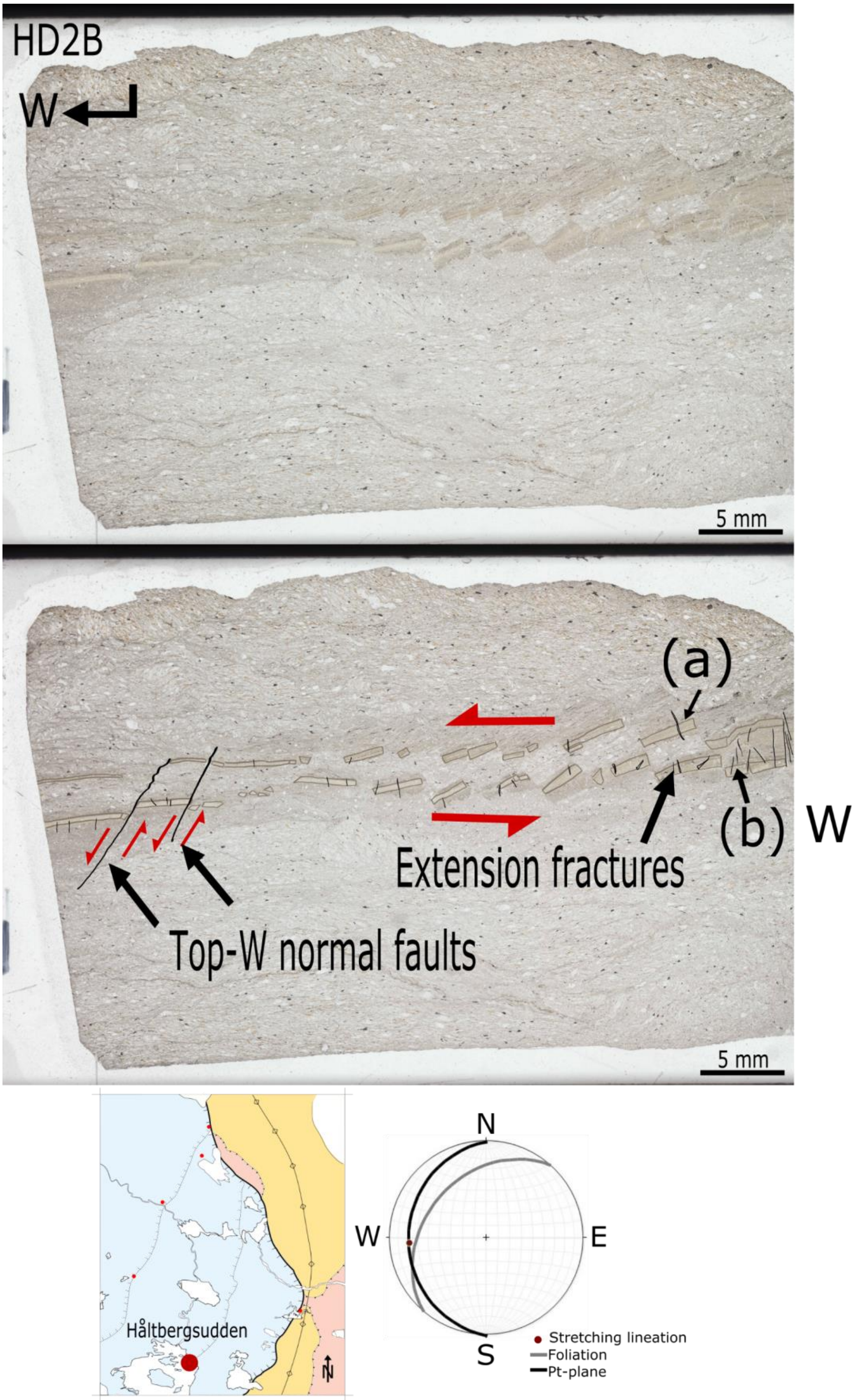


Figure 10, sample HD2B – Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The black arrow in the top left corner give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane).

Sample HD2B
Host rock and Minerals The host rock have mylonitic foliation with some top-E sear bands. In the upper part, the host rock has a higher content of biotite than the unit below the fracture veins, which also appears more cataclastic. However, both units appears to have been kinked, faulted and foliated. Feldspar, quartz, biotite (going to chlorite), white mica, sericite, calcite, opaque minerals (sheared with the foliation), some red-brown weathered minerals.
Fracture vein Fracture veins (a) and (b) are parallel to each other. To the left in the sample there is two top-W normal fault, crosscutting both veins and host rock. In the middle and to the right in the sample fracture veins appears as boundins, however, this structure is a bit unclear. The fracture veins have compositional banding of darker and lighter brown color. Vein (a) is smaller and contains more of the darker brown matrix. There is cataclastic material surrounding vein (b) on both sides, this material has a sharp contact to the host rock whereas the material surrounding vein (a) has a more gradual transition to the host rock. In the both vein (a) and (b) there are an abundance of calcite infilled extensional fractures, some tilted with the faulting, but most at an angle.
Order of events First, the mylonitic foliation during ductile deformation, then kinking and faulting, at the same time or later the Pt formed in brittle phase. The veins then faulted to the W. Latest brittle event caused calcite filed extensional fractures in E-W direction. D1 – Ductile phase, mylonitic foliation, top-E shear. D2 – Shortening, folding and kinking of the host rock. D3 – Brittle phase, Pt and cataclasite formation. D4 – Brittle phase, normal faulting of Pt both to the E and W. D5 – Brittle phase, E-W extension.

Locality - Håltbergsudden

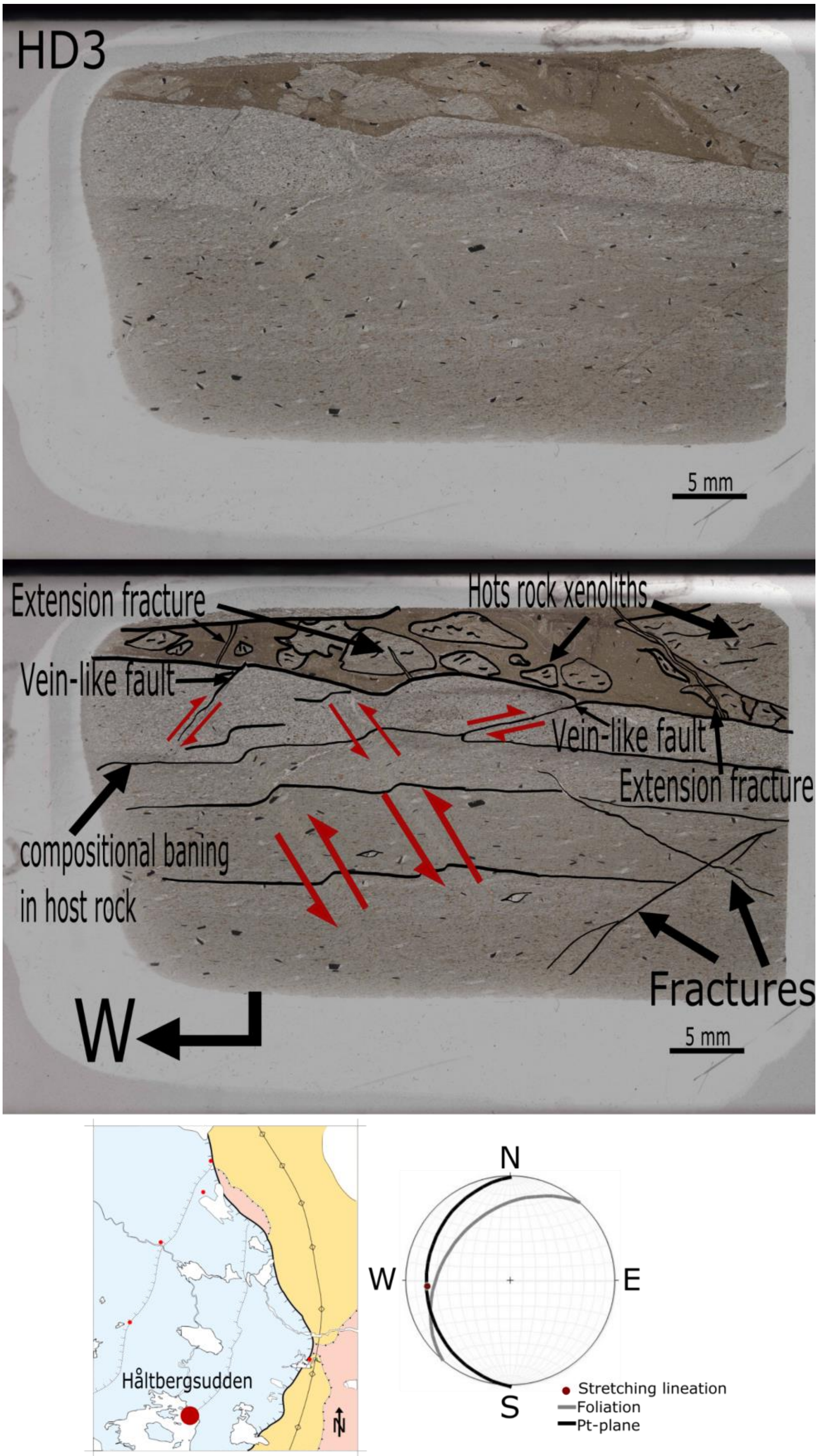


Figure 11, sample HD3 – Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The black arrow in the lower left give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane).

Sample HD3
Host rock and Minerals At the outcrop area, this sample was defined as a cataclasite, due to the large host rock clasts. Closer to the cataclasite the host rock have a distinct lighter color which could be caused by the larger feldspar crystals and in general less sheared material. In this lighter colored unit, there is an abundance of red-brown weathered minerals. The units further away from the cataclastic vein have a more fine-grained matrix and a darker color. Positive slip flanking folds (top-W) can be traced in both the lighter and darker colored units without offsets between the two units. However, one such fold is being offset by a top-E, vein-like reversed fault. An other injection vein follows a low-angle, top-E reversed fault or possibly top-E positive slip flanking fold. Feldspar, quartz, biotite (going to chlorite), white mica, sericite, calcite, opaque minerals (some euhedral and some sheared with the foliation), some red-brown weathered minerals.
Fracture vein The fracture vein was dark brown, with some flow structures and small rounded to sub-angular feldspar clasts as well as larger host rock xenoliths. There are two injection veins connected to top-E normal faults. Extensional fractures can be seen in the matrix as well as in the host rock xenoliths within the fracture vein.
Order of events First the mylonitic foliation during ductile deformation, then E-W compaction giving rise to the positive slip flanking folds, then later or at the same time faulting to the W, off-setting the kink. The cataclasite vein is crosscutting all these structure, and has then been overprinted by fractures suggesting E-W extension. D1 – Ductile phase, mylonitic foliation. D2 – Shortening, folding and kinking of the host rock. D3 – Brittle phase, cataclasite formation. D5 – Brittle phase, E-W extension.

Locality - Finntjärnen

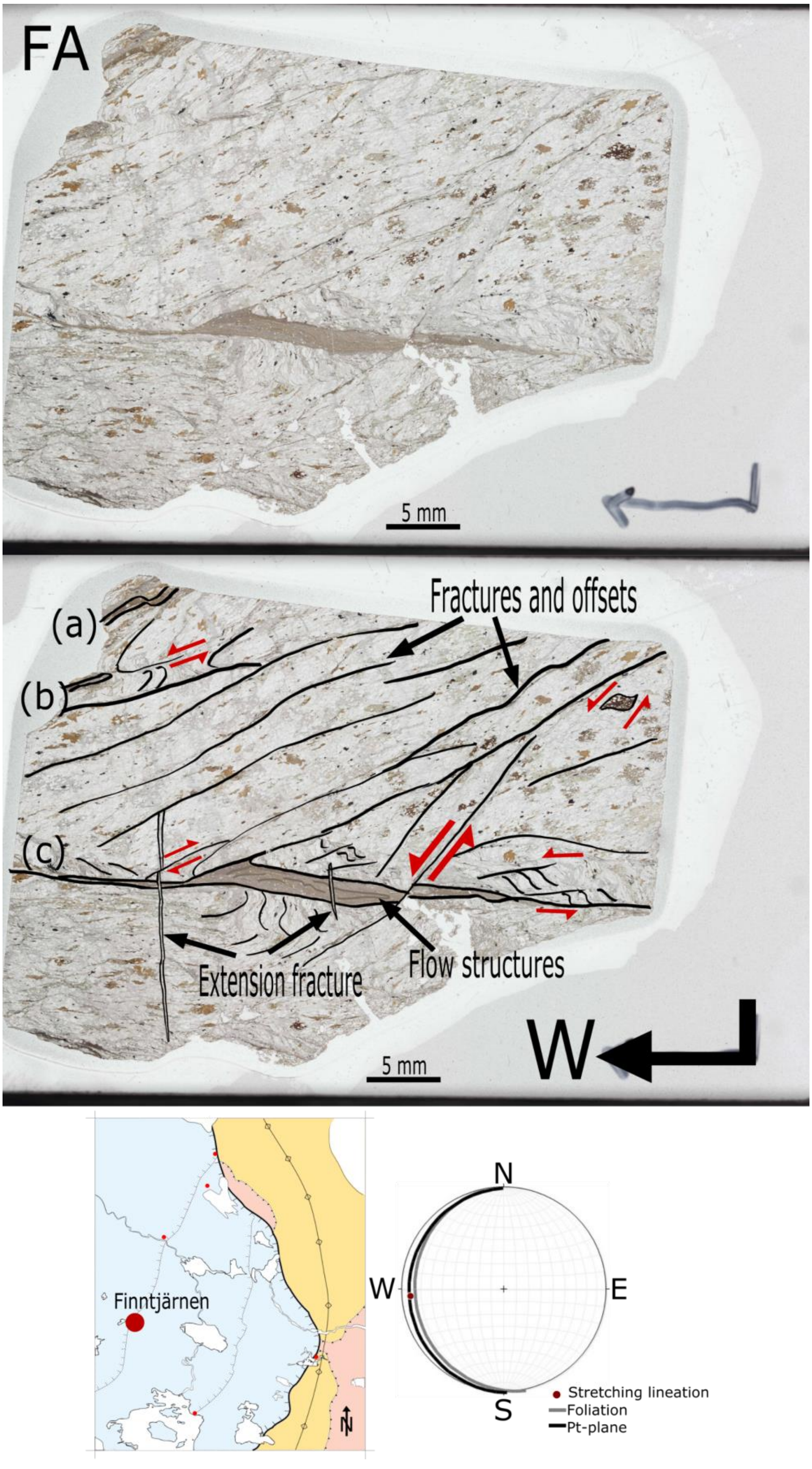


Figure 12, sample FA – Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The black arrow in the lower right corner give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane).

Sample FA
Host rock and Minerals There are two distinct foliations in this rock. In the upper half the foliation is dipping to the W but is more horizontal in the lower half. In the upper part many minerals displays offset by faults and folds, as displayed by the lines “Fractures and offsets” in the sketch. These fractures can be traced to where they are being crosscut by Pt (c). Right above this Pt-layer (c) there are some C-type shear bands giving a top to the W shear sense. In the lower foliation is horizontal, except for right under the thick part of fracture vein (c), where the host rock bends into the fault plane. Feldspar, quarts, biotite, chlorite, white mica, calcite with poikilitic texture in big crystals, dark red-brown poiklitic crystals and opaque minerals (even in the p-tach).
Fracture vein Several fracture veins are noted in this sample. In the upper left corner vein (a) and (b) appears parallel to the steeper foliation. In both these veins the matrix is brown and contains some rounded feldspar clasts. Fracture vein (c) cross the top foliation and runs parallel with the horizontal foliation in the lower part of the thin section. However, it appears to tapper off in both ends. This vein has sharp edges to the host rock. In the thick part, the matrix contains rounded feldspar clasts and has a compositional banding and some flow structures. One end is crosscut by a later top-W normal fault. There are also two clear extension fractures in the E-W direction; these can be traced into the host rock on both sides of the vein.
Order of events First the mylonitic folation formed, then an episode that folded and faulted these rocks in a brittle regime, crosscutting minerals. Another brittle faulting then juxtaposed the two foliations. Later E-W extension caused calcite infilled fractures. D1 – Ductile phase, mylonitic foliation, top-E shear. D2 – Shortening, folding and kinking of the host rock.

Locality - Finntjärnen

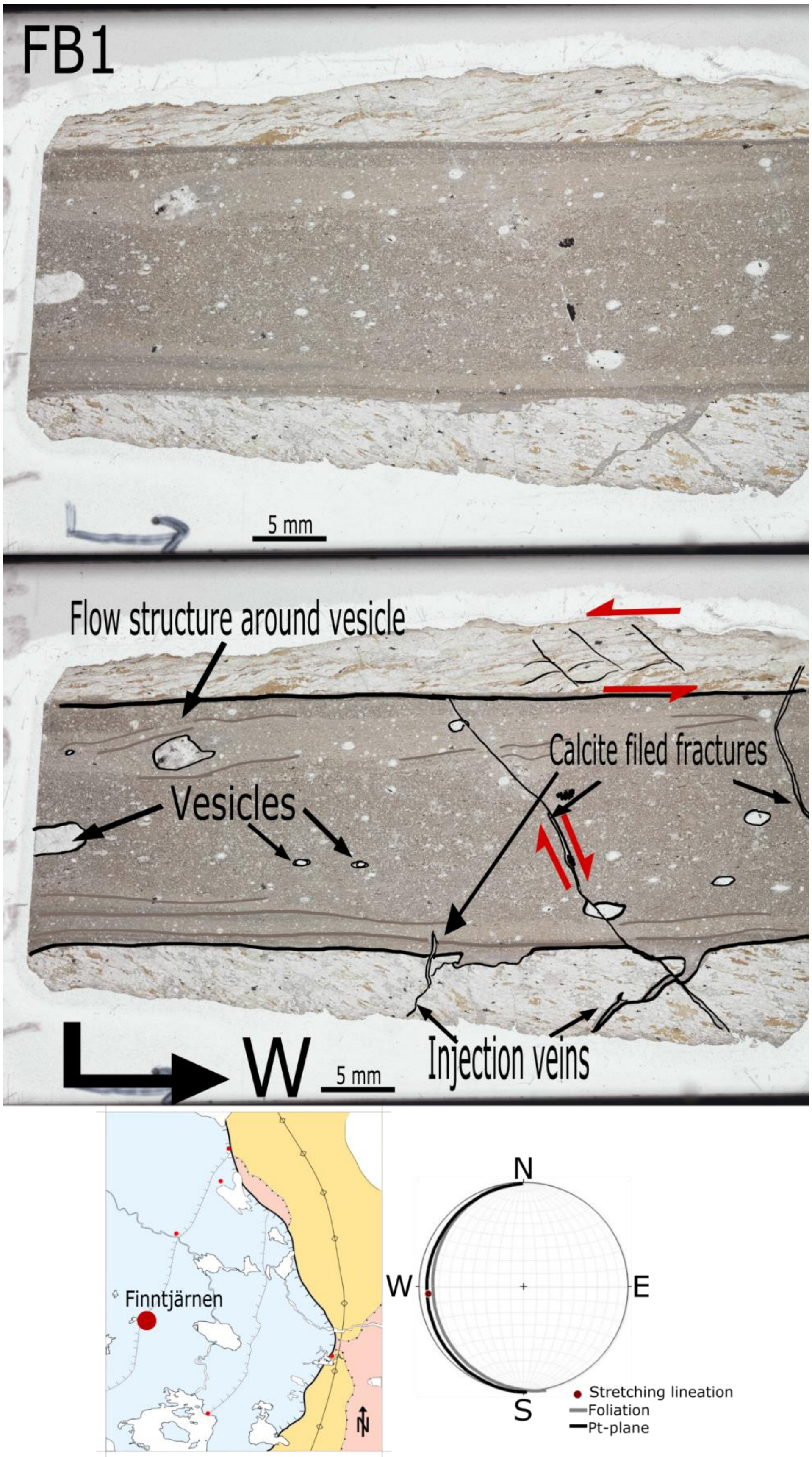


Figure 13, sample FB1 – Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The black arrow in the lower left corner give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane).

Sample FB1
Host rock and Minerals There appears to be a differenc in the foliation above and below this Pt-plane. Above fracture vein the foliation appears to dip towards the E but underneath it dips towards the W. A slight difference in the composition of the host rock can also be recognized; the rock above the melt seems to have a higher amount of biotite and chlorite (possibly some poikilitic, sheared amphiboles) whereas the rock under the vein have larger poikilitic calcite grains. Some C'-type shear bands giving a top-E shear sense. Feldspar, quarts, biotite being chloritized, poikilitic calcite, poikilitic amphibole, and opaque minerals (pyrite, elongated when found in the middle of the vein but more euhedral at the edges and in the nodules).
Fracture vein The fracture vein is a thick fine-grained layer, blue to gray in hand sample and light brown with compositional banding in thin section. Some greener minerals are probably caused by chloritization and weathering of the matrix. There are some big rounded vesicles of feldspar and calcite, most of them elongated parallel to the fault plane. The vein has a sharp crosscutting relationship to the host rock on both sides. One injection vein is seen. This injection vein is being crosscut and slightly offset by a top-W normal fault that can be followed all the way through the Pt-vein. In some of the vesicles, opaque minerals have grown and acquired a euhedral shape. Small extension fractures are seen to affect both the fracture vein and the host rock.
Order of events First the mylonitic foliation in ductile phase, then a brittle deformation causing the formation of the fracture vein, lastly some E-W extension with faulting. D1 – Ductile phase, mylonitic foliation, some top-E sheare sense. D3 – Brittle phase, Pt formation. D5 – Brittle phase, E-W extension and top W normal faulting.

Locality - Finntjärnen

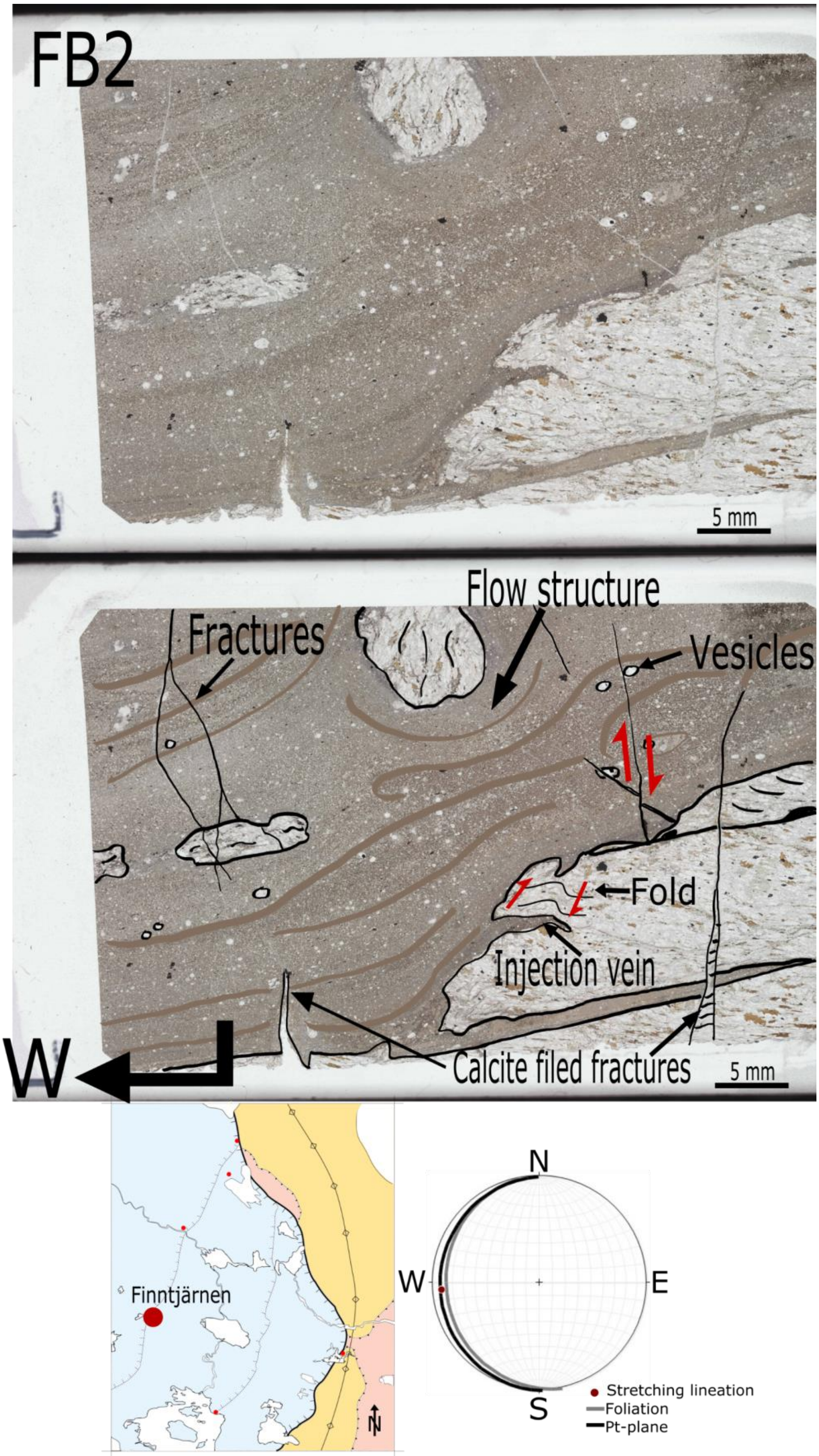


Figure 14, sample FB2 – Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The black arrow in the lower left corner give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane

Sample FB2
Host rock and Minerals The foliation is dipping slightly to the E. There is one positive slip-flanking fold giving a top to the E shear sense before it gets cut off by the melt. Feldspar, quartz, biotite being chloritized, calcite, amphibole and opaque minerals (pyrite, some sheared out in the host rock and in the melt but some are more euhedral both in the host rock and in the melt).
Fracture vein The fracture vein is blue to gray in hand sample and brown in thin section with greener mineral alternation, probably chloritization due to weathering. The matrix display a compositional banding with flow structures. There are elongated feldspar and calcite filled nodules, stretching in the same direction as the fault plane. Smaller amygdales and vesicles are present within the vein. There are several injection veins, were the longest one is being crosscut and offset by a vertical fracture. A feldspar nodule is being offset by at top-E normal fault.
Order of events First, the mylonite was formed, and then the fold during contraction, then in a brittle phase the Pt formed, crosscutting the other structures. Latest is the E-W extensional phase. D1 – Ductile phase, mylonitic foliation. D2 – possibly some top-E fold. D3 – Brittle phase, Pt formation. D5 – Brittle phase, E-W extension.

Locality - Finntjärnen

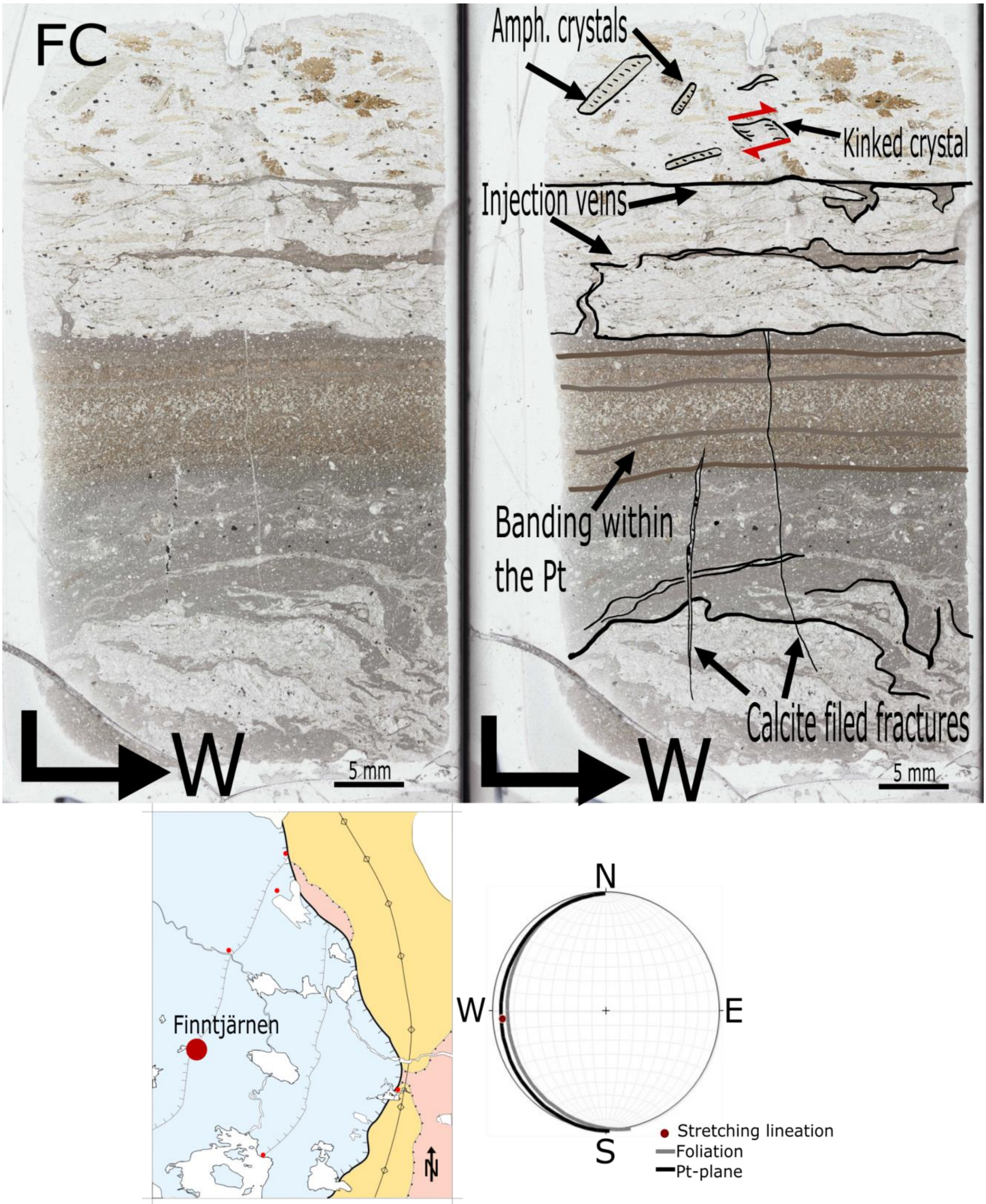


Figure 15, sample FC– To the left is the scanned image of the thin section. Important features are enhanced in the sketch to the right. The black arrows in the lower left corners give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane).

Sample FC
Host rock and Minerals Above the fracture vein the host rock has a folation parallel to the fault plane. An early lineation is captured in the porphyroblastic amphiboles and a second lineation, defined by white mica, is behind around the amphiboles. Between the top most injection vein and the thicker fault plane there is a cataclastic unit. The host rock under this fracture vein has been affected by the melt and no foliation is seen. In this lower unit no amphiboles or biotite are found. There are two fractures affecting the fault plane; one is thin and goes through the entire fracture vein and one is only reaching the lower boundary of the fracture vein. The shorter one is thicker and contains larger, cubic opaque minerals (pyrite). Feldspar, quartz, biotite being chloritized, calcite, amphibole, garnet and opaque minerals (pyrite, there are no opaque minerals in the Pt-layer but they become more and more sheared out closer to the fracture vein)
Fracture vein In the hand sample the fracture vein is visible as a 5 mm thick fine grained, blue layer in clear contrast to the cataclastic rock surrounding it. Compositional banding can be seen with the naked eye. Between the fracture vein and the host rock above it, only a small amount of cataclastic is material present. Below the vein, however, most of the rock in the sample is made up by reworked material. In the thin section it is shown that the fracture vein and the cataclastic material have less sharp contact and that the transition is mostly defined by a change in color from gray (cataclasite) to brown (Pt) with some green weathering mineral. The clast within the fracture vein of the fault layer are rounder than those in the cataclastic material. Amygdales and vesicles are abundant. Smaller injection veins are seen, as well as thin bands of melted material above the Pt layer. The topmost of these bands is shown to follow the kink in the host rock, and is crosscutting amphibole crystals. The lower such band could be connected to the injection vein and is shown to crosscut the foliation in the surrounding host rock.
Order of events First myloinitsation creating the lineation in the host rock. Then the kink during E-W shortening. Then a brittle event creating the first fracture vein and cataclastic material. More brittle deformation caused the formation of the fracture vein during faulting in the cataclastic unit. Later E-W extension caused the extension fractures. D1 – Ductile phase, mylonitic foliation. D2 – Possibly some top-E fold. D3 – Brittle phase, Pt formation. D5 – Brittle phase, E-W extension.

Locality - Stalltjärnstugan

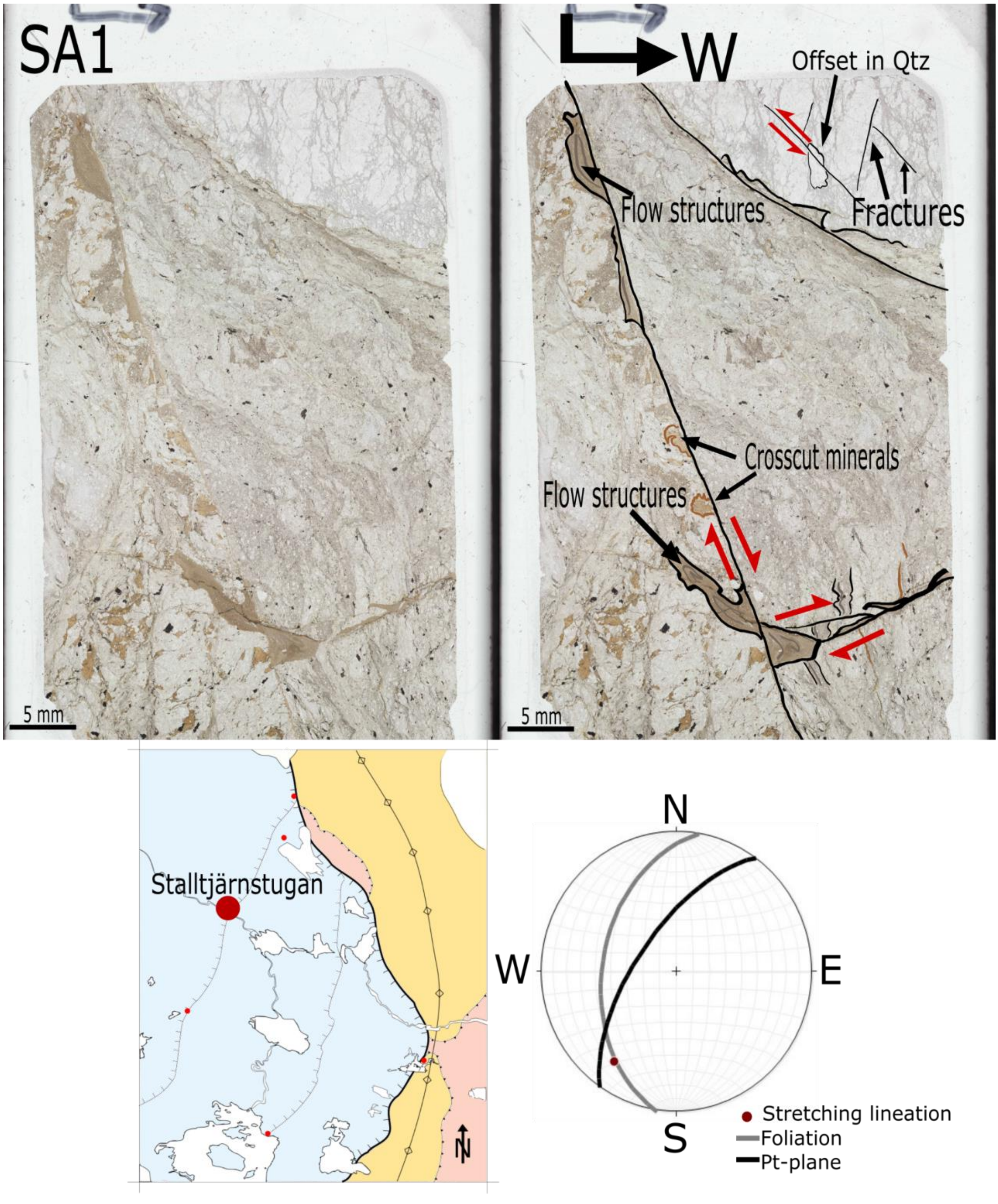
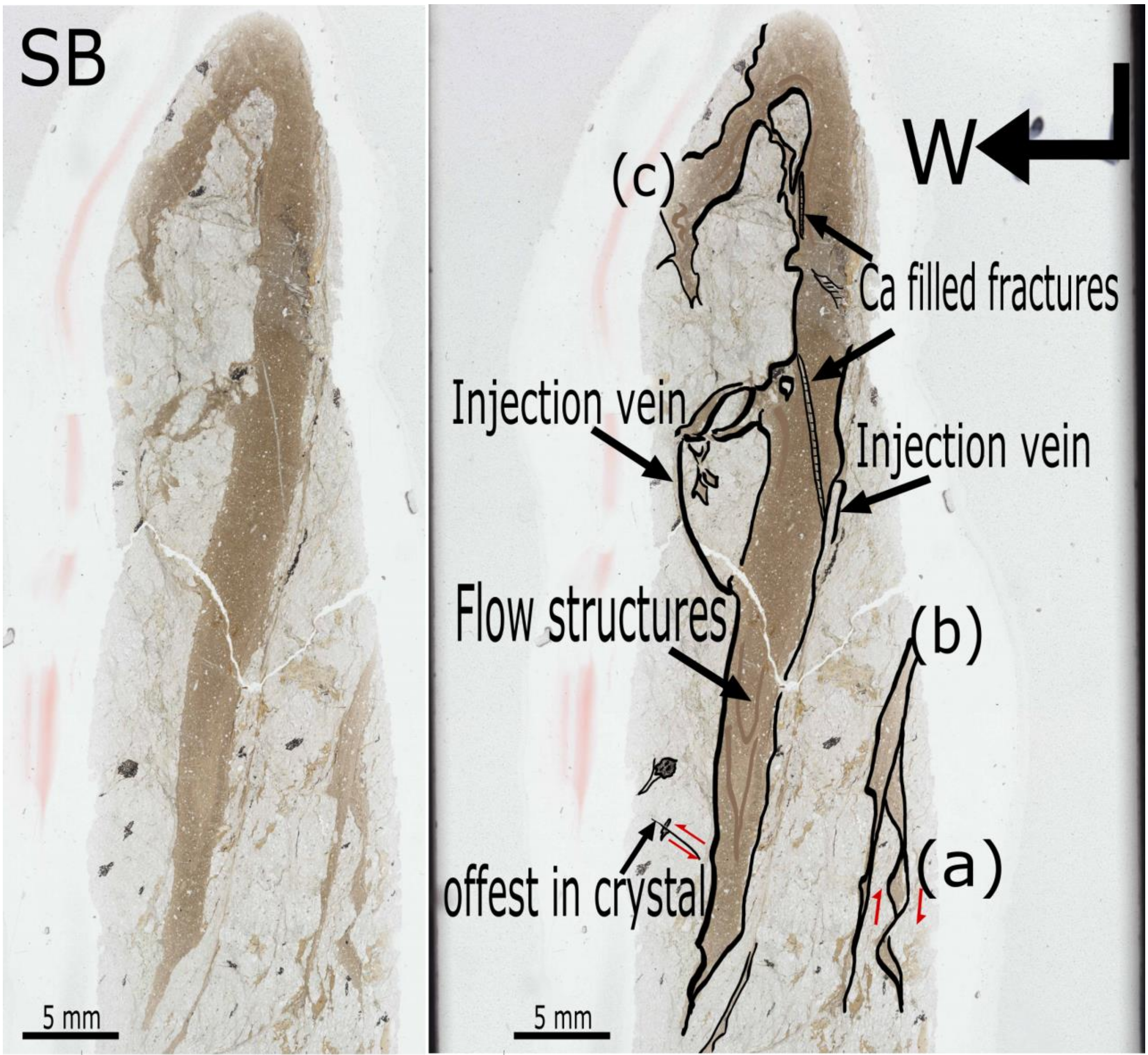
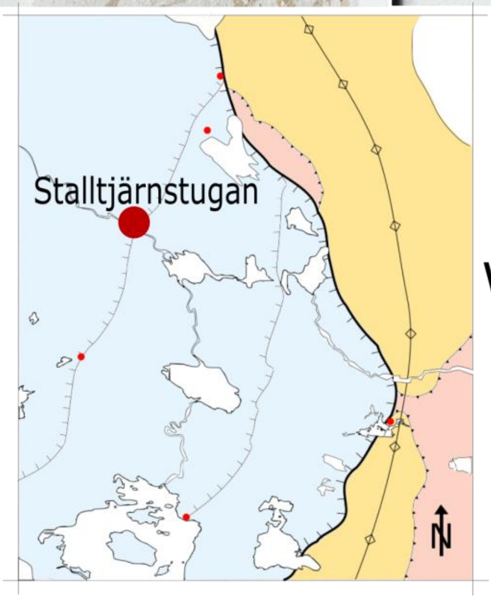


Figure 16, sample SA1 – To the left is the scanned image of the thin section. Important features are enhanced in the sketch to the right. The black arrow at the top of the image give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane).

Sample SA1
Host rock and Minerals In the top right corner of the thin section there is a part of a thicker quartz vein in the rock. This vein displays smaller fractures in two sets at about 90 degrees to each other. The host rock in this sample is affected by some kind of faulting, juxtaposing two rock units. The left hand side unit is slightly lighter in color and contain more sheet silicates. The melt on the plane separating these two units suggests a fault to the W. Feldspar, quartz, white mica, chlorite, biotite. Opaque minerals, more sheared out in the darker cataclastic layer, angular to cubic in the left side unit and not present at all in quartz vein.
Fracture vein This sample is made up of cataclastic material with some possible melt pockets and veins. These fractures of melt have a brownish color and compositional banding and flow structures. One of the melt pockets display an offset by top-w normal faulting.
Order of events Ductile event with mylonite formation of the clasts in the cataclasite, then brittle event forming the cataclysite. Possible extension E-W shown by the faulting. D1 – Ductile phase, mylonitic foliation. D3 – Brittle phase, Pt and cataclasite formation. D4 – Brittle phase, top-W normal faulting.

Locality - Stalltjärnstugan





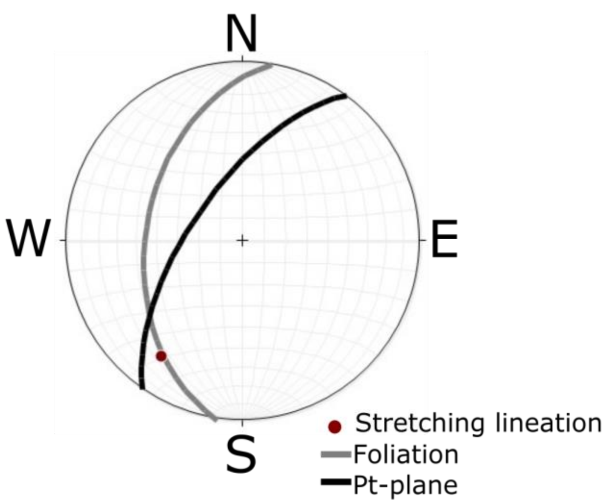


Figure 17, sample SB – To the left is the scanned image of the thin section. Important features are enhanced in the sketch to the right. The black arrow at the top right corner give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane).

Sample SB
Host rock and Minerals The foliation has a steep dip towards the W. The foliation is broken up by many fractures in the rock as well as bands of mineral alternation. There are some opaque minerals being sheared in the same direction as the foliation. One of these shows an offset by a fault with a top-W direction. This fault is not seen within the fracture vein fault plane. Feldspar, quartz, white mica, chlorite biotite. Isotropic mineral, poikilitic texture, aligned with the foliation.
Fracture vein Vein (a) is small (lower right corner) with shear band boundins parallel to the foliation, indicating that the relative movement of the right hand side is down whereas the left side is up. This small fracture vein (a) is crosscut by vein (b). Vein (c) is thicker and looks to be folding around the host rock at the top of the thin section, but since the top part is missing it is hard to draw any definite conclusions. All of the fracture veins are parallel with each other, but at a steeper angel towards the W compared to the foliation. The fracture veins all display compositional banding, sharp contacts to the host rock and contain rounded to sub-rounded clasts. Vein (c) show injection veins and large extension fractures infilled with calcite.
Order of events First the foliation in a ductile event, then a brittle deformation event forming vein (a) followed by a phase of extension causing it to form boundins. This is crosscut during another brittle event forming vein (b) and possibly vein (c) at the same time. A later phase of extension in E-W direction is evident by the extension fractures. D1 – Ductile phase, mylonitic foliation. D3 – Brittle phase, Pt (a) formation. D4 – Brittle phase, boundins of Pt (a) and formation of Pt (b) and (c). D5 – Brittle phase, E-W extension.

Locality - Stalltjärnstugan

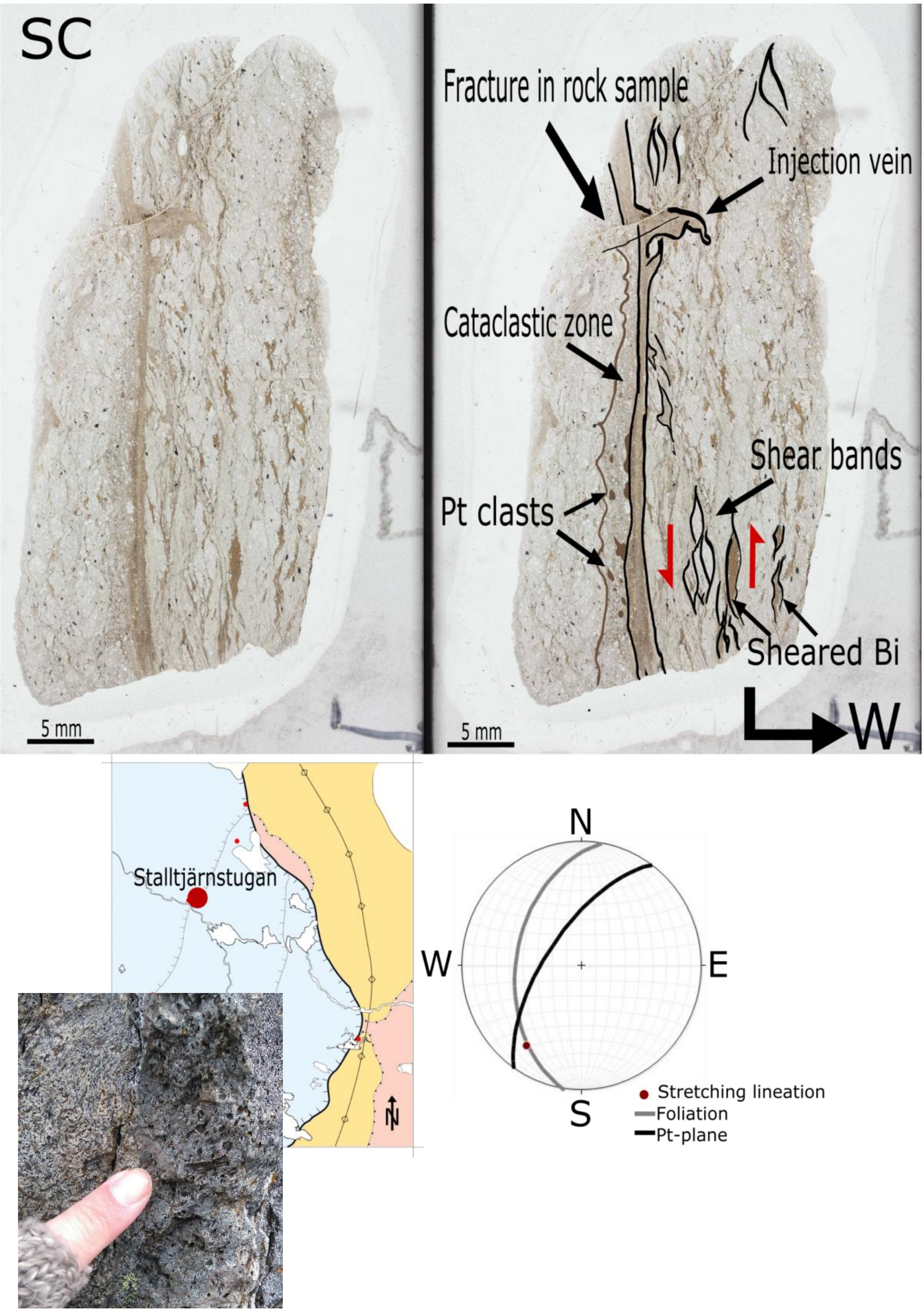


Figure 18, sample SC – To the left is the scanned image of the thin section. Important features are enhanced in the sketch to the right. The black arrow in the lower right corner give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane). The image in the lower left corner clearly show two dfferent rock units separated by a thin fracture vein.

Sample SC
Host rock and Minerals This fracture vein is dividing two host rock units. The one to the W has more sheet silicates and stronger foliation where as the one to the E is darker in color and looks more cataclastic This is also seen in the outcrop image attached in the lower left corner. What looks to be Pt-clasts is found in the cataclastic zone to the left of the fracture vein. Feldspar, quartz, white mica, chlorite, biotite with halos, and opaque minerals more or less following the foliation (only small amount is seen in the fracture vein).
Fracture vein The fracture vein is steep and sub-parallel to the foliation. This vein has compositional banding, an injection vein and a sharp contact to the host rock on the W side (right hand) and a more gradual contact on the E side. Towards the E side, there is a darker band of cataclastic material which contains clast of the fracture vein.
Order of events First the foliation and shearing ductile event forming the C'-type shear bands, then a brittle deformation causing fracturing of the rock and fracture vein formation. After this, another brittle deformation phase must have occurred along the fault plane, breaking up pieces of the fracture vein. D1 – Ductile phase, mylonitic foliation and shear bands. D3 – Brittle phase, Pt-formation. D4 – Brittle phase, cataclasite formation on the E side, ripping Pt-clasts with it.

Locality – Wästra Häggsjön

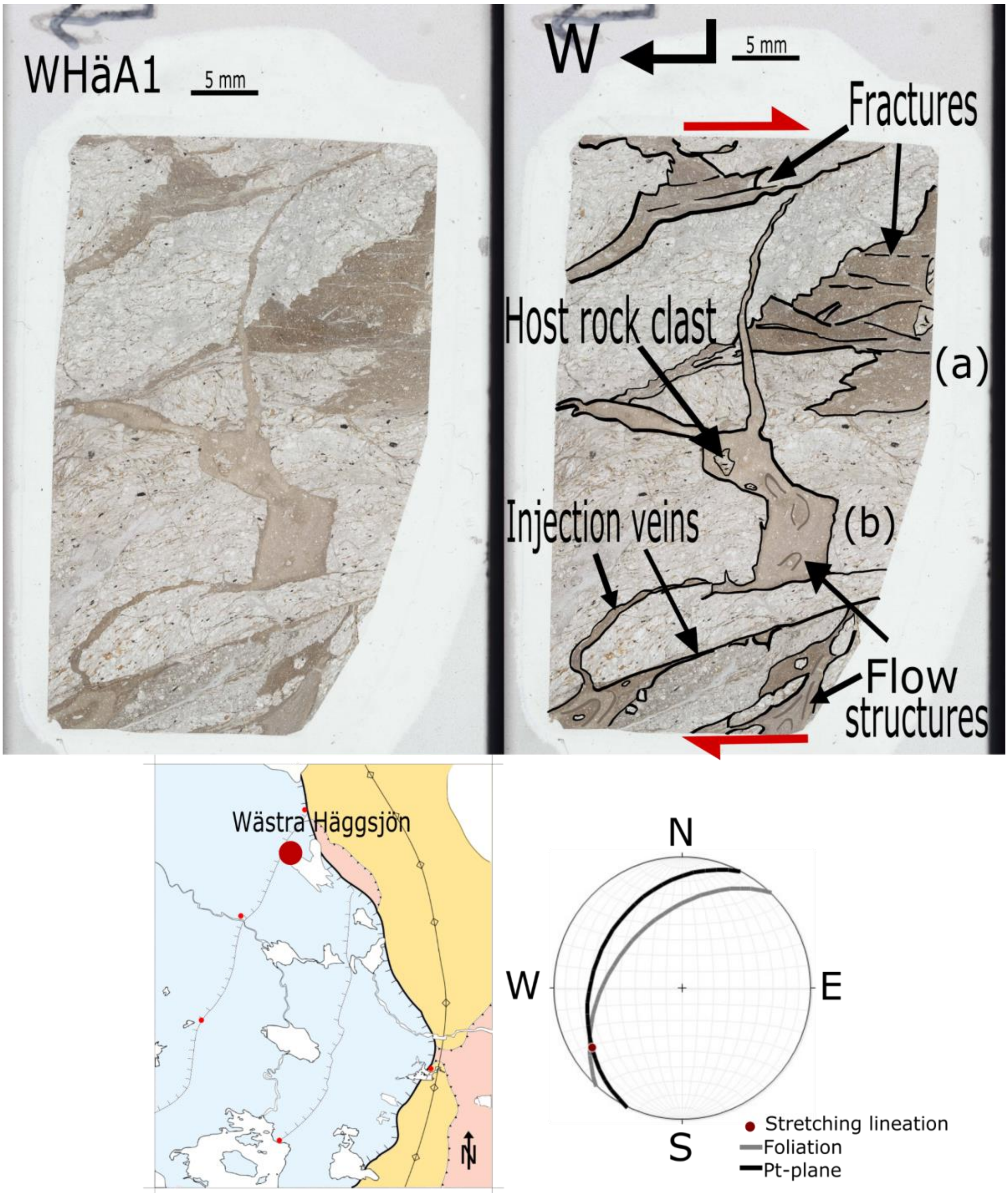
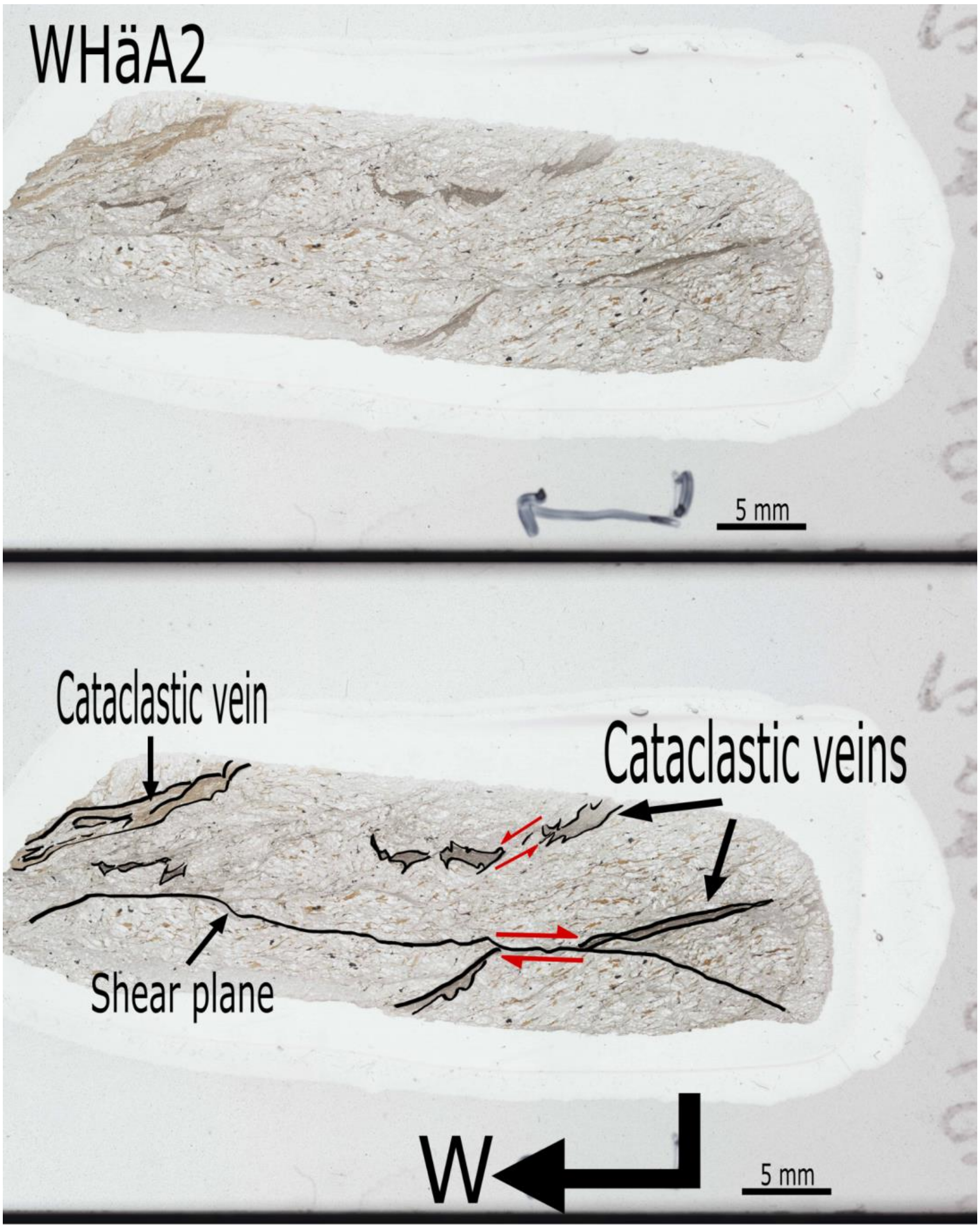


Figure 19, sample WHäA1 – To the left is the scanned image of the thin section. Important features are enhanced in the sketch to the right. The black arrow at the top give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane).

Sample WHäA1
Host rock and Minerals The host rock appears to be foliated and then strongly deformed. The host rock is in sharp contrast to the fracture veins. Feldspar, quartz, biotite, white mica, calcite and opaque minerals with inclusions shear out with the foliation.
Fracture vein This sample contains two generations of fracture veins, crosscutting each other. The early one (a) is dark brown with compositional banding and rounded to sub-sounded clasts. Small pieces of biotite-looking minerals can be found in the vein material. This first generation of fracture veins has undergone brittle deformation. The veins contain calcite infilled fractures, mostly going horizontally. A lighter colored cataclasite-looking structure (b) is crosscutting parts of one of the deformed Pt-planes. This cataclastic structure (b) does not appear as a plane and could be an injection vein, possibly originating from the friction vein seen in the lower part of the thin section where both cataclastic material and melt are present. The vein connected to structure (b) show some flow structures.
Order of events First the foliation then some brittle deformation forming the fracture veins. Then more brittle deformation causing deformation of the veins and the second generation of brittle vein and cataclasite formation. D1 – Ductile phase, mylonitic foliation. D3 – Brittle phase, Pt (a) formation. D4 – Brittle phase, cataclasite (b) formation.

Locality – Wästra Häggsjön



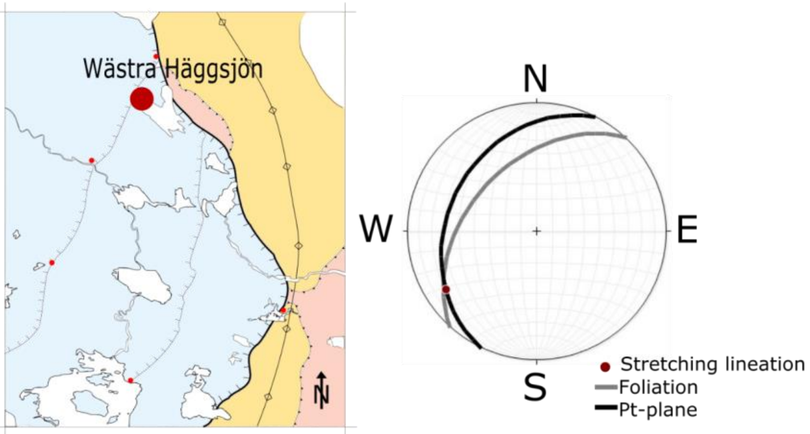


Figure 20, sample WHäA2 – Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The black at the bottom of the image give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane

Sample WHäA2
Host rock and Minerals The host rock has a foliation that has been deformed with fractures and faults both horizontally and with the foliation. Feldspar, quartz, biotite, white mica, possibly some fibrous calcite, small sheared out amphiboles, calcite and opaque minerals with inclusions.
Fracture vein This sample display several fracture veins and/or cataclastic veins, all running sub-parallel to the foliation. The cluster of vein melts in the top left corner have a light brown color with compositional banding. These veins have crosscutting relationship and appears to be affected by later deformation. The other veins are darker brown, also with compositional banding, and occurs as sheared out segments. Towards the lower right corner, the vein appears to be offset by a horizontally fault, giving a top to the E shear sense. Part of the sheared out vein have been infilled by calcite.
Order of events First the foliation, then brittle deformation causing the fracture veins to form, then more deformation causing the dark brown vein to shear out. At some point after this or during this top-E shearing event the formation of the light brown veins occurred. D1 – Ductile phase, mylonitic foliation. D3 – Brittle phase, Pt formation and faulting. D4 – Brittle phase, fracturing and faulting of the Pt-melts.

Locality – Wästra Häggsjön

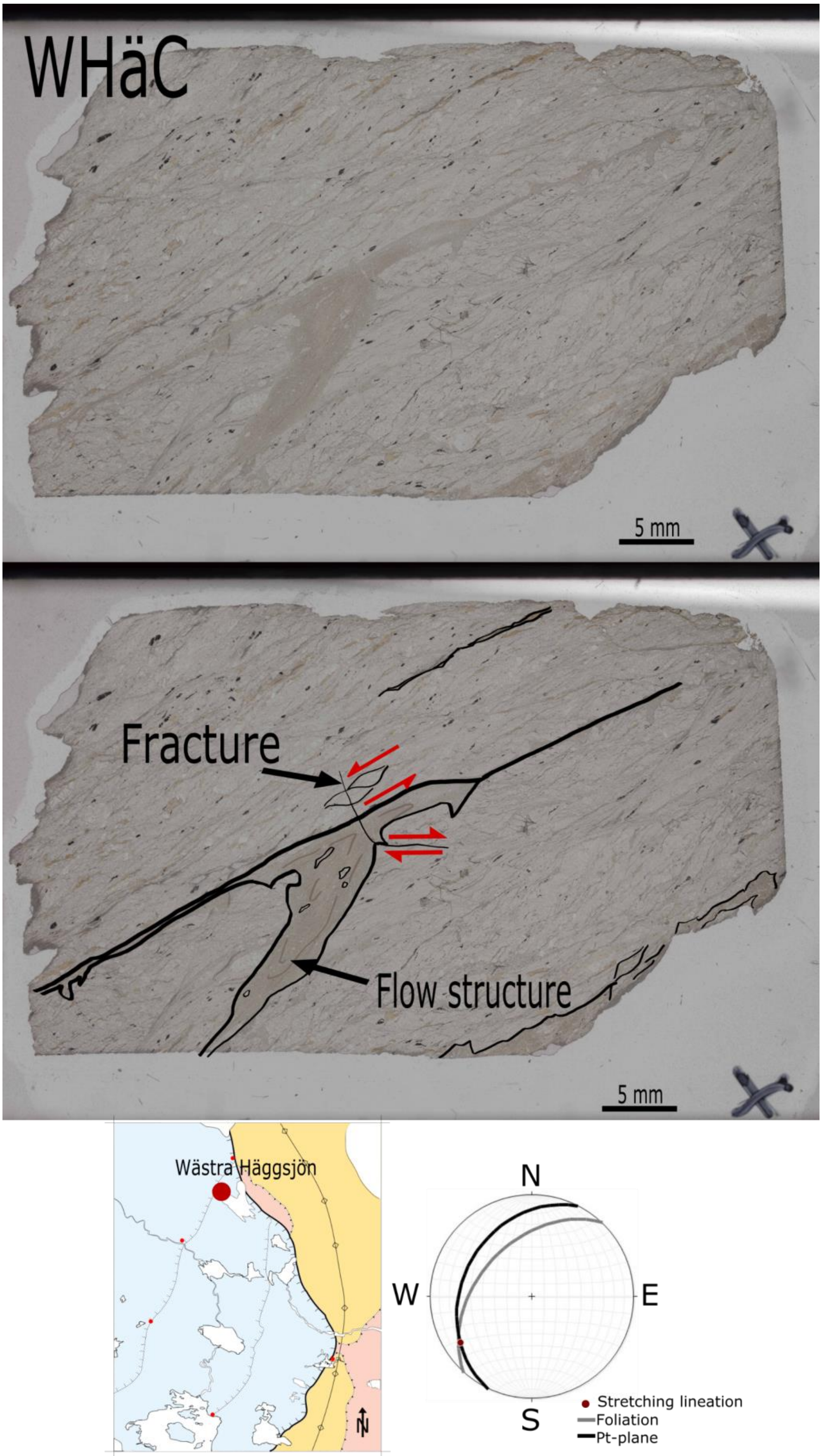


Figure 21, sample WHäC – Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane).

Sample WHäC
Host rock and Minerals This sample was not oriented. The host rock has a foliated texture with shear bands giving a top to the left shear sense. There is one fracture that is bending at the Pt-plane but the direction of faulting is somewhat unclear. Feldspar, quartz, biotite, white mica, calcite, some poikilitic amphibole and opaque minerals with inclusions shear out with the foliation.
Fracture vein There is a fracture vein with the foliation from which a larger melt injection is emanating. There are small, rounded to sub-rounded clasts, compositional banding and flow structures both in the fault plane and the injection vein.
Order of events First foliation, then brittle deformation causing fraction vein formation. D1 – Ductile phase, mylonitic foliation. D3 – Brittle phase, Pt formation. D4 – Brittle phase, faulting of the Pt-melt.

Locality - Häggsjön

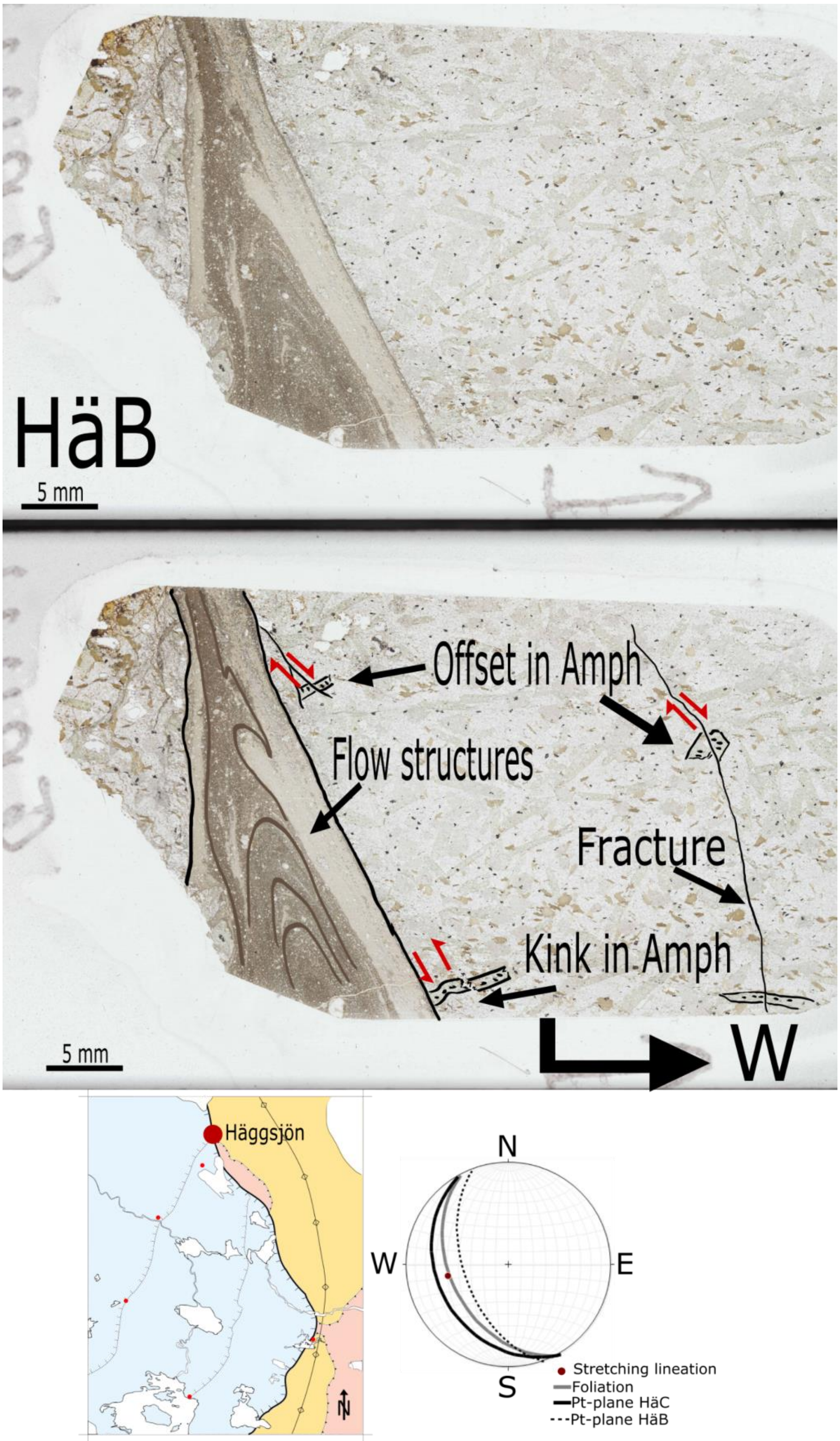


Figure 22, sample HäB – Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The black arrow in the lower right corner give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane).

Sample HäB

Host rock and Minerals

In the host rock there is an abundance of amphiboles and calcite, both with poikilitic texture and with a non-preferred orientation. The foliation is defined by the preferred alignment of the biotite minerals, dipping towards the W, which is also seen in the poikilitic crystals. However, there is an alignment of smaller white mica crystals suggesting a second foliation at an angel to the biotite. Some of the amphibole crystals show kinking whereas other show evidence of top-W faulting. Stretching

Feldspar, quartz, biotite, white mica, amphiboles, calcite and opaque minerals with inclusions (the opaque minerals are not present in the fracture vein).

Fracture vein

One thick Pt melt is present, with clear compositional banding and flow-structure. The contacts to the host rock on both sides of the plane are sharp and crosscut host rock minerals. The clasts in the p-tach are rounded. The fault plane is sub-parallel to the foliation, at a steep angel towards the W. Some clasts or blasts of biotite are present in the fracture vein, in contact with a feldspar clast.

Order of events

First the foliation formed. This was the preserved in the poikilitic amphiboles during a metamorphic event. Then a stage of contraction forming the kink in the amphibole crystal. Then a brittle phase causing faulting of the amphiboles and the Pt formation.

D1 – Ductile phase, mylonitic foliation.
D2 – Formation of main foliation, S_2.
D3 – Brittle phase, fracturing, faulting and kink of amphibole.
D4 – Brittle phase, formation of Pt-melts.

Locality – Häggsjön

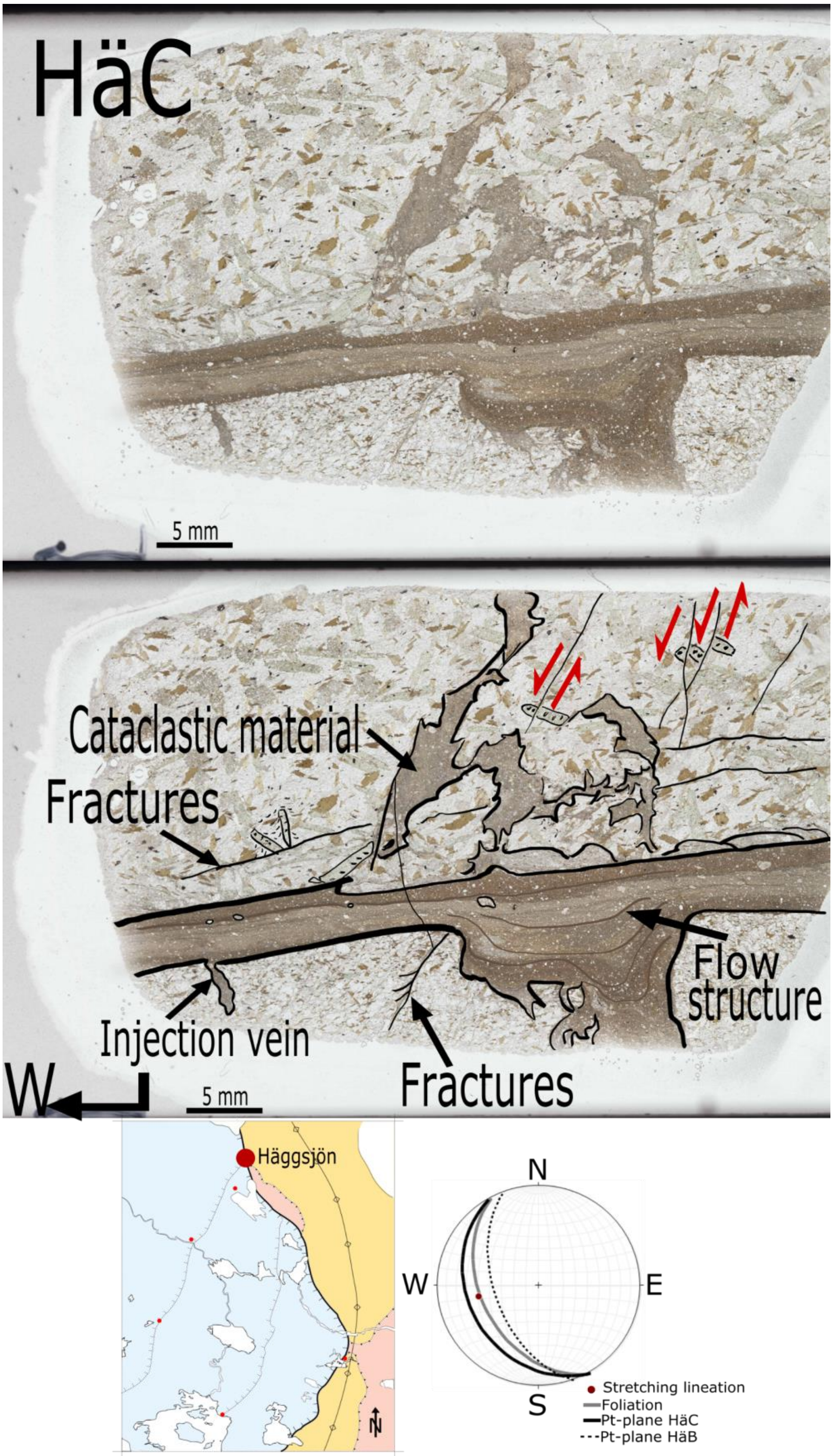


Figure 23, sample HäC – Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The black arrow in the lower left corner give way up and points to the west. The locality of the sample is marked on the map. The stereonet show the stretching lineation and the foliation of the host rock, as well as the orientation of the sampled fault plane (Pt-plane).

Sample HäC
Host rock and Minerals The host rock above the fracture vein contains large poikilitic amphiboles and calcite crystals which gives the direction of the first foliation, S_1. The foliation preserved in these porphyroblast is largely the same as the foliation given by the main schistosety, defined by the white mica crystals, which are seen to bend around amphiboles that have grown perpendicular to the foliation. However, biotite crystals in combination with smaller opaque minerals give a foliation with a slightly shallower dip. In the top right corner of the thin section, amphibole crystal is faulting towards the W. There are also fractures running parallel with the Pt-plane, crosscutting minerals, but are in turn crosscut by injection veins from the melt. The host rock below the fault plane is less sheared and do not contain any of the poikilitic amphiboles and calcites. This rock appears to be severely fractured. Feldspar, quartz, biotite, white mica, amphiboles, calcite and opaque minerals with inclusions. Most of the opaque minerals are seen in the upper host rock unit, and only small crystals of the opaque minerals are present in the Pt melt.
Fracture vein The fracture vein of the fault plane has sharp edges with crosscutting relationship to the host rock on both sides. The fracture vein has compositional banding, injection veins and rounded clasts. A top to the W motion is inferred by rotation of feldspar clast in the top part of the melt, giving the melt a top-E shear sense. One extension fracture filled with calcite is cutting through the fault plane and into the surrounding host rock. Cataclastic material is in contact with the upper part of the fracture vein.
First foliation S_1 formed, later metamorphic phase causing the growth of the amphibole and calcite minerals which capture this first foliation. A new foliation formed causing sheet silicates to bed around the amphiboles. Then came a brittle deformation phase, with faulting towards the W as well as horizontal fault crosscutting the porhyroblastic amphibole minerals. An even later brittle event led to Pt formation and juxtaposing of the two host rock units seen below and above the fault plane. D1 – Ductile phase, mylonitic foliation S_1. D2 – Formation of S_2. D3 – Brittle phase, top-W normal faulting, possible formation of catatclastic material. D4 – Brittle phase, formation of the Pt-melt.

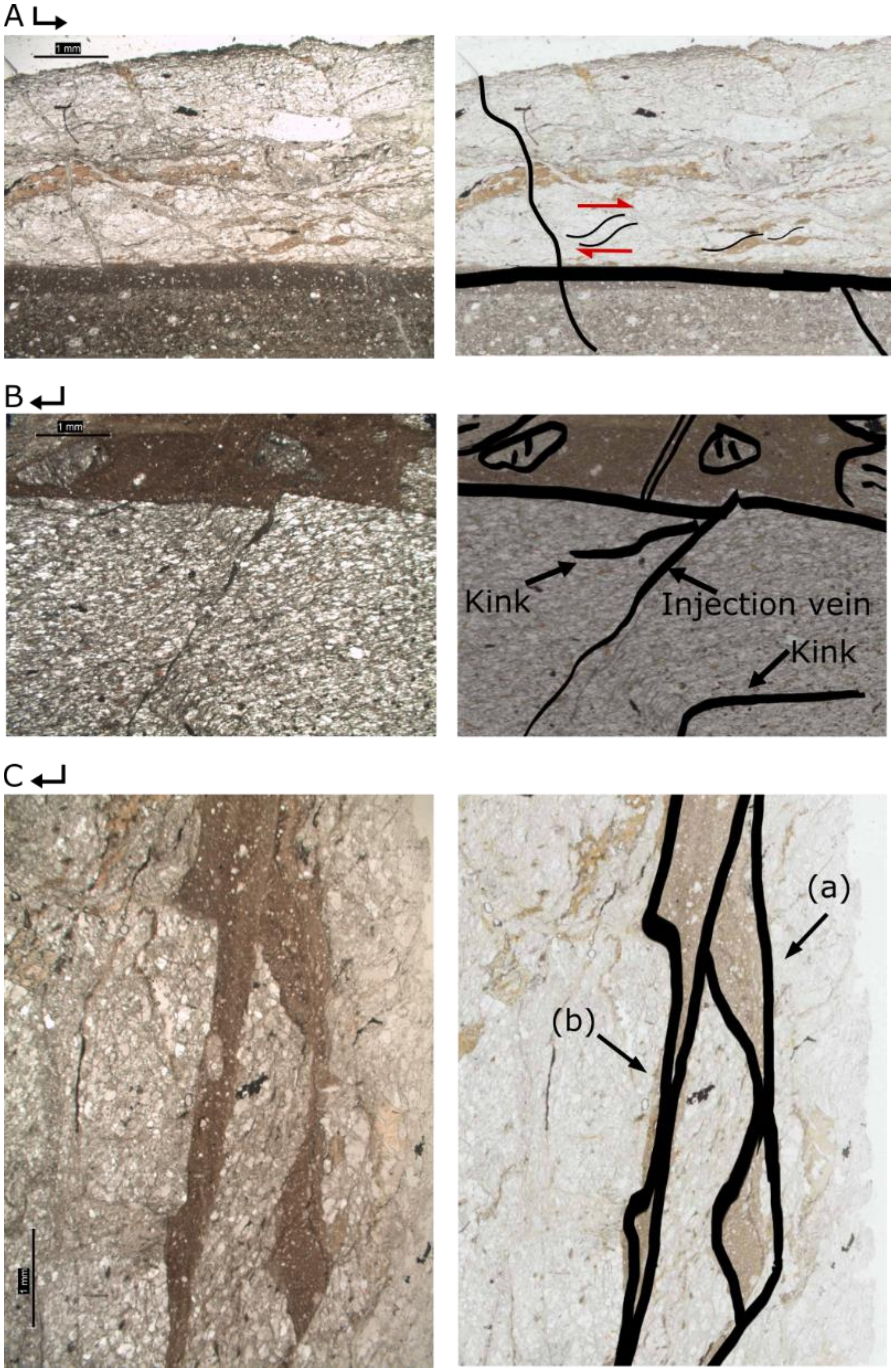
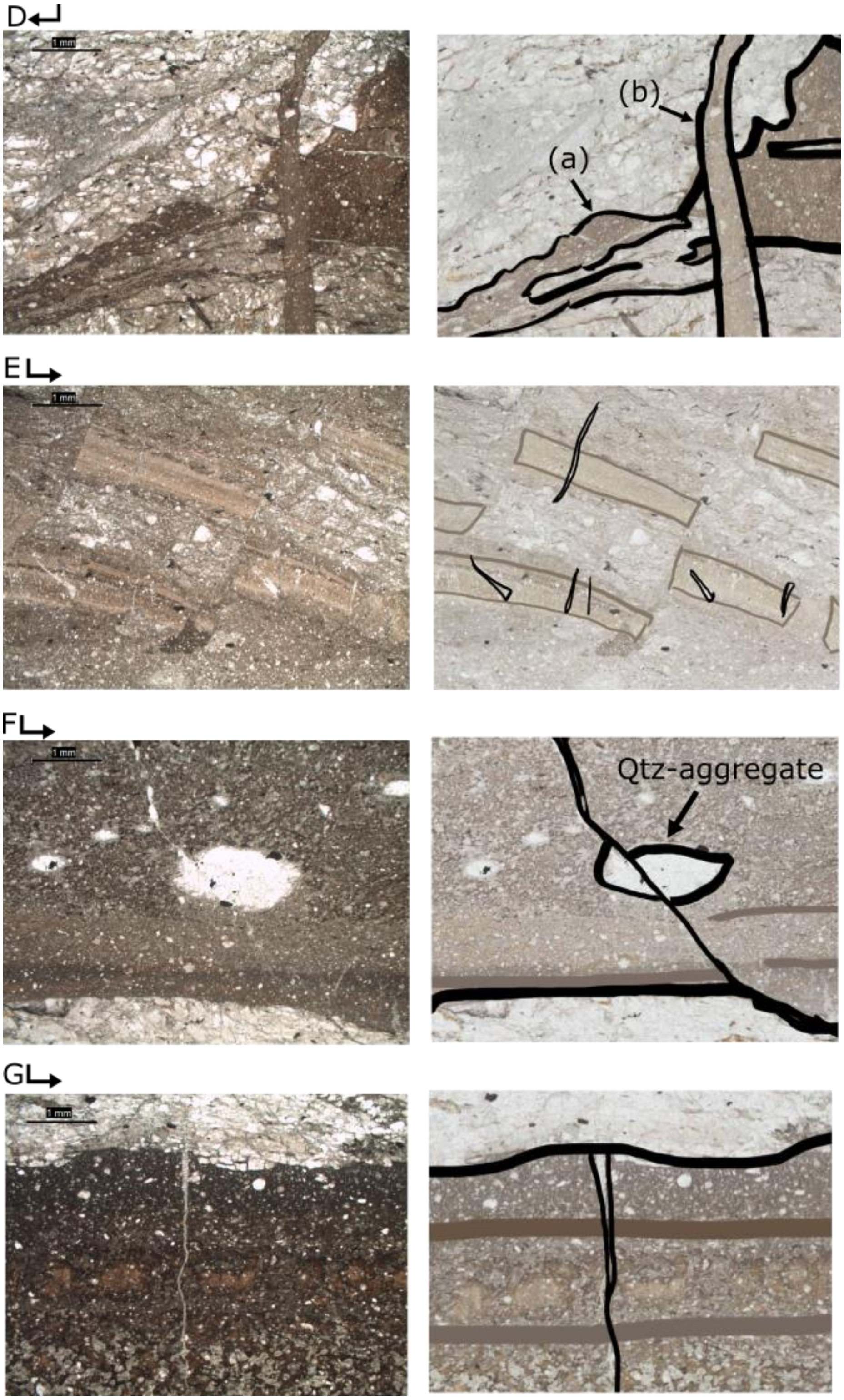


Figure 24 – Arrows give way up and point to the W. Images to the left are photographed from the microscope, images to the right are from a thin section-scanner. The deformation events in order. **A:** Deformation 1, mylinitic foliation showing top-W shear, also with fractures going from the host rock into the fracture vein, whereas other fractures are contained within the fracture vein (sample FB1). **B:** Show deformation 2, post foliation kink and host rock clasts in the fracture vein. An injection vein and a late-stage, calcite in-filed fracture is also seen (sample HD3). **C:** Deformation 3 and 4, evidence for two Pt-formation events, as fracture vein (a) is being crosscut by fracture vein (b) (sample SB).



Continuation of figure 24 – The arrows give way up and point to the W. Images to the left are photographed from the microscope, images to the right are from a thin section-scanner, both in plane polarized light. **D**: Deformation 3-4, as displayed by crosscutting relation between two fracture veins. The full structure of the fracture veins have yet not been understood (sample W-A1). **E:** Deformation 4, display faulting or domino boundins of two parallel fracture veins. The veins have compositional banding and show extension fractures filled with calcite going into the mylonitic host rock (sample HD2B). **F:** Deformation 5, the fracture vein have sharp contacts to the host rock, compositional banding and extension fractures and top-W normal faulting. This faulting offsets a quartz and calcite aggregate. This sample also contain vesicles and amygdales (sample HD1C). **G:** Deformation 5, E-W extensional fracture, infilled with calcite. This sample also show the contact between the hots rock and the fracture vein with bigger host rock xenoliths closer to the contact. Some compositional banding is seen in the fracture vein, as well as a bubbly texture of potential microlites. Some smaller vesicles and some weathered material is also present (sample FC).

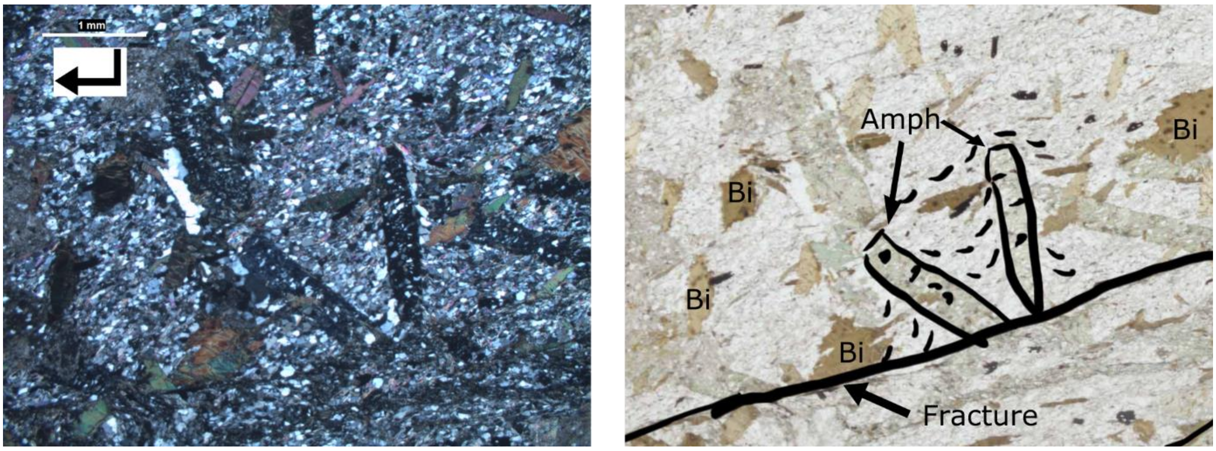


Figure 25 – The arrow give way up and point to the W. Left: crossed polarized light. Right: plane polarized light. Bi = Biotite, Apmh = Amphibole. The earliest foliation S_1 seen preserved in the poikilitic amphiboles, the second foliation is bending around the amphiboles. The fracture divides the host rock from the area closest to the Pt in this sample (Sampel HäC)

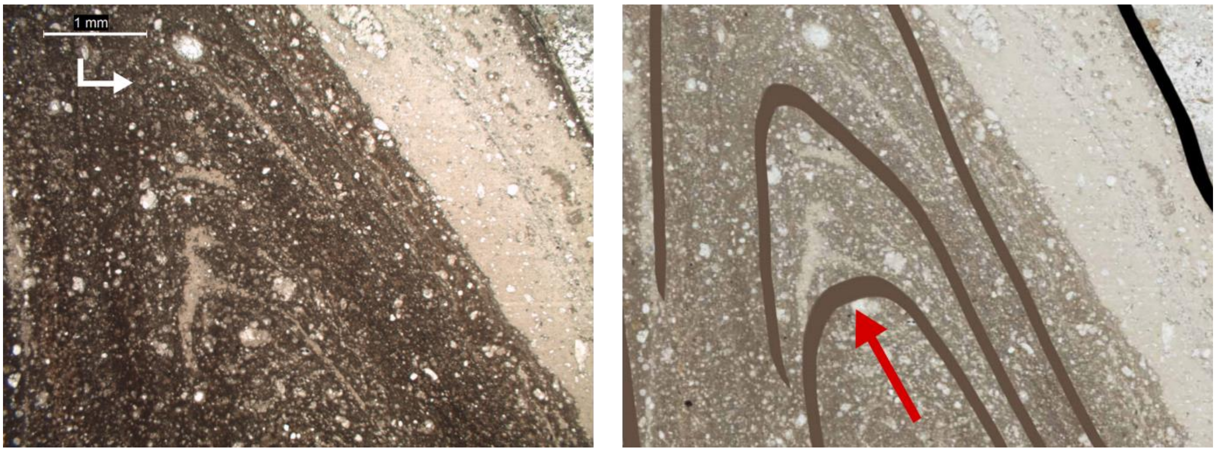


Figure 26 – To the left is a scanned image of the thin section, to the right is a sketch enhancing features of interest. The white arrow give way up and point to the W. The red arrow indicate direction of flow in a sheet- folded flow structure seen in the compositional banding of lighter and darker brown color. The melt also contains rounded amygdales filled with euhedral quartz and calcite crystals. There is also some smaller vesicles (sample HäB).

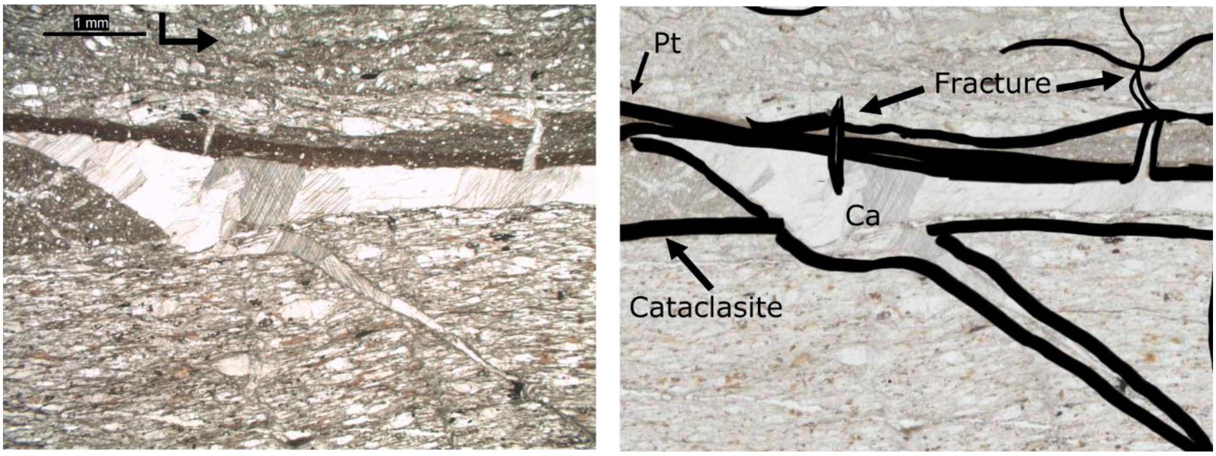


Figure 27 – To the left is a scanned image of the thin section, to the right is a sketch enhancing features of interest. The arrow give way up and point to the W. Pt = pseudotahylite, Ca = calcite. Image shows a calcite infill in a cataclastic unit which a fracture vein in the middle of it, from location Håltbergsudden. The extensional fractures giving an E-W extension direction. How such a large amount of fracture vein matgerial have been removed in order for the calcite to fill the area is still unclear (sample HD2A).

Summary of deformation events

The deformation events are inferred from the thin section analysis from the localities of Håltbergsudden, Finntjärnen, Stalltjärnstugan, Wästra Häggsjön and Häggsjön. The first deformation event (D1) is that which give rise to the mylonitic foliation S_1 during a ductile deformation phase. In the mylonitic foliation, some shear sense indicators can be seen (fig. 24 A). However, the shear sense indicates both top to the W and top to the E sense of movement. In the grabenschiefer around Häggsjön, the early S_1 foliation is preserved in poikilitik porfyroblasts of amphiboles, whereas the second foliation is seen to bend around the crystals (fig. 25). Some post foliation kinks and positive slip-flanking folds have been identified as the second deformation event (D2) (fig. 24 B). Two pseudotachylite forrmation event are evident by fracture veins crosscutting relation observed in the samples (fig. 24 C-D). The fracture veins also shows to have been faulted and/or boundins during shear, which is seen in figure 24 C-D. The first Pt-formation is marking the third deformation event (D3) whereas the second Pt-melt marks the fourth deformation event (D4). Some top-W normal faulting, as well as top-E normal faulting has been seen in correlation to D4. Last is the E-W extension (D5), which is seen to crosscut the other structures (e.g. fig. 10, fig. 24 E and 24 G). In this late stage of brittle deformation there is again some top-W normal faulting with calcite infilling in the fault planes (fig. 24 F). In table 1 a summary of the deformation and structures of each locality is listed.

Summary of pseudotachylite identification features

Although these fracture veins have evidently been overprinted by later events, the sampled fracture veins from the foliated rock (all localities excepted Greningen) all showed features indicative of a melt origin. Most commonly, the samples displayed banded composition (fig. 24 A-G) in which some displayed clear flow structures that even indicate the direction of the flow with a sheet-fold-like structure (fig. 26). The samples also show a variety of host rock clasts, quartz aggregates and minerals such as biotite, present within the melt. Most of these clasts and aggregates are rounded and their long axis is commonly seen parallel to the fault plane (fig. 24 C and 24 F). Another re-occurring feature is that of injection veins (fig. 24 B). Furthermore are amygdales with quartz and calcite crystals found in most of the samples (e.g. fig. 24 F). Smaller features such as vesicles are also present in varying amounts appearing as a “bubbly” texture in the samples (fig. 24 A-G). Noteworthy is how in one of the samples an abundance of fracture vein occurs as a band in a cataclastic layer with larger parts of it appearing to have been replaced by calcite (fig. 9 and fig. 27). In this sample clear extensional fractures are also recognized.

Table 1 – The deformation events as inferred from the thin section analysis from the localities of Håltbergsudden, Finntjärnen, Stalltjärnstugan, Wästra Häggsjön and Häggsjön. Five different deformation events are evident in the thin sections, listed from D1 to D5. Pt = Pseudotachylite. The mylonitic foliation S_1 is seen in all the samples, however in the localitys of Wästra Häggsjön and Häggsjön this foliation is only preserved in poikilitic amphibole porphyroblasts. The second foliation S_2 largely follows the same orientation as the first. White mica crystals that are bending around the porphyroblastic amphiboles define foliation S_2. These structures are crosscut by pseudotachylite and cataclastic material. These first melt and crush structures are overprinted by faulting and boundins and then crosscut by younger fault planes, which form the second generation of pseudotachylites and cataclasites. The latest structure is that of extensional fractures infilled with calcite, giving an E-W direction.

Locality	**D1 - Ductile**	**D2 - Ductile to brittle**	**D3 - Brittle**	**D4 – Ductile/Brittle**	**D5 - Brittle**
Håltbergsudden	Mylonitic foliation S_1 some top-W shear but mostly top-E shear sense.	Folding and kinking top-E deformation.	First Pt formation.	Second Pt formation and top-W normal faulting of older Pt and top-E normal fault of Pt-planes.	E-W extension fractures.
Finntjärnen	Mylonitic foliation S_1 preserved in poikilitic porphyroblasts. Some top-E shear sense.	Folding and kinking possibly top-E. Main foliation, S_2, formed.	First Pt formation	Breakup of older Pt-veins and new Pt formation.	E-W extension fractures and top-W normal faulting.
Stalltjärnstugan	Mylonitic foliation S_1.		First Pt formation.	Reworking of older Pt-veins and formation of younger Pt-veins, also some top-W normal faulting.	E-W extension fractures.
Wästra Häggsjön	Mylonitic foliation S_1 preserved in poikilitic porphyroblasts.	Main foliation, $S_{2,}$ formed.	First Pt formation and faulting of the rock.	Crosscutting and faulting of the older Pt and formation of the second Pt and cataclasite faults.	
Häggsjön	Mylonitic foliation S_1 preserved in poikilitic porphyroblasts.	Main foliation, S_2, formed.	Top-W normal faulting. Cataclastic material formed.	Pt formation.	

(This page was intentionally left blank.)

Detailed study of Greningen

At lake Greningen a more detailed study of both the bedrock and the fault planes were carried out. The map (fig.28) display an area along the coastline where the bedrock was particularly well exposed. Dark veins and network of glassy material was easily distinguishable from the quartzitic host rock. A total of 67 measurements of fracture veins appearing on fault planes were taken. Five samples were made into thin sections, the sample sites are marked on the map (fig. 28). The area of lake Greningen contained both clearly defined veins and cataclastic material (fig. 8). The map in figure 28 shows the foliated rock in contact with brecciated rock (phyllite and quartzite) which gradually move into a purer quartzitic unit. The same phyllite-breccia-quartzite succession was seen further up north along this outcrop. On the east side of the shoreline the breccia makes some reappearances as small zones in the quartzite. The contacts between the breccia and the quartzite was unclear and the orientation of the contacts shown on map have only been visually estimated. The complicated relationship of thicker veins and bands of crushed cataclastic material is shown in figure 6, where a vein of dark material to the right is in connection, via injection veins, to a cataclastic "pocket" with big host rock clasts within. The measurements of these type of panes shows two conjugates sets, one dipping shallowly towards the west and one dipping steeply towards the southeast. The complete dataset shows fault plane in all directions (Greningen-plot in fig. 5), but with two significant main sets: on striking NE-SW with a steep dip and the other strike N-S with a shallow dip ("Mean of all Pt-planes"- plot in fig. 28).

The thin section analysis from Greningen was carried out in the same manner as for the previously described localities. The result is presented as a scanned image together with a sketched image and a descriptive text.

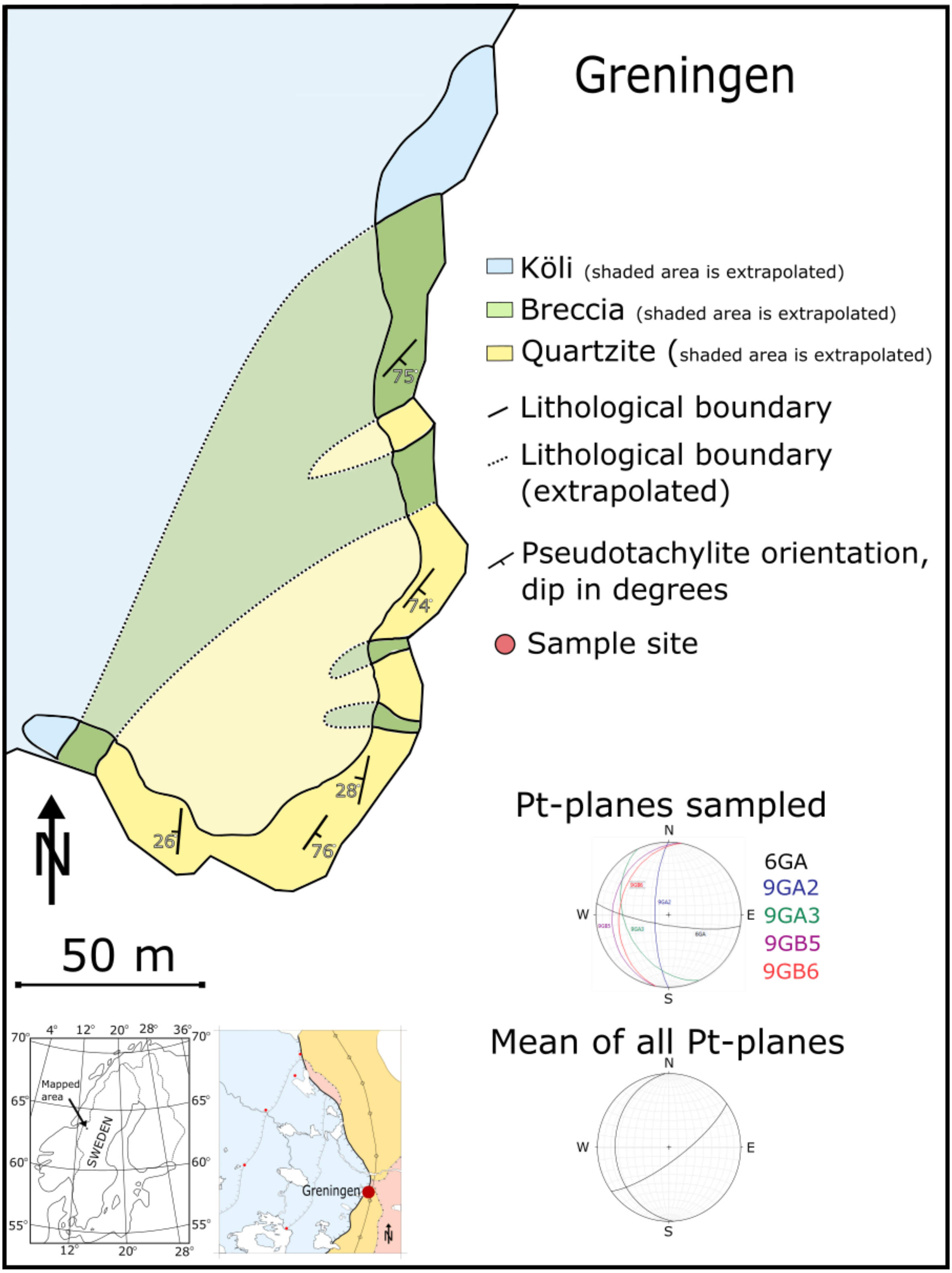


Figure 28 – Detailed map of locality Greningen showing the phyllite-breccia-quartzite units of rock together with the five different sample sites. The orientation of the fracture veins sampled are shown in the top most stereonet plot. The lower most stereonet plot shows the mean of all measured planes.

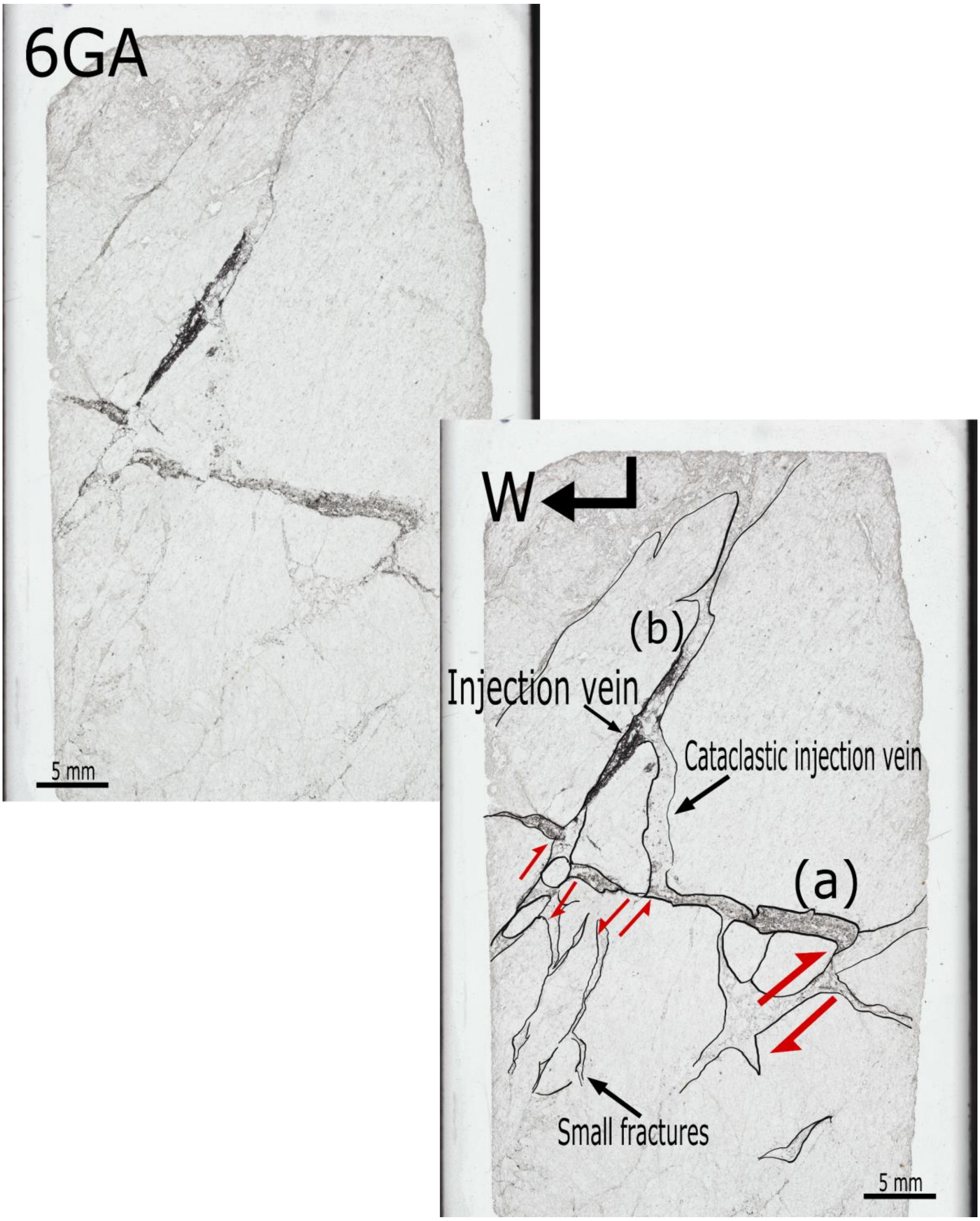


Figure 25, sample 6GA - Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The arrow give way up and points to the west.

Sample 6GA
Hostrock and Minerals This sample is acquired at only a few meters distance from the brecciated rock unit. This quartzite appears to have been deformed in a brittle phase, as is evident by the cut-off minerals at fracture and fault planes. Angles of 120 degrees between mineral boundaries of quartz are common. In between the cataclastic material the foliation of the host rock dips steeply to the W. Quartz, white mica, small red crystals (possibly carbonates?), opaque minerals, and small amounts of brown, green mineral in the vein itself.
Fracture vein In this sample black veins of glassy material can be found both with and perpendicular to the general foliation. The vein material is black in color and contains small, elongated micro crystals, but no compositional banding or flow structures can be recognized. Vein (a) have been faulted by a top-E reversed fault and crosscut by vein (b). Injection veins can be seen from vein (b).
Order of events Brittle event causing vein (a) to form perpendicular to the foliation, then more deformation causing faulting of vein (a) and formation of vein (b).

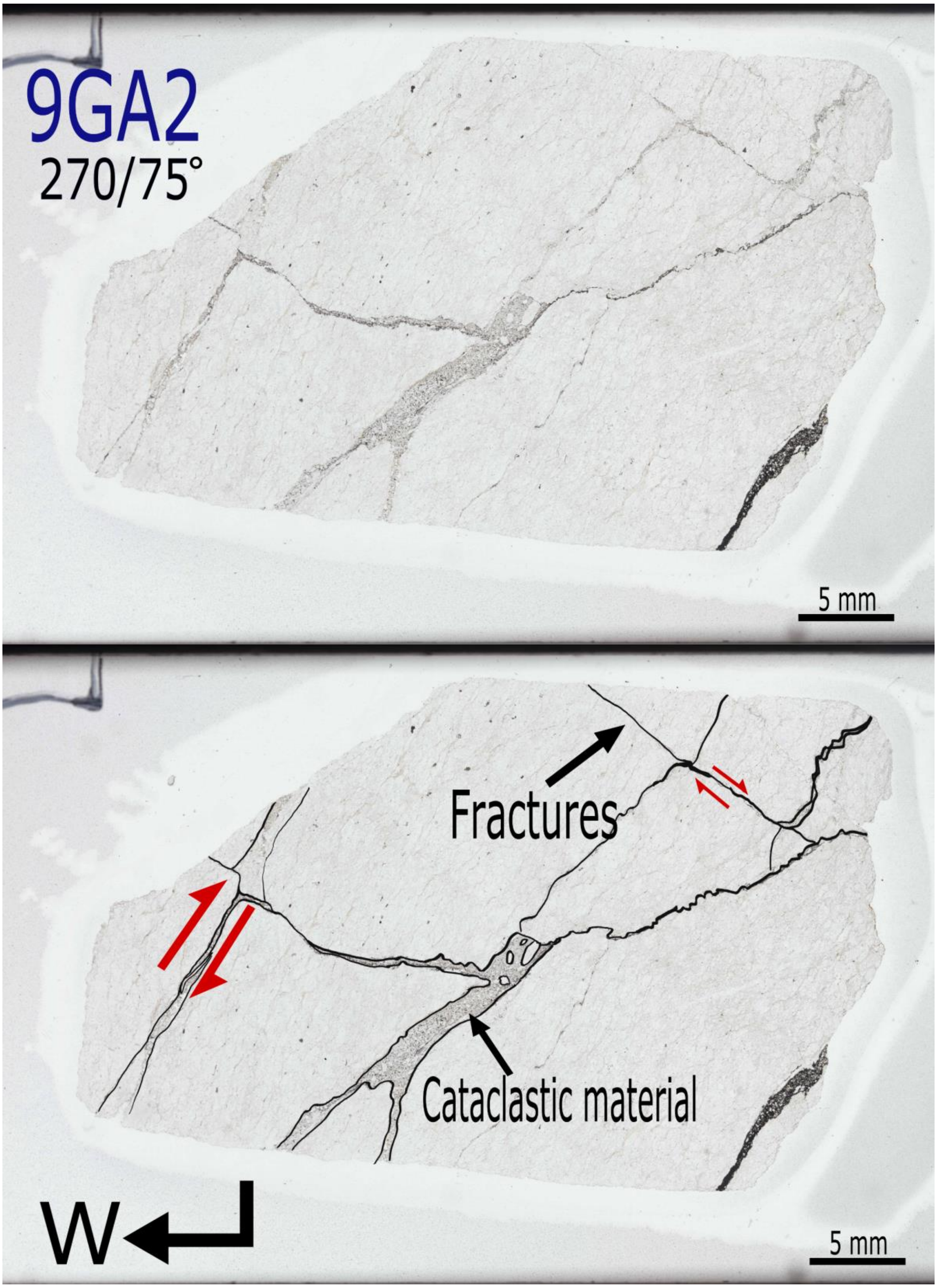


Figure 26, sample 9GA2 - Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The arrow give way up and points to the west.

Sample 9GA2
Host rock and Minerals The quartz minerals are uniform in size, angles of 120 degrees between mineral boundaries are common. Some lineation could be interpreted by the preferred orientation of the white mica minerals, in a steep dip towards the W. Quartz, white mica, opaque minerals, and small amounts of brown, green mineral in the vein itself. Stretching
Fracture vein This sample contain more of the cataclastic material and one darker fault plane (lower right corner of the sample). Most of the cataclastic units and the darker vein are parallel with the lineation, dipping steeply to the W. However, there are other cataclastic veins, which cross both the lineation and the W-dipping fracture veins. From the cataclastic material in the center of the thin section, injection veins are shooting off in an orientation perpendicular to the lineation. The material in the cataclasite and the more glassy looking fracture vein is mostly made up of dark, elongated micro crystals.
Order of events First the foliation, then a brittle event causing the fracturing of the rock and the cataclastic material to form.

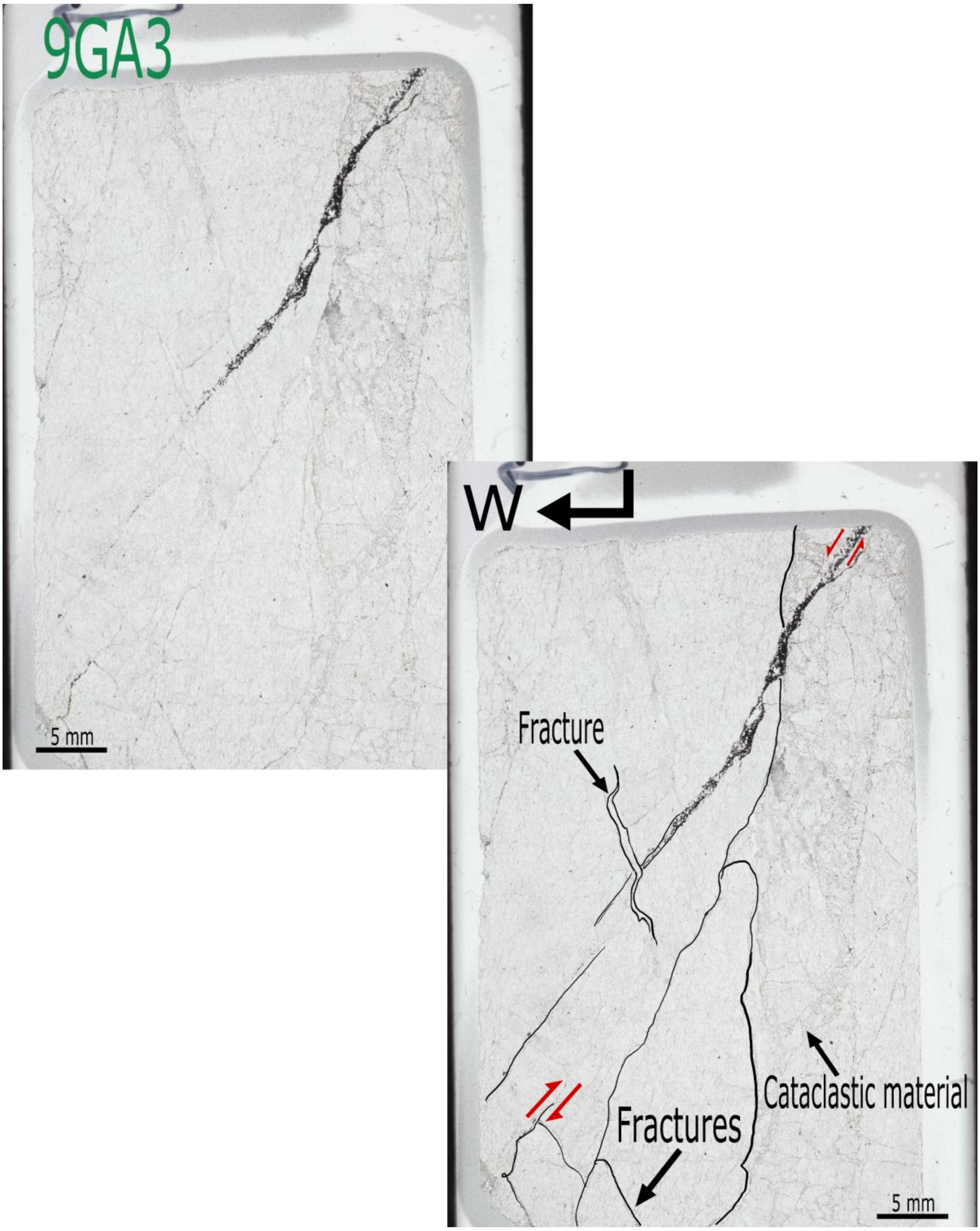


Figure 27, sample 9GA3 - Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The arrow give way up and points to the west.

Sample 9GA3
Host rock and Minerals This sample was taken in close proximity to the brecciated rock unit and cataclastic material present in the thin section. Angles of 120 degrees between quartz mineral boundaries are common. Quartz, white mica, opaque minerals, possibly some biotite in the dark vein, some small, red crystals also in the dark vein (close-up in image 13).
Fracture vein This sample contain one dark vein, going from the top right corner and down towards the left where it thins out and disappears. The vein is oblique to the lineation and appears with a couple of injection veins. In the dark matrix, elongated micro sized crystals are seen. At the top of the vein some quartz minerals appears to be on the verge of being ripped off by the dark vein material, which could suggest a top-W normal faulting of the vein-plane
Order of events First the foliation, then a brittle event causing the fracturing of the rock and the cataclastic material to form, followed by more brittle deformation causing the fracture vein to crosscut the cataclasite material.

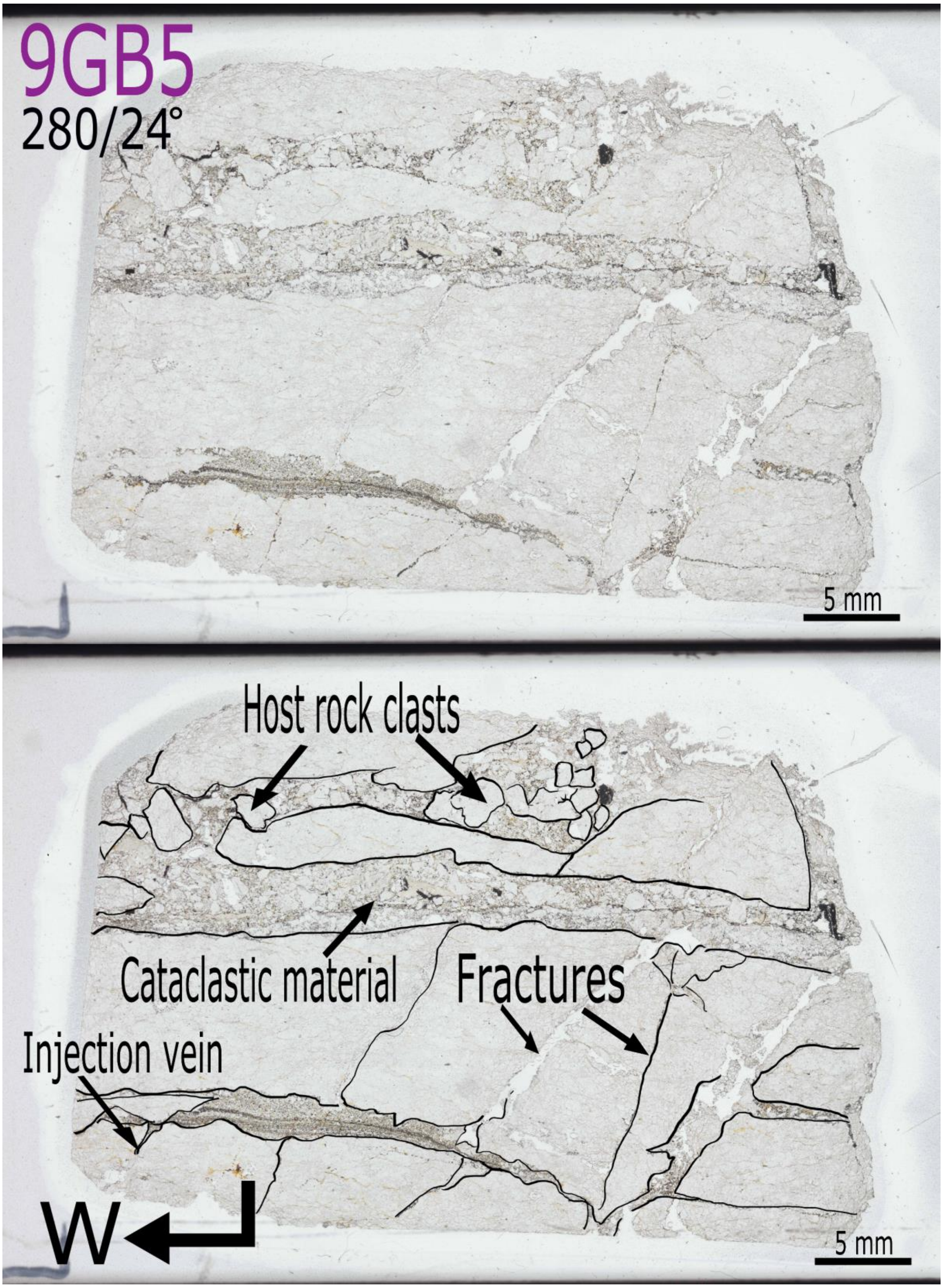


Figure 28, sample 6B5 - Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The arrow give way up and points to the west.

Sample 9GB5
Host rock and Minerals This quartzite display no evidence of a lineation. However, some 120 degree angles between the quarts grains are identified. Network of thin bands made up by smaller quartz grains are found and over all, this sample appears to be a cataclasite. Quartz, white mica, opaque minerals, small amounts of brown, green mineral in the fractured bands.
Fracture vein This sample contain three horizontal planes of cataclasite bands. Two of them are intertwining with each other and could be the same only separated by a bigger host rock clast in the middle of it. The lowest cataclastic band is more fine grained and has a darker band in the center of it. In all the cataclastic fractures green minerals are present. Large clusters of sericite are also present as well as cubic opaque minerals.
Order of events Brittle event causing the fracturing of the rock and the cataclastic material to form.

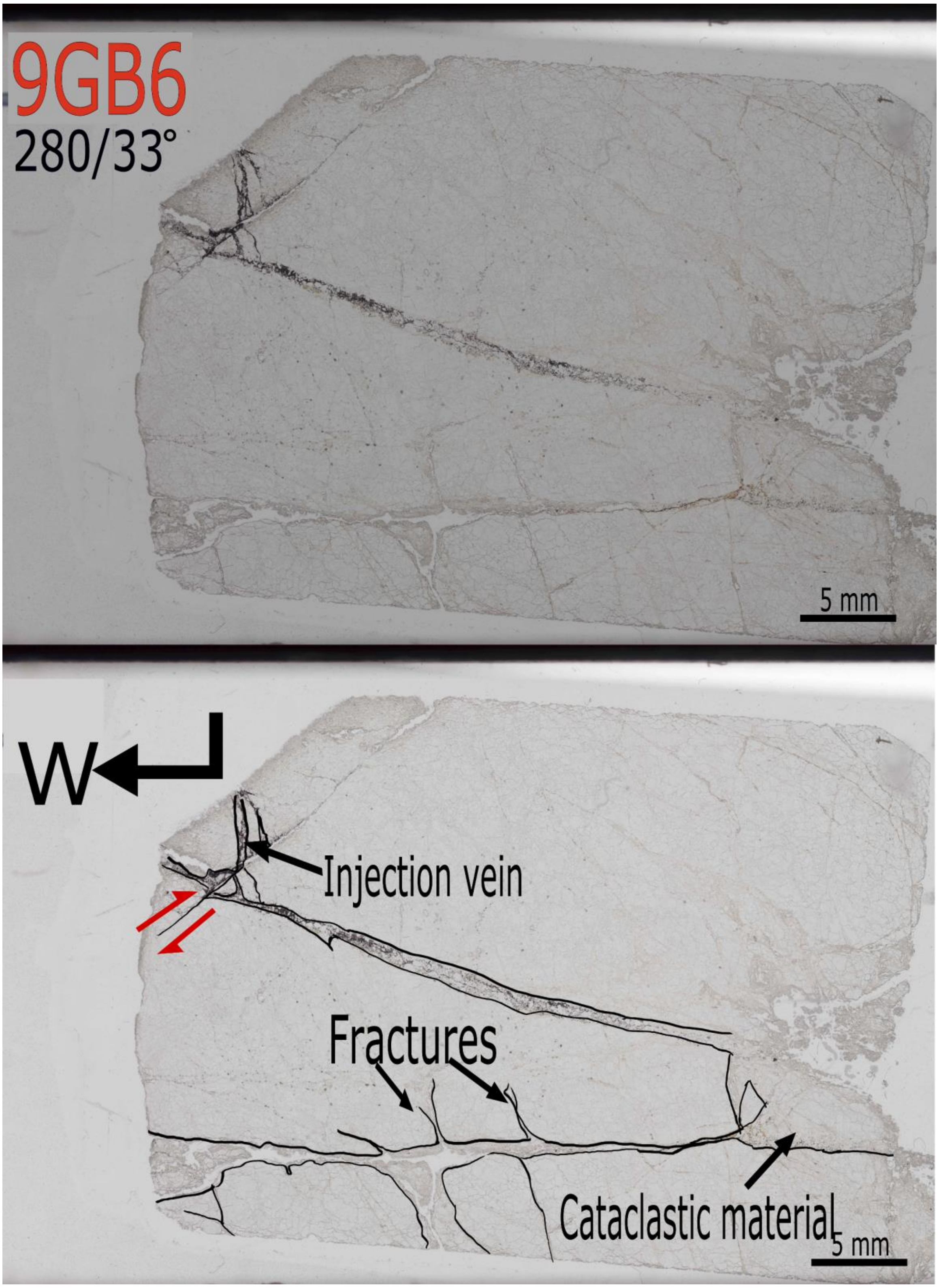


Figure 29, sample 9GB6 - Topmost is a scanned image of the thin section, important features are enhanced in the sketch below. The arrow give way up and points to the west.

Sample 9GB6
Host rock and Minerals The quartzite display no evidence of a lineation, but some 120 degree angles between the quartz grains are identified. In the quartzite there are thin bands of small quartz grains, going in straight lines in the rock. Quartz, white mica, opaque minerals, a small amounts of brown, green mineral and some small purple grains in the dark vein.
Fracture vein This sample also contain one black vein, with other cataclastic material going sub-parallel to it. The black vein has some injection veins attached to it and thins out further to the right in the sample. At the top left corner there is a top-E reverse fault offsetting both the cataclasite as well as some injection veins.
Order of events First the foliation, then a brittle event causing the fracturing of the rock and the cataclastic material to form.

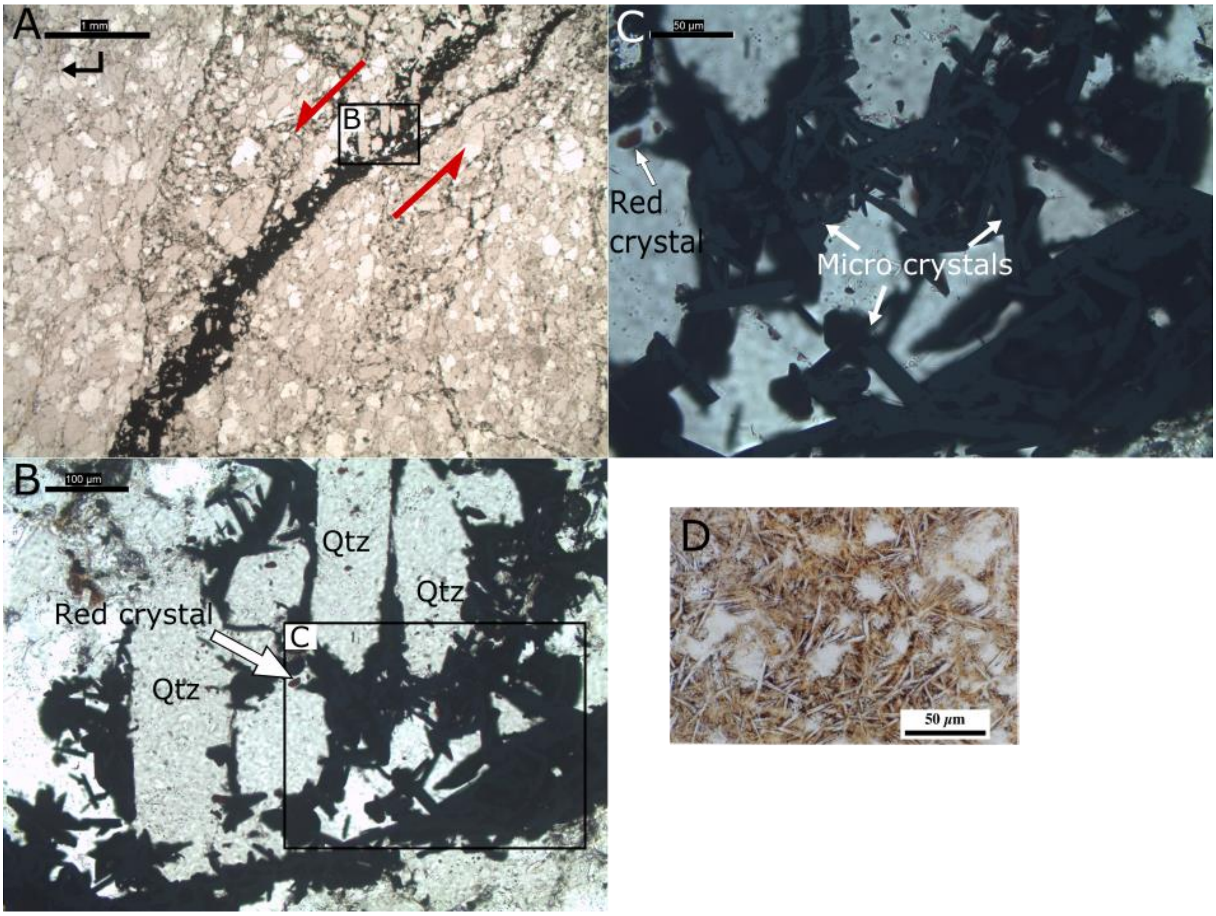


Figure 30 – All images are in plane polarized light (sample 9GA3). **A**: A dark vein is crossing a cataclastic zone in the quartzite of Greningen. The fracture vein is full of quartz crystals from the host rock. Quartz grains are sticking out like teeth, suggesting a top-W normal fault plane. **B:** Some red crystals are seen in the dark material which are showing to be constituted of a crystalline matrix. **C:** The micro crystals show a lath-like structure of what possibly could be hematite or magnetite microlites. **D:** For comparison, image of lath-like microlites from Lin (2008).

Summary of the thin section analysis of Greningen

At the locality of Greningen the vein within the fault planes appears different, both in hand sample and in thin sections. On the outcrop, the dark, glassy structure appears as thin bands or networks in a complicated fashion (fig. 6). Some of these dark structures appear as planes of melt, whereas others appear as “pockets” of cataclastic material. The dark, glassy veins and cataclastic planes measured in field are reviled to be organized in a conjugate fault set (fig.4). However, the samples acquired from the locality only represent the shallow, westward dipping set, along with two steeper planes not directly connected to any of the main fault orientations. In general, the black veins and cataclastic material from this locality have no compositional banding, and seems to consist mostly of dark micro scale crystals (fig. 30 B-C). These crystals are clearly distinguishable in the quartzite host rock and appear to grow in all directions. Furthermore does the crystals show the typical microlitic shape of “acicular” to “lath-like” when compared to actual microlites (fig. 30 D). The major difference between the microlites and the micro crystals in the Greningen samples is the size. The Greningen sample contains veins made up by dark crystals of about 50μm in length. However, in between the micro crystals some smaller, red to purple colored crystals are observed.

Discussion

Melt originated pseudotachylites

To conclude if these fine grained, planar features are melt generated pseudotachylites or not, was one of the main aims for this thesis. These dark to light -gray, millimeter thick bands within the Köli Nappe Complex looked different from locality to locality in the field, but showed to be more similar in thin section. However, a distinct exception is that of the dark veins from the locality of Greningen (fig. 30). These black veins were first of all discovered in an un-foliated quartzite that have not yet been correlated to any deformation sequence. Furthermore is the size of the micro crystals within the veins problematic. These micro crystals are what constitutes the black veins first noted in the quartzite and although they have a glassy appearance, the crystal within the vein are about 50 µm in size. These crystals have much in common with microlites, and could be argued to belong to the Simple-Group with the “lath-like” shape that are commonly found in melt driven pseudotachylites (fig. 2). However, they are much bigger than that of the typical size of microlites of about 6-7 µm. Compared to the microlites in image 30 D, the dark crystals of Greningen are not small enough to indicate the rapid cooling that would be associated with crystals forming from sudden frictional heat (Lin, 1994a). In the optical microscope, it becomes more evident that other pseudotachylite-like features are lacking from these samples. How the micro scale crystals formed on these fracture planes are still unclear but their presence appears to have little to do with pseudotachylite formation.

Nevertheless, in the foliated rock from the other localities the more classical evidence of a melt origin pseudotachylite are present. Most of the samples showed compositional banding (fig. 24 A-G) in which flow structures could be identified (fig. 26). Another strong indicator of a melt origin is the presence of vesicles and amygdales which speak of a phase of gas extrusion from a melt (Lin, 2008, 1994b). In the sample form Finnån, textures previously described as “sphaerulites in ‘bubbly’ matrix” (Beckholmen, 1982) could be argued to belong to the Spherulitic Group of microlites. This bubbly texture is recognized in many samples presented in this thesis (fig. 7- fig. 23 and fig. 24 A-G). Based on the frequent occurrence of microlites in pseudotachylites (Lin, 2008) it could be inferred that the microlites are most commonly of the Spherulite Group, probably radiating from nucleolus of feldspar or quartz.

Other interesting features are found in the pseudotachylites, two of which are represented by sample HD2A (fig. 9 and fig. 27). On the lower most fault plane seen in sample HD2A (fig. 9) the pseudotachylite appears in a zone of cataclastic material. This speaks for the occurrence of a fault zones with cataclastic precursor presiding the high-pressure pseudotachylite-melt deformation event. This is also noted in other samples as discussed in the section “Deformation events”. The second interesting founding in this sample is however less clearly interpreted. As can be seen in the lowermost pseudotachylite vein, a section have been replaces by calcite crystals. Due to the sharp edges of the calcite, this appears to have formed after the deformation event causing the pseudotachylite formation. What happened to the original material on this fault plane is still unclear.

Deformation events

At Wästra Häggsjön and Häggsjön two foliation events are evident. The early one is preserved in poikilitic porphyroblats of amphibole and somewhat in biotite that formed in a metamorphic event after the first foliation. Not until after this metamorphic event was the main schistosity (S_2) formed, as defined by the white mica bending around amphibole and garnet crystals as seen in the locality of Finntjärnen (fig. 15 and fig. 25) and the two localities around Häggsjön (sample HäB and HäC). This second schitosety is also apparent in the stretching of amphibole crystals as seen in the Grabenshifer at Stalltjärnstugan (fig. 5). The amphiboles appears to be un-oriented, however, those aligned in the stretching direction have been boudinaged. These foliation events are separated by a metamorphic event allowing the growth of amphibole porphyroblasts, which later get crosscut by the pseudotachylite melt plane, this would argue, as Beckholmen also noted (Beckholmen, 1983), that the pseudotachylite formation happened post peak metamorphism.

Six different deformation events have previously been applied to the area of Tännforsfältet, with the formation of pseudotachylites marking the latest event (Beckholmen 1982). A larger number of folding events were inferred to have occurred between the first foliation in D_1 and that of the latest event causing pseudotachylite formation in a brittle phase. These folding events are somewhat represented in the samples as well, presumably in what have been described as faults and kinks in the host rock during D2, as defined in this thesis. However, the greatest difference concerning deformation events in this thesis compared to that of previous studies (e.g. Beckholmen, Gee, Kulling) is that here, more than one pseudotachylite-forming event is presented. In the samples from the area around Häggsjön, Stalltjärnstugan and the Håltbergsudden localities, the presence of at least two pseudotachylite- formation event is clear (fig. 7, 17, 19 and fig.24 C-D). As stated by Di Toro (Di Toro et al., 2005) and referenced therein, pseudotachylite melt planes are often found with at cataclastic precursor and the pseudotachylite itself confirms our current understanding of re-activation of fault planes. However, one of the samples studied showed the opposite relation with a cataclastic event following a pseudotachylite faulting. This reversal of deformations is suggested by fractures of apparent pseudotachylite fault material within the cataclastic unit adjacent to the melt plane (fig. 18). For the melt material to occur as clasts in the cataclasite, it must have formed prior to the cataclasite. This would then mean that a higher pressure event occurred prior to a lover one.

There also appears to have been some ductile deforming component during the deformation of the first Pt-plane as evident in the image of boundins/faulted Pt-melts, where the surrounding host rock appears to have been ductily sheared around the pseudotachylite fragments (fig. 10, 17 and fig. 24 E). This is especially clear in the sample from Stalltjärnstugan (fig. 24 C) where the first generation Pt-plane itself appears to have been boundinaged in a more ductile deformation phase. Another example of the existence of a more ductile regime after the first brittle Pt-formation is apparent in one of the samples from Håltbergsudden (fig. 9 and fig. 24 E) where the host rock displays a mylonitic texture around the brittlely faulted pieces of the melt layer. This extension event have stretched out the pseudotachylite plane into what appears as domino boundins at Håltbergsudden (fig. 10) and sheared boundins at Stalltjärnstugan (fig.

17). This myloniticly deformed material surrounding the domino boundins especially speaks for a deformation phase with a ductile component taking place after the brittel pseudotachylite formation event. This entails that the brittle pseudotachylite event is not, as previously thought, the last stage of deformation. The stages of exhumation of these rock units are therefore inferred to most likely have gone from a ductile to brittle stage, forming the first melt generation, then back to a warmer regime with ductile deformation before the second melt generation, again back in a brittle system.

In one sample from Håltbergsudden a large part of the cataclastic material surrounding a melt plane have been replaced with calcite (fig. 9 and fig. 27). How the cataclastic material was removed is still unclear, however, some very clear extensional fractures are seen adjacent to this structure. These extensional fractures, as well as the others seen in the samples, have calcite grains growing perpendicular to the fracture plane, which indicates that the extension direction happened in the E-W orientation. As these calcite infilled fractures appear in almost all samples and crosscut all the previous structures, they are inferred to be derived from the latest stage of deformation D5, evidently in a brittle system.

The question remains when in the deformation sequence the pseudotachylites formed. Evidence of shortening occurs overprinted by the pseudotachylite planes, whereas the pseudotachylite themselves are overprinted by extension features such as faulting and calcite infilled fractures. It could be that any offsetting relation between the host rock above and below the pseudotachylite fault plane are separated by a distance exceeding the length of a thin section. Evidence for the direction of movement of the host rock during the faulting event should therefore not be investigated in confined space of a thin section, but should be searched for in the field.

Conclusion

The structural analyses of the thin sections reveal the presence of at least five deformation events, most of which occurred in a brittle, cold system. What is also evident is that, contrary to what was previously described, the pseudotachylites of Tännforsfältet originate from two separate deformation events. Furthermore, evidence of a ductile deformation component reworking the first pseudotachylite generation suggests that exhumation of the rock unit did not occur in a straightforward manner, going from a ductile to brittle phase. This adds to our current understanding of the tectonic history, and the exhumation, of the rocks in Tännforsfältet whereas the occurrences of more than one pseudotachylite generation itself confirms our current understanding of re-activation of fault planes.

Acknowledgments

First and foremost I give my thanks to Hagen Bender for proposing this project and for helping me along the way. I also give great thanks to my supervisor Prof. Uwe Ring, who has been especially helpful in the structuring of this thesis work. I would like to give my warmest of thanks to Bjarne Almqvist who stayed eternal positive during the supplementary analyses done in Uppsala and to Dan Zetterberg who help with the sample preparation. When I get back in academia, we will sort the results out. Furthermore, I would also give a special thanks to Monica Beckholmen who has been very enthusiastic about this project, since it in part literally follows her footsteps in the Tännforsen area. Lastly, I thank Hildred Crill for helping me fined the weaknesses in my text and in general giving advice during the writing process. This text would not have been what it is without your help.

References

Beckholmen, M., 1984a. Structural and Metamorphic Zonation in Tännforsfältet Western Jämtland, Swedish Caledonides. Medelande från Stockholms universitets geologiska institution N:r 258

Beckholmen M., 1984b. The Köli Nappe Complex in Tännforsfältet Western Jämtland, Swedish Caledonides. Department of Geology, Stockholm University, S-106 91 Stockholm, Sweden

Beckholmen, M., 1983. The deformation sequence in the Häggsjö- Musvaltjärnen-Rensjönäset area in western Jämtland , Swedish Caledonides. GFF (Geologiska Foren. i Stock. Forh. 105, 119–130. doi:10.1080/11035898309454555

Beckholmen, M., 1982. Mylonites and pseudotachylites associated with thrusting of the Koli Nappes, Tannforsfaltet, central Swedish Caledonides. Geol. Foren. i Stock. Forh. 104, 23–32. doi:Cited By (since 1996) 2\rExport Date 14 January 2013

Beckholmen, M., 1978. Geology of the Nordhallen—Duved—Greningen area in Jämtland, central Swedish Caledonides. Gff 100, 335–347. doi:10.1080/11035897809454471

Berlenbach, J.W., Roering, C., 1992. Sheath-fold-like structures in pseudotachylytes. J. Struct. Geol. 14, 847–856. doi:10.1016/0191-8141(92)90045-X

Clough, C.T., Maufe, H.B., Bailey, E.B., 1909. The Cauldron-Subsidence of Glen Coe, and the Associated Igneous Phenomena. Q. J. Geol. Soc. 65, 611–678. doi:10.1144/GSL.JGS.1909.065.01-04.35

Di Toro, G., Pennacchioni, G., Teza, G., 2005. Can pseudotachylytes be used to infer earthquake source parameters? An example of limitations in the study of exhumed faults. Tectonophysics 402, 3–20. doi:10.1016/j.tecto.2004.10.014

Fabbri, O., Lin, A., Tokushige, H., 2000. Coeval formation of cataclasite and pseudotachylyte in a Miocene forearc granodiorite, southern Kyushu, Japan. J. Struct. Geol. 22, 1015–1025. doi:10.1016/S0191-8141(00)00021-3

Ferré, E.C., Geissman, J.W., Chauvet, A., Vauchez, A., Zechmeister, M.S., 2015. Focal mechanism of prehistoric earthquakes deduced from pseudotachylyte fabric. Geology 43, 531–534. doi:10.1130/G36587.1

Gee, D.G., Fossen, H., Henriksen, N., Higgins, a K., 2008. From the early Paleozoic platforms of Baltica and Laurentia to the Caledonide orogen of Scandinavia and Greenland. Episodes 31, 44–51.

Gee, D.G., Janak, M., Majka, J., Robinson, P., van Roermund, H., 2012. Subduction along and within the Baltoscandian margin during closing of the Iapetus Ocean and Baltica-Laurentia collision. Lithosphere 5, 169–178. doi:10.1130/L220.1

Jackson, J. A. (2005). Glossary of geology. *Glossary of Geology, by JA Jackson. 2005 Approx. 900 p. 5th revised and enlarged ed. ISBN 3-540-27951-2. Berlin: Springer, 2005.*, 5th.Kirkpatrick, J.D., Rowe, C.D., 2013. Disappearing ink: How pseudotachylytes are lost from the rock record. J. Struct. Geol. 52, 183–198. doi:10.1016/j.jsg.2013.03.003

Kulling, O., 1933. Bergbyggnaden inom Björkvattnet—Virisen-området i Västerbottensfjällens centrala del: En studie i den kaledoniska bergskedjans geologi. Gff 55, 167–422. doi:10.1080/11035893309450934

Lin, A., 2008. Fossil Earthquakes: The Formation and Preservation of Pseudotachylytes, Lecture Notes in Earth Sciences. Springer Berlin Heidelberg, Berlin, Heidelberg. doi:10.1007/978-3-540-74236-4

Lin, A., 1999. Roundness of clasts in pseudotachylytes and cataclastic rocks as an indicator of frictional melting. J. Struct. Geol. 21, 473–478. doi:10.1016/S0191-8141(99)00030-9

Lin, A., 1994a. Microlite Morphology and Chemistry in Pseudotachylite, from the Fuyun Fault Zone, China. J. Geol. 102, 317–329. doi:10.1086/629674

Lin, A., 1994b. Glassy pseudotachylyte veins from the Fuyun fault zone, northwest China. J. Struct. Geol. 16, 71–83. doi:10.1016/0191-8141(94)90019-1

Lin, A., Maruyama, T., Aaron, S., Michibayashi, K., Camacho, A., Kano, K.I., 2005. Propagation of seismic slip from brittle to ductile crust: Evidence from pseudotachylyte of the Woodroffe thrust, central Australia. Tectonophysics 402, 21–35. doi:10.1016/j.tecto.2004.10.016

Magloughlin, J.F., Spray, J.G., 1992. Frictional melting processes and products in geological materials: introduction and discussion. Tectonophysics 204, 197–204. doi:10.1016/0040-1951(92)90307-R

Nesse W. D., 2012: Introduction to Mineralogy, Oxford University Press, 2nd edition (No. 549 NES)

Peach, B.N., Horne, J., Gunn, W., Clough, C.T., Hinxman, L., Cadell, H.M., 1888. Report on the Recent Work of the Geological Survey in the North-west Highlands of Scotland, based on the Field-notes and Maps: (Read April 25, 1888.). Q. J. Geol. Soc. 44, 378–441. doi:10.1144/GSL.JGS.1888.044.01-04.34

Ray, S.K., 2004. Melt - Clast interaction and power-law size distribution of clasts in pseudotachylytes. J. Struct. Geol. 26, 1831–1843. doi:10.1016/j.jsg.2004.02.009

Ray, S.K., 1999. Transformation of cataclastically deformed rocks to pseudotachylyte by pervasion of frictional melt: Inferences from clast-size analysis. Tectonophysics 301, 283–304. doi:10.1016/S0040-1951(98)00229-7

Reimold, W.U., 1995. Pseudotachylite in impact structures - generation by friction melting and shock brecciation?: A review and discussion. Earth Sci. Rev. 39, 247–265. doi:10.1016/0012-8252(95)00033-X

Robinson, P., 1995. Extension of Trollheimen tectono-stratigraphic sequence in deep synclines near Molde and Brattvag, Western Gneiss region, southern Norway. Nor. Geol. Tidsskr. 75, 181–198.

Shand, S.J., 1916. The Pseudotachylyte of Parijs (Orange Free State), and its Relation to "Trap-Shotten Gneiss" and "Flinty Crush-Rock." Q. J. Geol. Soc. 72, 198–221. doi:10.1144/GSL.JGS.1916.072.01-04.12

Sibson, R.H., 1975. Generation of Pseudotachylyte by Ancient Seismic Faulting. Geophys. J. R. Astron. Soc. 43, 775–794. doi:10.1111/j.1365-246X.1975.tb06195.x

Törnebohm, A.E., 1888. Om fjällproblemet. Geol. Foereningan i Stock. Foerhandlingar 10, 328–336. doi:10.1080/11035898809444211

Wallace, R.C., 1976. Partial fusion along the Alpine Fault Zone, New Zealand. Geol. Soc. Am. Bull. 87, 1225–1228. doi:10.1130/0016-7606(1976)87<1225:pfataf>2.0.co;2

Wenk, H.R., Johnson, L.R., Ratschbacher, L., 2000. Pseudotachylites in the Eastern Peninsular Ranges of California. Tectonophysics 321, 253–277. doi:10.1016/S0040-1951(00)00064-0

Softwares used:

Turner-Jones, B. (2017) RockLogger (v. 1.9) [Mobile application software] Retrieved from http://play.google.com/store/apps/details?id=com.rockgecko.dips&hl=sv

Stereonet -Allmendinger, R. W., Cardozo, N. C., and Fisher, D., 2013, Structural Geology Algorithms: Vectors & Tensors: Cambridge, England, Cambridge University Press, 289 pp.

Cardozo, N., and Allmendinger, R. W., 2013, Spherical projections with OSXStereonet: Computers & Geosciences, v. 51, no. 0, p. 193 - 205, doi: 10.1016/j.cageo.2012.07.021

Appendix

Field measurements

Tabel 1, the lineation and foliation measurements from field.

Lokal	GPS (UTM)		Foliation		Lineation		Additional information
	X	Y	DD (dipdir.)	D (dip)	T (trend)	P (plunge)	Minera showing lineation.
Finntjären	374141	7031467	340	15	260	10	white mu, amphibole
Finntjären	374247	7031487	310	24	284	12	chl
Finntjären	374141	7031467	340	20			
Finntjären (telefon)	374051	7031443	80	20,2			
Finntjären (telefon)	374054	7031447	59,9	18			
Finntjären (telefon)	374048	7031453			64,8	9,2	Overturned.
Finntjären (telefon)	374045	7031451	47,5	16,8			
Finntjären (telefon)	395104	7027474	13	23,9			
Finntjären (telefon)	374044	7031455	44,5	10,7			
Finntjären (telefon)	374052	7031443	89,6	14,6			
Håltbergsudden	380988	7020480	320	34	272	30	qtz, mu chl
Håltbergsudden	380988	7020480	318	30			
Håltbergsudden	380988	7020480	310	32	300	30	qtz, mu chl
Håltbergsudden	380988	7020480	340	34			
Håltbergsudden	381117	7020384					
Håltbergsudden	381625	7020257	320	30	280	22	qtz, mu chl
Håltbergsudden	381625	7020257	276	28			
Håltbergsudden	381586	7020250			261	13	qtz, mu chl
Håltbergsudden	381568	7020261	309	30	260	20	qtz, mu chl
Håltbergsudden	381568	7020261	335	25			
Håltbergsudden	381568	7020261	310	32			
Håltbergsudden	381459	7020262	323	48	275	24	qtz, mu chl
Håltbergsudden	381459	7020262	283	64			
Håltbergsudden	381459	7020262	321	48			
Håltbergsudden	381459	7020262	322	30			
Håltbergsudden (telefon)	380992	7020492	44,5	37			
Håltbergsudden (telefon)	380992	7020491	41	38,5			
Håltbergsudden (telefon)	380992	7020491	38,6	35,9			
Håltbergsudden (telefon)	380993	7020496	22,7	38			
Håltbergsudden (telefon)	380990	7020496	8,4	38,2			

Håltbergsudden (telefon)	381118	7020374	2,6	15			
Håltbergsudden (telefon)	381723	7020293	37,9	35,5			
Håltbergsudden (telefon)	381724	7020285			89,9	24,7	
Håltbergsudden (telefon)	381626	7020255	40,4	30,4			
Håltbergsudden (telefon)	381588	7020255	84,1	28,1			
Håltbergsudden (telefon)	381587	7020255			36,6	16,5	
Håltbergsudden (telefon)	381562	7020249	49,6	32,8			
Håltbergsudden (telefon)	381561	7020252	24,9	25,3			
Håltbergsudden (telefon)	381560	7020259	50,9	29,7			
Håltbergsudden (telefon)	381566	7020256			80	19,9	
Håltbergsudden (telefon)	381462	7020270	77,3	64,1			
Håltbergsudden (telefon)	381462	7020271	36,5	48,6			
Håltbergsudden (telefon)	381461	7020269	38,4	48,6			
Håltbergsudden (telefon)	381463	7020273	38,4	60,9			
Stalltjärnstugan	377693	7040981	220	20	260	10	chl
Stalltjärnstugan	377705	7040938	252	38	260	7	
Stalltjärnstugan	377772	7041152	340	52			
Stalltjärnstugan	377618	7041173	310	38			
Stalltjärnstugan	377618	7041173	318	52			
Stalltjärnstugan	377618	7041173	316	40			
Stalltjärnstugan	377772	7041152	279	65	208	21	chl
Stalltjärnstugan	377772	7041152	320	52	259	19	
Stalltjärnstugan	377772	7041152	322	52			
Stalltjärnstugan	377772	7041152	312	50			
Stalltjärnstugan	377772	7041152	310	50	219	12	chl, bi
Stalltjärnstugan	377772	7041152	310	68	230	14	bi, plag
Stalltjärnstugan	377770	7041143			228	20	
Stalltjärnstugan	377658	7041156	258	20	138	36	
Stalltjärnstugan	377610	7041168	242	21	203	20	
Stalltjärnstugan	377562	7041153	282	30	210	26	
Stalltjärnstugan	377562	7041153	277	38	198	14	
Stalltjärnstugan	377562	7041153			210	17	
Stalltjärnstugan	377497	7041206	280	20	230	18	
Stalltjärnstugan	377497	7041206	271	22	222	11	chl, bi
Stalltjärnstugan (telefon)	377772	7041141	39,1	52			
Stalltjärnstugan (telefon)	377774	7041119	82,5	59,1			Overturned.
Stalltjärnstugan (telefon)	377771	7041138	88,7	59,2			Overturned.
Stalltjärnstugan (telefon)	377767	7041141	84,5	65,4			Overturned.
Stalltjärnstugan (telefon)	377768	7041141	60,8	87,6			Overturned.

Stalltjärnstugan (telefon)	377768	7041141	77,3	78,9			Overturned.
Stalltjärnstugan (telefon)	377769	7041142	71	66,6			Overturned.
Stalltjärnstugan (telefon)	377770	7041143	78,2	67,1			Overturned.
Stalltjärnstugan (telefon)	377770	7041143	88,7	55,8			Overturned.
Stalltjärnstugan (telefon)	377604	7041161	62,9	21,1			
Stalltjärnstugan (telefon)	377603	7041165			23,1	20,4	
Stalltjärnstugan (telefon)	377558	7041163	82,3	37,3			
Stalltjärnstugan (telefon)	377558	7041159			18,6	14,6	
Stalltjärnstugan (telefon)	377558	7041160			29,5	17,3	
Stalltjärnstugan (telefon)	377488	7041197	88,7	22,6			
Stalltjärnstugan (telefon)	377486	7041195			42,5	11,3	
Häggsjön	383150	7052034	268	12			
Häggsjön	383159	7052029	226	74			
Häggsjön	383161	7052026	260	72	348	20	
Häggsjön	383131	7052039	22	86			
Häggsjön	383123	7052043	60	90			
Häggsjön	383149	7052084	22	90	194	18	
Häggsjön	383538	7051540	210	12	232	14	
Häggsjön	383535	7051543	2	12	60	6	
Häggsjön (telefon)	384064	7050977	39,8	47,3			
Häggsjön (telefon)	383253	7051968	80	33,9			
Häggsjön (telefon)	383109	7052068	86,5	23,5			
Wästra Häggsjön	382371	7047655	300	52			
Wästra Häggsjön	382371	7047655	296	50	242	10	bi
Wästra Häggsjön	382366,2	7047645, 27	300	60	232	22	
Wästra Häggsjön	382371,5	7047643, 51	320	8			
Wästra Häggsjön	382366	7047646	332	50	312	20	
Wästra Häggsjön	382363	7047650	322	58			

Fault planes of Greningen

Table 2, the measurements of the pseudotachylite-like fault planes at lake Greningen, red numbers = uncertain, o = overturned

Kordinates (UTM)		Pesudotacholyte/fault plane		
X	Y	DD (dipdir.)	D (dip)	
394986	7027355	144,5	85,6	
394976	7027329	291,6	84,4	
394978	7027326	292,7	81,4	
394977	7027324	36,5	16,2	
394977	7027323	176,5	83,7	
394977	7027321	305,2	87,1	
394977	7027321	294,2	78,6	
394974	7027317	178,4	88	
394974	7027321	126,9	78,6	
394978	7027319	136,9	79,8	
394979	7027319	288,8	29,6	
394979	7027319	276,7	17,1	
394979	7027319	293,3	22,7	
394979	7027323	173,6	85,3	
394979	7027322	259,5	25,7	
394980	7027321	147,3	76,9	
394981	7027323	327,6	78	o
394979	7027320	157,2	87	
394979	7027320	126,4	83,4	o
394982	7027321	118,1	78,7	
394984	7027322	117,5	83,7	
394983	7027321	279,8	23	
394989	7027322	238,2	33,4	
394988	7027319	148,1	73,2	
394987	7027319	48,6	83,4	o
394987	7027319	246,1	23,2	
394986	7027321	338,2	52,9	
394985	7027321	221,1	54,4	
394988	7027319	343,1	75,2	
394988	7027319	327,7	88,1	o
394988	7027319	342,7	89,1	
394989	7027320	195,9	81,7	
394988	7027320	176,1	88,4	
394987	7027323	96,1	63,6	o
394986	7027323	251,7	39,3	
394986	7027323	301,6	27,5	
394987	7027321	232,8	40,8	
394989	7027324	152,5	77,6	
394989	7027324	216,4	55,8	

394989	7027324	273,4	21,7	
394989	7027325	271	25,1	
394988	7027323	140,4	70,1	o
394991	7027323	257,7	37,5	
394991	7027325	261,3	30,5	
394991	7027325	260	32,6	
394991	7027327	152,9	74	
394992	7027329	206,6	49,9	
394993	7027329	148,7	76,1	
394992	7027329	141,5	77,7	
394992	7027331	162,8	74,5	
394992	7027331	155,4	68,9	
394995	7027331	138,9	77,6	
394995	7027331	141,5	68	
394995	7027331	127,1	66	
394993	7027332	294,3	14,5	
394992	7027332	82	78,1	
394993	7027332	164,8	87,3	
394994	7027336	154	77	
394994	7027335	157,7	77,9	
394995	7027336	160,4	70,6	
394994	7027335	249,7	13,1	
394993	7027336	152,3	71	
394993	7027336	79,9	84,7	o
394994	7027336	118,8	86,1	
394989	7027338	300,5	34	