P-07-111

Forsmark site investigation

The character and kinematics of deformation zones (ductile shear zones, fracture zones and fault zones) at Forsmark – report from phase 3

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Geological Survey of Norway, Trondheim, Norway

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 250, SE-101 24 Stockholm
Tel +46 8 459 84 00

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Keywords: Forsmark, AP PF 400-07-028, Structural geology, Deformation zone, Shear zone, Fracture zone, Fault zone, Mylonite, Cataclasite, Fault breccia, Kinematics.

Abstract

This report presents the results of a study of predominantly brittle structures, i.e. faults and fractures, observed within 14 deformation zones of four boreholes at Forsmark. The work expands on previously reported studies and aims to document the character of the brittle deformation history of the area, including the kinematics of brittle deformation zones.

Structural data were obtained from selected, previously defined possible deformation zones of drill cores from four boreholes (KFM02B, KFM08D, KFM11A and KFM12A). The character of each deformation zone is described in terms of fracture frequency and the distribution of transition zones and fault core. Polished thin sections from samples collected from the drill cores were studied using standard petrographic techniques. Observations from thin sections combined with data from drill cores form the basis for the conclusions of this study.

The investigated structures include different types of cataclasite and some breccias cemented by various minerals. In most drill cores, there are abundant fractures and fracture sets, commonly with minor offset. These are in most cases coated or filled with a range of different minerals reflecting the changing conditions during successive brittle events. The minerals coating the fault planes exhibit striations and slickensides that were observed on numerous fault planes. Such data were obtained, to a variable extent, from most of the possible deformation zones. The amount and quality of acquired kinematic structural data are quite variable. However, in many cases excellent data were obtained, and in general this manner of obtaining data adds substantially to the value of structural information that can be effectively retrieved from the drill cores.

The main set of brittle structures recorded in this study are steep faults oriented NW-SE to WNW-ESE. These faults occur in KFM11A (the Singö deformation zone) and in DZ1 and DZ2 of drill core KFM12A (the Forsmark deformation zone). Faults along this trend reveal variable sense of movement and probably record periodic reactivation along the regional fault and shear zone. Some faults dip to the east, SE and south and have variable shear sense. In addition, gently south-dipping, reverse, minor faults oriented NE-SW to ENE-WSW are present in several dill cores.

Among the oldest observed brittle structures are the epidote- and quartz-sealed fractures and fracture networks with some chlorite. Striated fault surfaces are commonly coated with chlorite and hematite, and steps defined by calcite and laumontite allow determination of the sense of movement on many faults. Chlorite- and hematite-coated faults are commonly reactivated and/or cut by faults and fractures with laumontite, calcite, and less commonly adularia and prehnite. In some cases, these minerals have sealed breccias and cataclasites. Late fracture minerals include quartz, calcite, pyrite and clay minerals. These observations corroborate the findings from the earlier phases of this study and provide further evidence that the main faults and fracture systems have been reactivated and coated/filled with a variety of minerals in response to changes in hydrothermal regime and stress conditions.

Sammanfattning

Denne rapporten presenterer resultatene fra en undersøkelse av i hovedsak sprø strukturer, dvs. forkastninger og sprekker, gjennomført på 14 deformasjonssoner i 4 borehull i Forsmark. Arbeidet er en forsettelse av tidligere undersøkelser der det viktigste målet er å dokumentere geometri og kinematikk relatert til sprø deformasjon.

Strukturdata ble samlet inn fra utvalgte, tidligere definerte deformasjonssoner i kjerner fra 4 borehull (KFM02B, KFM08D, KFM11A og KFM12A). Hver deformasjonssone er beskrevet med hensyn til sprekkefrekvens, fordeling av overgangssoner (transition zones) og forkastnings-kjerner (fault core), og kinematikk. Polerte tynnslip fra borekjernene ble studert ved hjelp av standard petrografiske teknikker. Observasjoner fra tynnslip sammen med data fra borekjerner danner basis for konklusjonene i dette arbeidet.

De undersøkte strukturene omfatter flere typer kataklasitt, og breksjer som er sementert av ulike mineraler. I de fleste borekjerner fins det flere sprekkesett, i mange tilfeller med kinematiske indikatorer. Sprekkene er i de fleste tilfeller dekket eller fylt med ulike mineraler som reflekterer forholdene under flere deformasjonshendelser. Mengde og kvalitet på kinematiske data varierer. I mange tilfeller ble det samlet inn en betydelig mengde nye data som vil øke nytten av den strukturelle informasjonen som blir samlet inn fra borekjerner.

De viktigste sprø strukturene observert i denne undersøkelsen er steile forkastninger orientert NV-SØ til VNV-ØSØ. Disse forkastningene finnes i KFM11A (Singö deformation zone) og i DZ1 og DZ2 i KFM12A (Forsmark deformation zone). Forkastninger med denne orienteringen viser varierende relativ bevegelse, noe som reflekterer periodisk reaktivering i langs regionale forkastningssoner. En del forkastninger har fall mot øst, sørøst og sør med variererende bevegelse. I tillegg fins det i flere borekjerner en del mindre reversforkastninger orientert NØ-SV til ØNØ-VSV.

Epidot- og kvartsfylte sprekker og sprekkenettverk er blant de eldste observerte sprø strukturene. Slickensides på forkastningsplan er definert av kloritt og hematitt. Kalkspat og laumontitt danner i mange tilfeller steg på forkastningsplanet og gir dermed mulighet for å avklare relativ bevegelse langs forkastningen. Forkastninger med kloritt og hematitt er vanligvis reaktivert og/eller kuttet av forkastninger og sprekker forseglet med laumontitt, kalsitt og i noen tilfeller forseglet med adular og prehnitt. På yngre sprekker fins det mineraler som kvarts, kalsitt, pyritt og leirmineraler. Disse observasjonene støtter konklusjonene fra tidligere undersøkelser som viser at viktige forkastninger og sprekkesystemer har bitt reaktivert og fylt med ulike mineraler som respons på vekslende ytre forhold.

Contents

1 Introduction

This document reports the results of a study of the character and kinematics of a number of deformation zones at the Forsmark site. This study forms one of the activities performed within the site investigation work at Forsmark (Figure 1-1). The work was carried out in accordance with activity plan AP PF 400-07-028. Controlling documents for performing this activity are listed in Table 1-1. Both activity plan and method descriptions are SKB's internal controlling documents.

Original data from the reported activity are stored in the primary database Sicada, where they are traceable by the Activity Plan number (AP PF 400-07-028). Only data in SKB's databases are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in the databases may be revised, if needed. Such revisions will not necessarily result in a revision of the P-report, although the normal procedure is that major data revisions entail a revision of the P-report. Minor data revisions are normally presented as supplements, available at www.skb.se.

Figure 1-1. *General overview of the Forsmark site investigation area and the location of the studied boreholes.*

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

Activity plan	Number	Version
Karaktärisering av spröda deformationszoner, steg 3	AP PF 400-07-028	1.0
Method description	**Number**	**Version**
Metodbeskrivning för geologisk enhålstolkning.	SKB MD 810.003	3.0
Method descriptions	**Number**	**Version**
/Braathen 1999/	Tectonophysics 302, 99–121.	
/Braathen et al. 2002/	Norwegian Journal of Geology, 82, 225–241.	
/Braathen et al. 2004/	Tectonics, 23, TC4010, doi:10.1029/2003TC001558.	
/Nordgulen et al. 2002/	Norwegian Journal of Geology, 82, 299–316.	
/Osmundsen et al. 2003/	Journal of the Geological Society, London 160, 1–14.	
/Petit 1987/	Journal of Structural Geology 9, 597–608.	

2 Objective and scope

The aim of this study is to describe and document the characteristic properties, including the kinematics, of deformation zones in boreholes. Fault rocks were investigated in order to improve our understanding of the deformation mechanisms that controlled the local brittle structural history. Observations from thin sections combined with data from drill cores form the basis for the conclusions of the study.

This study is the third phase of the work carried out in accordance with activity plan AP PF 400-07-028. The first and second phases of the study were reported in the SKB P-reports 06-212 and 07-101 /Nordgulen and Saintot 2006, Saintot and Nordgulen 2007/. These expanded on the preliminary work carried out in the pilot project in 2005 /Nordgulen and Braathen 2005/.

A total of 14 deformation zones from four drill holes (KFM02B, KFM08D, KFM11A and KFM12A) were studied with the aim of providing a description of the nature of each deformation zone, and to examine faults and fractures searching for features that potentially would have significance for the understanding of the kinematic history of the faults. The deformation zones were selected by SKB based on the geological single-hole interpretation of individual boreholes. All zones that were assigned the highest confidence level (3) are included in the study. The drill holes and deformation zones that were inspected are listed in Table 5-1.

3 Equipment

3.1 Description of equipment

During inspection, the standard equipment for structural investigations was used, including compass, hand lens, diluted HCl, and digital camera. Samples collected from drill cores were cut in the core laboratory, and selected chips were correctly marked (felt pen) and sent for preparation of polished thin sections. The thin sections were petrographically analysed and some selected sections were analysed using SEM in backscatter mode.

4 Execution

4.1 Nomenclature

Faults occur on all scales in the lithosphere. They contribute to the spatial arrangement of rock units, may affect the topography, control the permeability of rocks and sediments and, more importantly, create deformation (strain plus rotation plus translation) during plate interaction and intraplate movements. The term fault zone is generally used for brittle structures in which loss of continuity and slip occurs on several discrete faults within a band of definable width. Shear zones, on the other hand, are ductile structures, across which a rock body does not lose cohesion so that strain is progressively distributed across a band of definable width. Based on this definition, a fault zone is a volume of rock where strain is highly localized.

Commonly fault zones can be divided into a series of distinctive constituent elements. These are 1) the *undeformed host rock*, 2) the *transition zone* /Munier et al. 2003/ (corresponding to the “damage zone” of /Gudmundsson et al. 2001/) and 3) the proper *fault core* /e.g. Caine et al. 1996, Evans et al. 1997, Braathen and Gabrielsen 2000/. The host rock consists of undisturbed rock with a low fracture frequency of < 4 fractures/m /Munier et al. 2003/ (Figure 4-1). The transition zone still contains undeformed rock, but the fracture frequency generally increases up to 9 fractures/m (Figure 4-1). Narrow zones or bands of fault rock may occur, especially closer to the transition to the fault core. The width of the transition zone varies with the size of the fault zone and the style of deformation, and can range from a few metres to tens of metres. The fault core is identified by the occurrence of fault rock or intensively fractured rock (Figure 4-1, Figure 4-2). Fault rocks may occur in lenses alternating with pods of relatively undeformed rock /Caine et al. 1996, Braathen and Gabrielsen 2000/. The width of the fault core may vary from a few centimetres to a few metres /Braathen and Gabrielsen 2000/. The deformation zones reported in this study exhibit minor occurrences of fault rocks, mainly in the form of narrow zones with cataclasite and cemented breccias. Fault core is therefore expressed as highly fractured rocks that may form zones of sealed fracture networks.

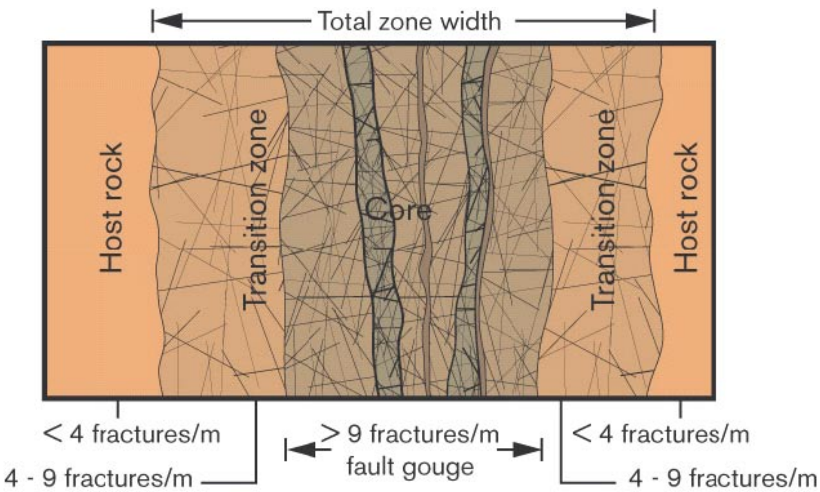


Figure 4-1. *Schematic illustration of a brittle deformation zone according to SKB definition /after Munier et al. 2003/*

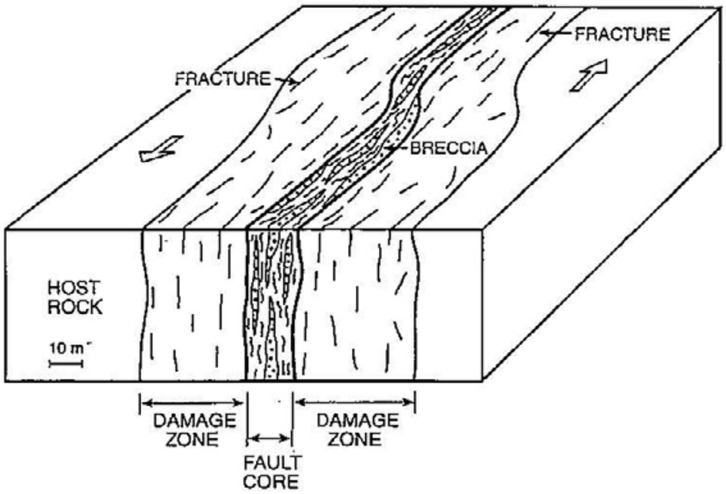


Figure 4-2. Schematic illustration of the architecture of an idealized fault zone /Gudmundsson et al. 2001/. Note that the term "damage zone" corresponds conceptually to the term "transition zone" of Figure 4-1.

Rocks that occur within fault zones provide primary evidence for the processes that occur there. It is therefore of great importance to characterize fault rock occurrences so as to better understand faulting processes at all scales. Fault rocks form in response to strain localization within faults and shear zones and reflect the interplay of a variety of physical and environmental parameters such as the finite amount of strain, lithology, style of deformation (i.e. frictional or plastic flow), presence or absence of fluids, strain rate, temperature, pressure, etc. Figure 4-3 shows the classification scheme suggested by /Braathen et al. 2004/ that we will use in this study to classify fault rock occurrences.

Brittle			← Deformation style →					**Ductile**		% matrix and grain-size
Frictional flow			← Dominant deformation mechanism →					**Plastic flow**		
Non-cohesive			Secondary cohesion		Primary cohesion					
			Cemented HB	Indurated HB			> 50% phyllosilicate	< 50% phyllosilicate		
Hydraulic breccia (HB)	Breccia series	Proto-breccia	Cemented proto-breccia	Indurated proto-breccia	Cataclasite series	Proto-cataclasite	Proto-phyllonite	Proto-mylonite	Blastomylonite	0-50% matrix
		Breccia	Cemented breccia	Indurated breccia		Cataclasite	Phyllonite	Mylonite		50-90% matrix
		Ultra-breccia	Cemented ultra-breccia	Indurated ultra-breccia		Ultra-cataclasite	Ultra-phyllonite	Ultra-mylonite		90-100% matrix
	Gouge		Cemented gouge	Indurated gouge						Sub-microscopic matrix
			Pseudotachylyte							

Figure 4-3. Fault rock classification scheme proposed by /Braathen et al. 2004/. A brief explanation of some of the terms is given in Table 4-1.

Table 4-1. Schematic description of different types of fault rocks classified according to /Braathen et al. 2004/.

Term	Description	Note
Fault rocks or fault-related rocks	Commonly formed through strain concentration within a tabular or planar zone that experiences shear stress.	1
Frictional flow	Pressure, subordinate temperature and fluid controlled deformation mechanisms which have a brittle style: granulation of grains by inter, intra and transgranular micro fracturing, and intra or intergranular frictional sliding with abrasion of fracture walls and grain margins	2
Plastic flow	Mainly thermally activated, continuous deformation without rupture, with a ductile style of deformation: dislocation creep and glide, solid state diffusion creep, diffusional mass transfer, and viscous grain boundary sliding	
Non-cohesive	Not consolidated	3
Secondary cohesion	Consolidated after formation, either through cementation of the matrix, or through compaction, recrystallisation or neo-mineralisation (see indurated)	
Primary cohesion	Cohesion preserved during formation	3
Hydraulic fracturing	Fracturing caused by fluid pressure: commonly random orientation of fractures and rough fracture surfaces. The resulting hydraulic breccia may not be tabular or planar, however, it is tectonically induced and frequently fault-related.	4
Cemented	Consolidated through mineral precipitation in pores of the matrix	
Indurated	Consolidated basically by compaction due to directed pressure, annealing by recrystallisation of grains, or neomineralisation (e.g., muscovitisation, silicification, albitisation, epidotisation, saussuritisation). The term disregards cementation unless related to general neomineralisation	
Phyllosilicate content	Content of sheet-minerals (characterised by weak '001' bonds) of the phyllosilicate group	5
Matrix	Fine-grained material in a fault rock formed by granulation or dynamic recrystallisation of grains, filling the interstices between larger clasts of original rock	
Breccia	Mainly chaotic, non-cohesive fault rock, generated by frictional flow	3
Cataclasite	Mainly chaotic fault rock that developed with cohesion, which is generated by mainly frictional flow	6
Phyllonite	Phyllosilicate-rich fault rock with distinct mineral fabric, and dominated plastic flow	7
Mylonite	Fault rock with distinct mineral fabric, and dominated by plastic flow	8
Blasto-mylonite	Fault rock in which dynamic recrystallisation and/or neomineralisation causing grain-size increase of clasts, outpace grain-size reduction	8

1. For classification of fault rocks, see: *Higgins* [1971], *Bell & Etheridge* [1973], *Zeck* [1974], *Sibson* [1977a], *Wise et al.,* [1984], *Schmid & Handy* [1991].
2. Term introduced by *Schmid & Handy* [1991]. See also description of *Bell & Etheridge* [1973].
3. Concept introduced by *Higgins* [1971].
4. For hydraulic breccias, see e.g., *Clark & James* [2003]
5. Clay content as factor in classification of faults rocks in sedimentary units, e.g., *Fisher & Knipe* [1998].
6. Possible application of phyllosilicate content in the sub-division of fault rocks in sedimentary rocks, e.g., *Fisher & Knipe* [1998].
7. Definitions following *Knopf* [1931], however, adding a limit to the phyllosilicate content.
8. See definitions of *Sibson* [1977a].

This study deals not only with faults, but also with brittle structures in general. It is therefore appropriate that the terminology that is used is clarified.

Fractures are all planar brittle structures.

Joints are extensional fractures (with the minimum stress axis perpendicular to the surface) along which no displacement can be observed with unaided eyes. The term is unfortunately not well constrained and the above definition is according to /Twiss and Moores 1992/: 'Most outcrops of rocks exhibit many fractures that show very small displacement normal to their surfaces and no, or very little, displacement parallel to their surfaces. We called such fractures joints.' The authors also noted at this point: 'Unfortunately, there is no universally accepted definition of the term joint. The definition set down here is conservative in that fractures satisfying this definition would be called joints by every other definition of the term'.

Note that the term '*shear joints*' is also used when two sets of joints are at 60 degrees from each other. It implies that the maximum stress axis is the bisector of the acute angle, the minimum stress axis the bisector of the obtuse angle, and the intermediate stress axis is parallel to the intersection of the joints. Here also, it is stipulated that no displacement can be observed with unaided eyes.

The term '*vein*' is descriptive and used for a fracture filled with a mineral (e.g. calcite) or rock (e.g. granite) forming a tabular or sheet-like body within a given host rock.

The term *tension gash* is genetic and interpretative. Tension gashes are inferred to be extensional fractures with a clear displacement normal to their sides (i.e. the minimum stress axis is roughly perpendicular to their sides, or there is little or no evidence of shearing acting along their sides). They are generally mineral-filled and commonly have mineral fibres that grew parallel to the tension axis. In this study, this term has therefore been used only if mineral fibres have been observed in the fracture, allowing for an estimate of the orientation of the minimum stress axis.

Mineral-filled fracture is a very general term that is used to describe fractures with at least some displacement normal to their sides (allowing mineral growth to take place). Provided that a shear component is documented, this would be a fault coated with minerals. This term is descriptive and non-genetic. It is used to describe a fracture with mineral coating on which the orientation of mineral fibres cannot be observed with the unaided eye, i.e. the orientation of the minimum stress axis remains uncertain. With the aided eye, it may be possible to distinguish between a tension gash (with the minimum stress axis roughly perpendicular and fibres parallel to the minimum stress axis) and a fault (shear fracture, with fibres oblique to the fractures).

4.2 Working procedure

Investigation of drill cores was conducted during two periods: December 11–14, 2006 and February 19–21, 2007. The standard procedure for obtaining the true orientation of linear structures (slickensides, striations, etc) on fault surfaces in drill cores with known orientation is as follows:

1. Fractures of potential interest were identified by visual inspection of drill cores from selected deformation zones, as defined previously by SKB.
2. Individual fractures were identified on the BIPS image of the borehole wall, which provided a mirror image of the core itself. Care had to be taken to ensure that the fracture selected on the image matched the one from the drill core. In some cases, this was challenging, particularly where abundant fractures cut the core at different angles. Independent checks that the correct fracture was selected could be carried out using data in the drill core database. These included the properties of the fracture itself, the acute angle α between the fracture and the drill core axis, and the angle β, which is the angle (measured counter-clockwise) from the lower intersection of the fracture with the drill core wall, to the top of the drill core.

3. Having identified the fracture of interest, the top of the drill core was marked based on visual inspection of the BIPS image and on the angle β. For each fracture, its orientation (strike and dip) was obtained using the information contained in the drill core database.
4. The drill core was positioned the right way up and at the true inclination using a core holder supplied by SKB. This device allowed the accurate adjustment of the drill core inclination as given in the database.
5. The orientation of the linear structure was determined by measuring its plunge direction (azimuth) and plunge.
6. When the sense of slip could be determined with confidence, the true movement of the hanging wall with respect to the footwall of the fault was established.
7. Relevant data were recorded in a database.

Five samples for thin section preparation were collected. The sections were studied at the Geological Survey of Norway (Trondheim) using standard petrographic techniques. These sections add to the 44 polished sections collected during phase 1 and 2 and during the pilot study.

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

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

4.3 Analysis and interpretation

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

A systematic analysis of fault slip data at the micro-scale to meso-scale has been made, which aims to establish an improved understanding of the kinematic pattern in the area of interest. It consists of the analysis of strike and dip of fault planes and of azimuth and plunge of their striae. It also provides the basis for paleo-stress inversion calculations that can aim at the reconstruction of the stress field evolution through time. Figure 4-4 provides the key to read stereoplots used throughout this report that represent the orientation and the kinematics of individual fault plane/striation pairs.

4.4 Data handling and processing

The data obtained in the study were transferred to SKB in a specified format that allows for transfer of the data to the internal database structure at SKB.

4.5 Nonconformities

No nonconformities have been noted.

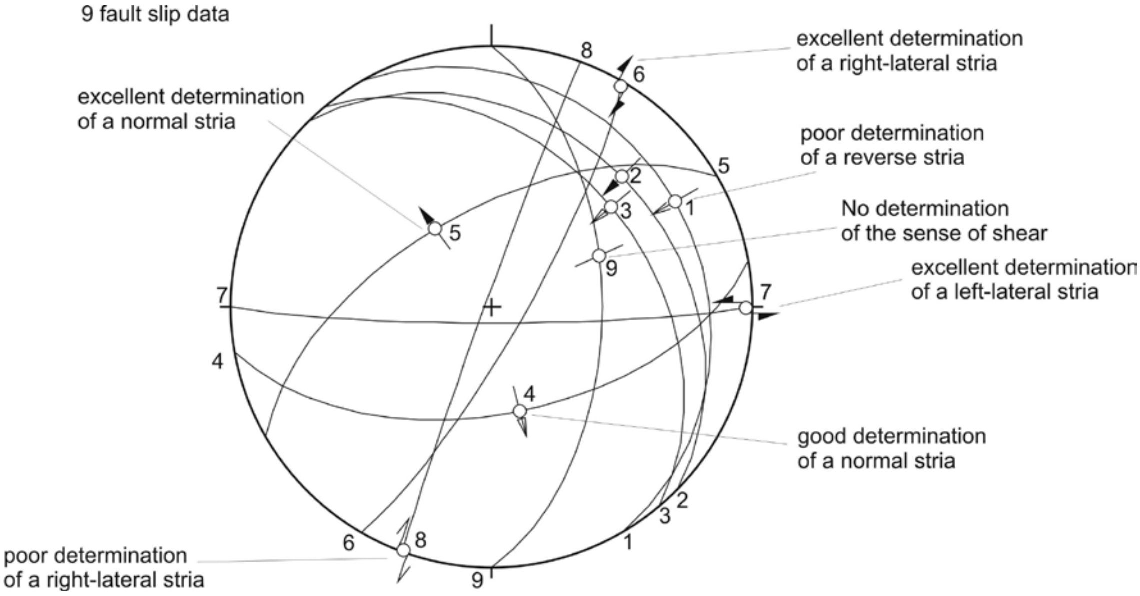


Figure 4-4. *Example of a stereoplot used for plotting kinematic information obtained from striated fault planes, Schmidt's projection, lower hemisphere. Keys for striae: outward directed arrow: normal striae (numbers 4 and 5 on stereoplot); inward directed arrow: reverse striae (numbers 1, 2 and 3); couple of arrows: strike-slip striae (numbers 6, 7 and 8); full black arrow: excellent constraints on the sense of shear (numbers 2, 5, 6 and 7); empty arrow: good constraints on the sense of shear (numbers 3 and 4); simple arrow: poor constraints on the sense of shear (numbers 1 and 8); thin line without any arrowhead: no constraints on the sense of shear (number 9).*

5 Results

5.1 Drill core investigations

5.1.1 Investigated drill cores

14 selected sections from four drill holes were inspected with the aim of investigating the style of deformation in the previously defined deformation zones (DZ) classified with confidence level 3 in the respective single-hole interpretations (Table 5-1). The interval between 498 and 630 m along DZ1 in KFM11A was identified during the single-hole interpretation as containing high frequency of open fractures and strong alteration. This interval was selected as the most suitable for kinematic studies. The geographic location of the drill holes is shown in Figure 5-1. During this investigation, samples for petrographic analysis were collected from characteristic fault rocks (see sample list in Appendix 1). The detailed studies of fracture mineralogy by /Sandström et al. 2004, Sandström and Tullborg 2005/ were also used.

5.1.2 KFM02B

The drill site is located in the central southeast part of the candidate area (Figure 5-1). The drill hole has a length of 574 m and is oriented 313/80 /Carlsten et al. 2007a/. The main rock type is a medium-grained metagranite-granodiorite with some occurrences of amphibolite and pegmatite. Six deformation zones with a combined length of 138 m were investigated (DZ1, DZ2, DZ3, DZ4, DZ5, DZ6).

10 striated faults have been measured along the studied intervals of the drill core (Figure 5-2). Most of the faults are oriented NE-SW and exhibit normal, reverse and oblique-slip movement (see below).

In the studied area, notable seismic reflectors that are reported to be dipping gently southeast were interpreted as thrusts by /Juhlin and Stephens 2006/. Some striated gently SE-dipping faults were observed. However, the sense of movement could not be determined.

Table 5-1. Overview of drill cores inspected in the project. These include borehole sections from the geological single-hole interpretation assigned with the highest level of confidence (3).

Drill core	Length, direction	Deformation zone section	Deformation zone identification
KFM02B	573.9 m, 313/80	98–115 m	DZ1 /Carlsten et al. 2007a/
		145–204 m	DZ2 /Carlsten et al. 2007a/
		411–431 m	DZ3 /Carlsten et al. 2007a/
		447–451 m	DZ4 /Carlsten et al. 2007a/
		462–473 m	DZ5 /Carlsten et al. 2007a/
		485–512 m	DZ6 /Carlsten et al. 2007a/
KFM08D	942.3 m, 100/55	371–396 m	DZ3 /Carlsten et al. 2007b/
		546–571 m	DZ5 /Carlsten et al. 2007b/
		621–634 m	DZ7 /Carlsten et al. 2007b/
		903–934.15 m	DZ12 /Carlsten et al. 2007b/
KFM11A	851.2 m, 040/61	498–630 m	Part of DZ1 /Carlsten et al. 2007c/
KFM12A	601.4 m, 036/61	125–158 m	DZ1 /Carlsten et al. 2007d/
		170–402 m	DZ2 /Carlsten et al. 2007d/
		513–523 m	DZ4 /Carlsten et al. 2007d/

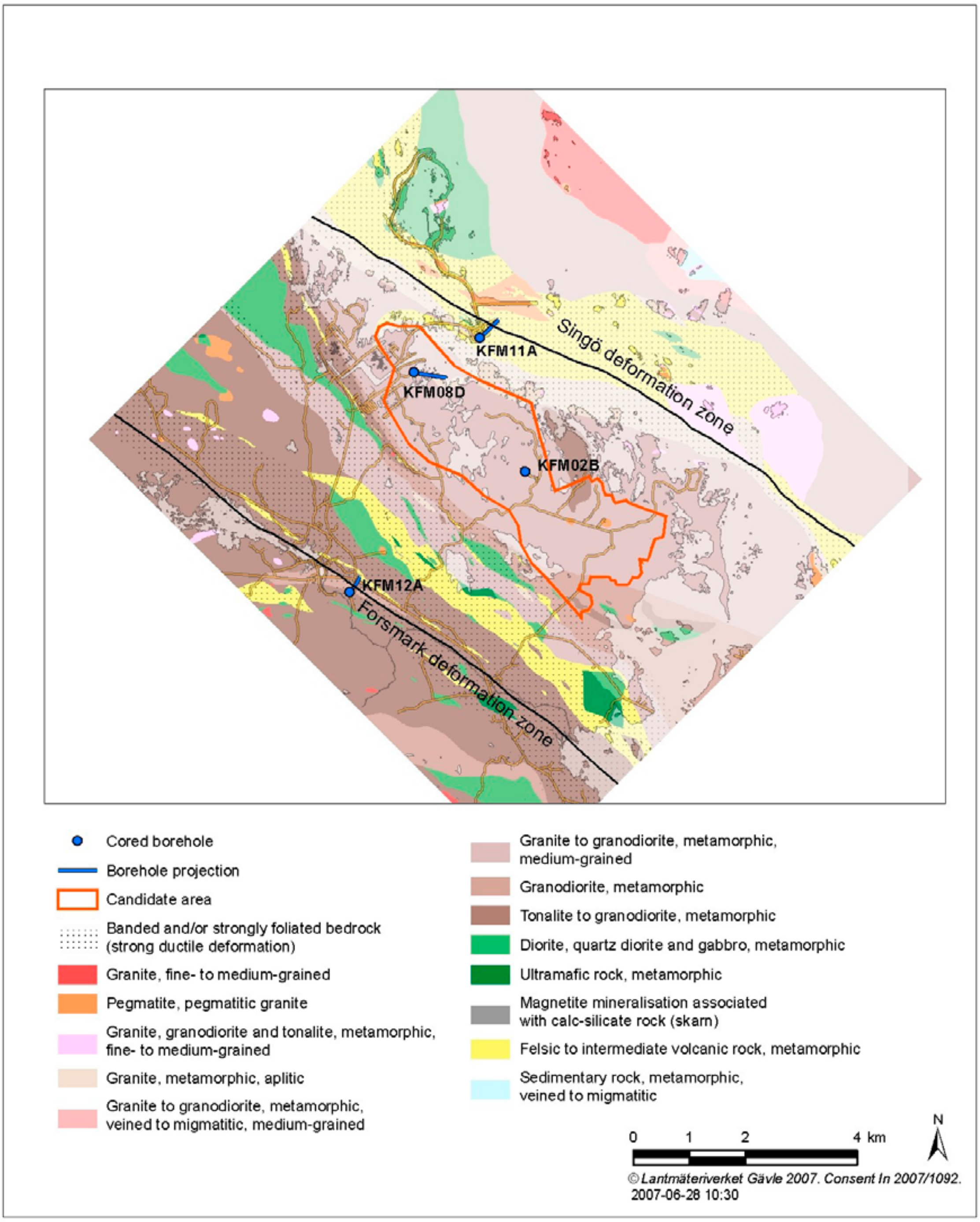


***Figure 5-1.** Bedrock geology map of the Forsmark area also showing candidate investigation area (red line) and the geographic location of the drill holes.*

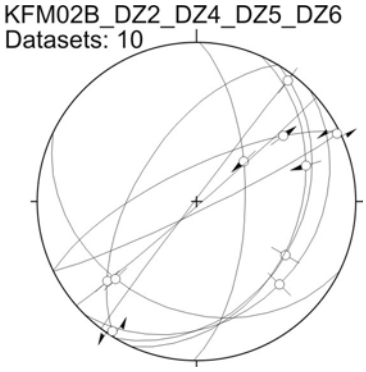


Figure 5-2. *Stereoplot showing all the fault slip data collected along all the studied DZ in drill core KFM02B.*

KFM02B: 98–115 m – DZ1

DZ1 transects medium-grained metagranite-granodiorite with subordinate amounts of amphibolite and pegmatitic granite. The zone exhibits a fairly moderate increase in the frequency of variably oriented open and sealed fractures (Figure 5-3). The fractures have variable orientations and are commonly gently dipping. Two minor crush zones occur in the lower part of the zone between 111 and 112.5 m. The most frequent fracture-filling minerals include chlorite, calcite and some hematite and adularia. DZ1 is a transition zone according to the definition of /Munier et al. 2003/. Striated faults were not observed.

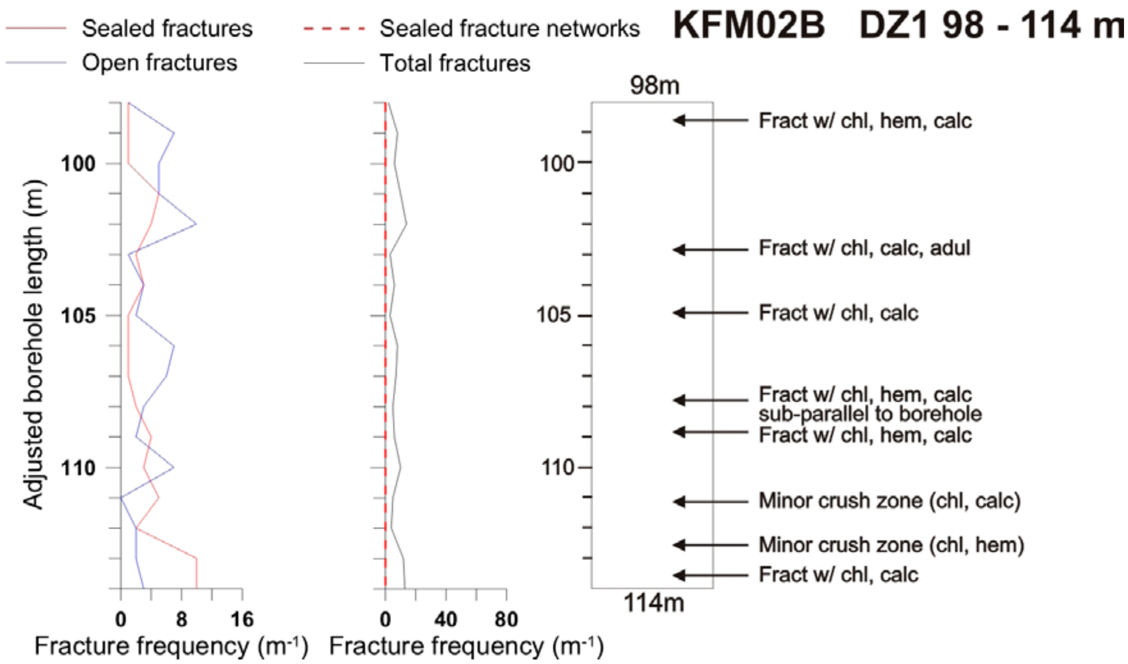


Figure 5-3. *Simplified drawing of DZ1 showing the most prominent brittle structures. Abbreviations used throughout the report: Calc=calcite, Chl=chlorite, Corr=corrensite, Ep=epidote, Fract=fracture(s), Freq=frequency, Hem=hematite, Lau=laumontite, Ox=oxides, min or mnl=mineral, Py=pyrite, Qtz=quartz, Ser=sericite, w/=with, Fol // = foliation-parallel, Core // = core-parallel.*

KFM02B: 145–204 m – DZ2

DZ2 transects medium-grained metagranite-granodiorite with subordinate pegmatite and amphibolite. The predominant brittle structures are fractures that strike NE with variable dips to the SE. The fracture filling minerals include chlorite, calcite, adularia, hematite and clay minerals. Vuggy granite with chloritization and partial dissolution of quartz occurs at ca 167–169 m (Figure 5-4). The highest fracture frequencies occur in the lower interval of the zone (Figure 5-4). The fracture networks with high fracture frequencies represent short intervals of coarse-grained pegmatite with short, variably oriented, sealed fractures. The DZ is generally considered a transition zone according to the definition of /Munier et al. 2003/.

Two striated faults with chlorite, calcite and clay mineral coating are present in DZ2 along KFM02B (Figure 5-5). The faults dip gently to the SE and display dip-slip striae defined by calcite. However, the sense of shear could not be determined.

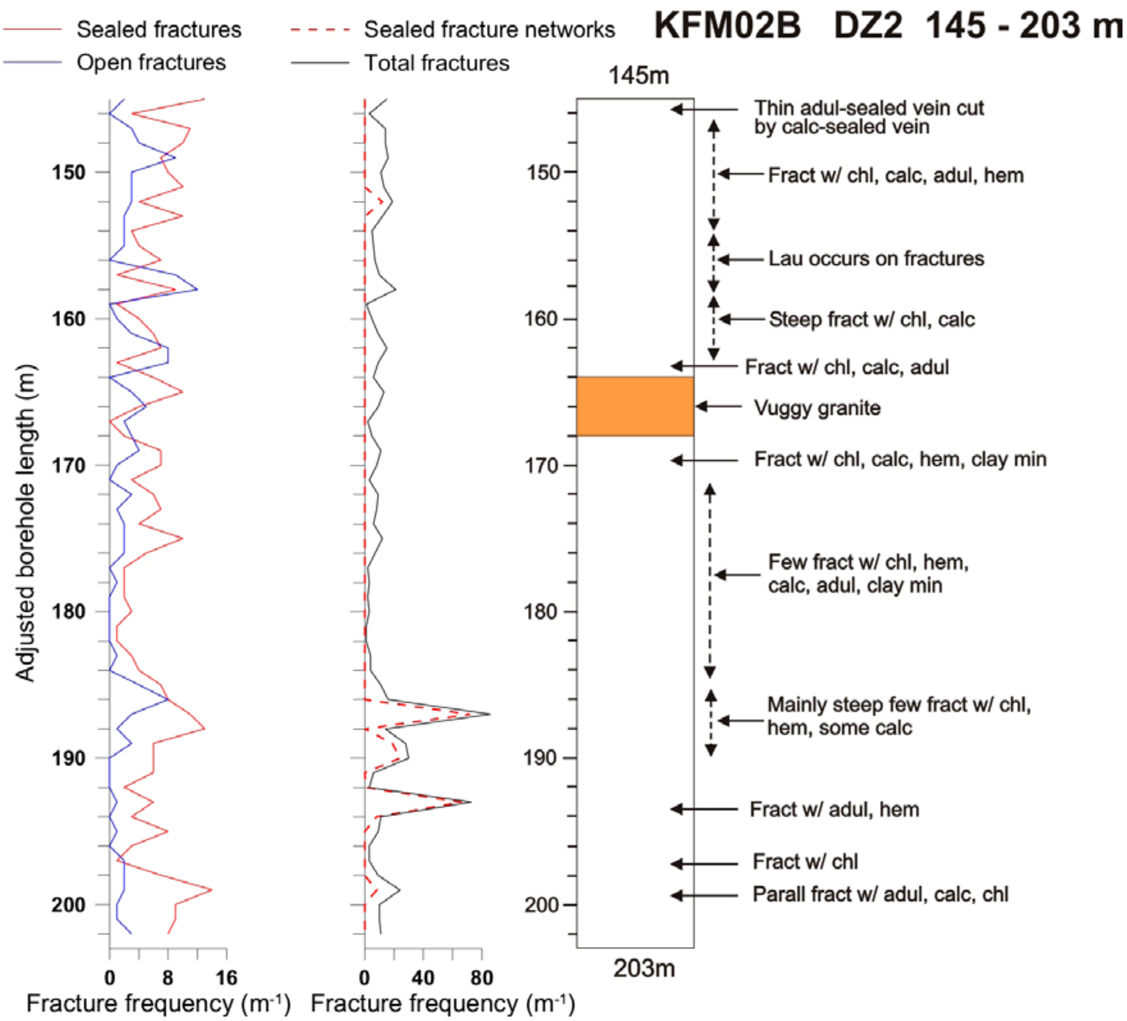


Figure 5-4. *Simplified drawing of DZ2 showing the most prominent brittle structures. The fracture networks with high fracture frequencies are present in short intervals of coarse-grained pegmatite with short, variably oriented sealed fractures. Abbreviations as in Figure 5-3.*

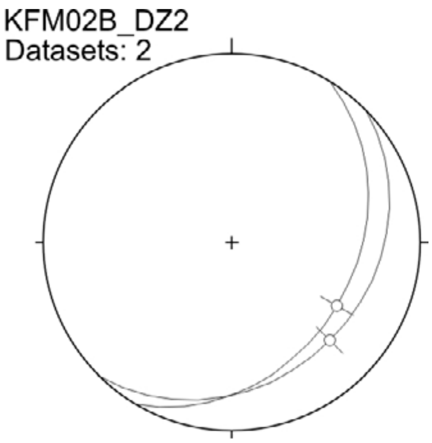


Figure 5-5. Stereonet of the two striated faults measured along DZ2 in KFM02B.

KFM02B: 411–431 m – DZ3

DZ3 along KFM02B exhibits an increased frequency of predominantly gently dipping open and sealed fractures. The fractures are quite uniformly distributed through the zone. Common fracture filling minerals include calcite and chlorite; minor hematite also occurs. However, a number of fractures do not have a visible mineral coating or filling (Figure 5-6, Figure 5-7). The host rock is pegmatitic granite and medium-grained metagranite-granodiorite. DZ3 is a transition zone according to the definition of /Munier et al. 2003/. Striated faults were not observed.

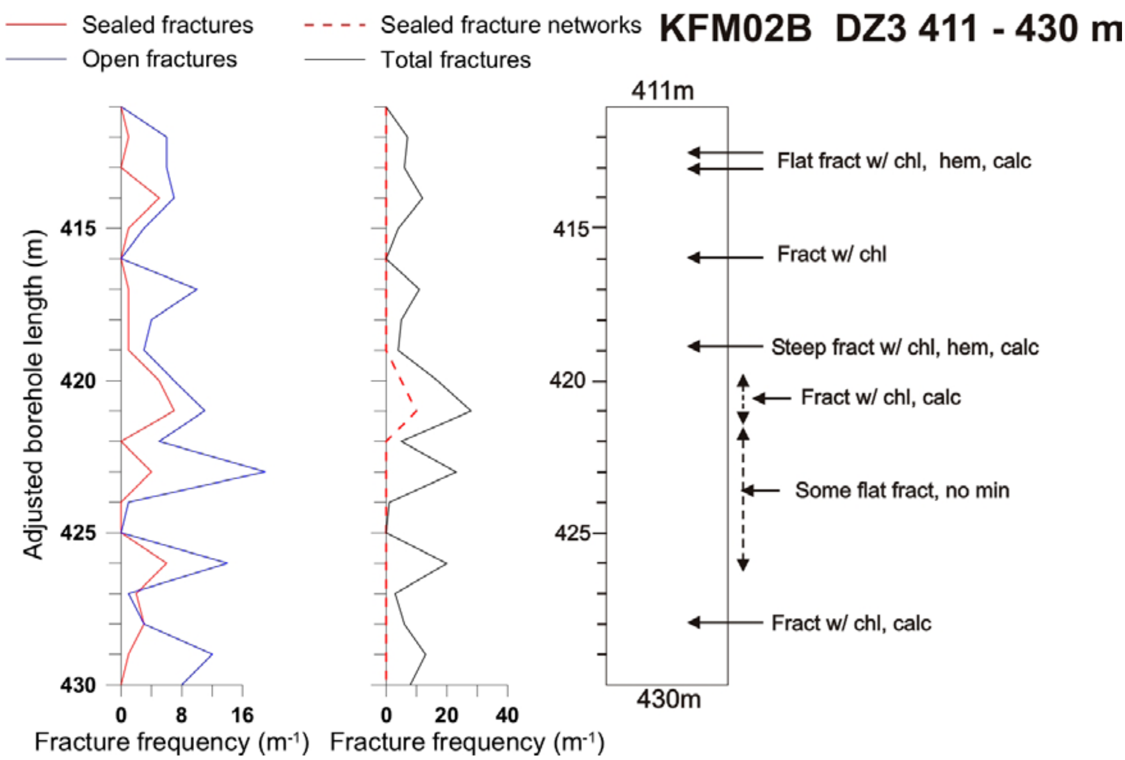


Figure 5-6. Simplified drawing of DZ3 showing the most prominent brittle structures. Abbreviations as in Figure 5-3.

Figure 5-7. Example of drill core from the lower part of DZ3 of KFM02B (425.5–431 m). Note the presence of gently-dipping un-mineralized fractures and some steep fractures with chlorite and minor calcite.

KFM02B: 447–451 m – DZ4

This is a short deformation zone in foliated, medium-grained metagranite-granodiorite. The zone shows an increased frequency of variably oriented open and sealed fractures and a 15 cm wide crush zone at the top of an amphibolite (449.50 m). Predominant fracture minerals are calcite and chlorite; clay minerals and prehnite also occurs. Several fractures do not have a visible mineral coating or filling. DZ4 is a transition zone according to the definition of /Munier et al. 2003/.

Two striated faults with epidote, chlorite, calcite and some prehnite are present in DZ4 (Figure 5-8). A WNW-dipping fault with epidote striation and steps with prehnite(?) shows sinistral sense of shear. A chlorite-striated fault dipping to the east shows reverse movement based on the presence of prehnite steps.

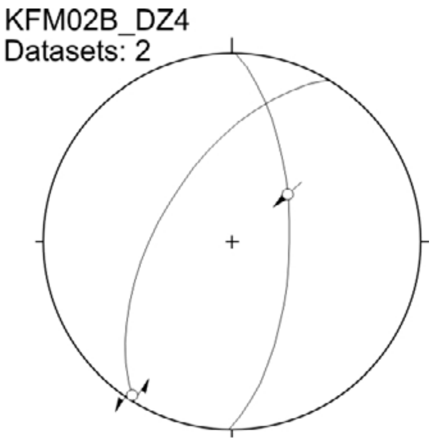


Figure 5-8. Stereonet of striated faults along DZ4 in KFM02B.

KFM02B: 462–472 m – DZ5

DZ5 along KFM02B transects foliated, medium-grained metagranite-granodiorite with some occurrences of amphibolite and pegmatite. Gently-dipping fractures dominate. However, steeply-dipping NNE-striking sealed fractures that dip to the ESE are also present. A crush zone is present at ca 471.5 m (Figure 5-9). Fracture minerals include calcite, chlorite and some clay minerals, prehnite and epidote. DZ5 is a transition zone according to the definition of /Munier et al. 2003/.

Four striated faults are present in DZ5 (Figure 5-10). An ESE-dipping fault with chlorite striae has reverse sense of movement based on calcite steps. A SSW-dipping fault with chlorite striation shows dip-slip movement. A steep NNW-dipping fault with chlorite striation and steps with clay minerals has oblique kinematics with dextral normal sense of movement. The steep NE-striking fault has a SE-plunging lineation of uncertain character, possibly an intersection lineation.

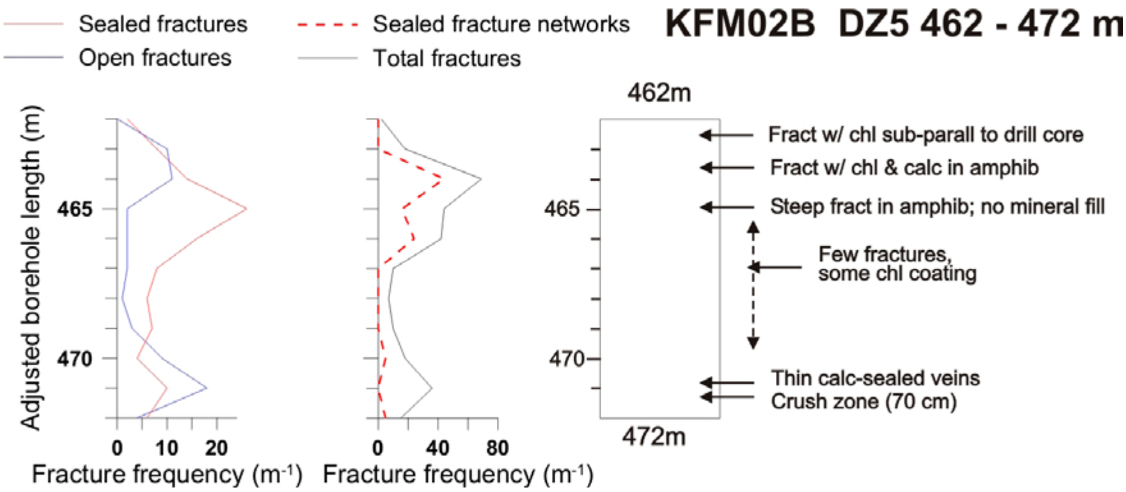


Figure 5-9. *Simplified drawing of DZ5 showing the most prominent brittle structures. Abbreviations as in Figure 5-3.*

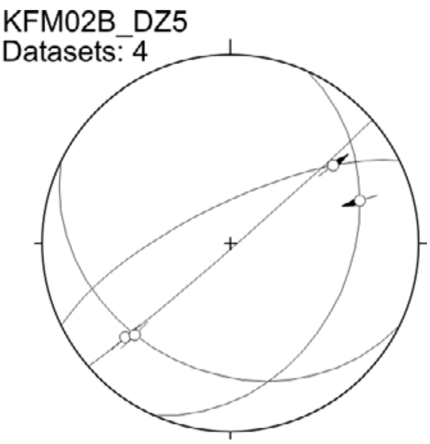


Figure 5-10. *Stereonet of striated faults measured along DZ5 in KFM02B.*

KFM02B: 485–512 m – DZ6

DZ5 along KFM02B transects foliated, medium-grained metagranite-granodiorite with some occurrences of amphibolite and subordinate pegmatite. Oxidation has occurred locally. The zone is characterized by an increased frequency of predominantly gently-dipping sealed, and in the central part, open fractures (Figure 5-11). Fracture minerals include epidote, chlorite, calcite, prehnite and clay minerals.

In the upper part of the deformation zone, steep fractures with epidote and some chlorite and gently dipping epidote-sealed thin fractures are present in amphibolite (Figure 5-12). Crushing of the drill core, possibly drilling-induced, has occurred at ca 499.7–501.3 m (Figure 5-11). Minerals coating the fractures in the crush zone are epidote, calcite and some prehnite. At 502.3 m, there is a gently-dipping, 2–3 mm wide proto-breccia with adularia and laumontite(?). At 503 m, gently dipping epidote-sealed fractures are cut by fractures sealed with chlorite + calcite, and by steep fractures cut adularia + calcite. Gently-dipping, thin, epidote-sealed fractures are common in the lower part of the deformation zone (Figure 5-11). Following the definition of /Munier et al. 2003/, this zone shows the character of a transition zone.

Two striated faults were observed within DZ6 of KFM02B (Figure 5-13). Epidote striations indicating strike-slip movement occur on a steep NNE-SSW fault. An ENE-striking fault with chlorite striations show sinistral sense of shear defined by calcite steps on the fault surface.

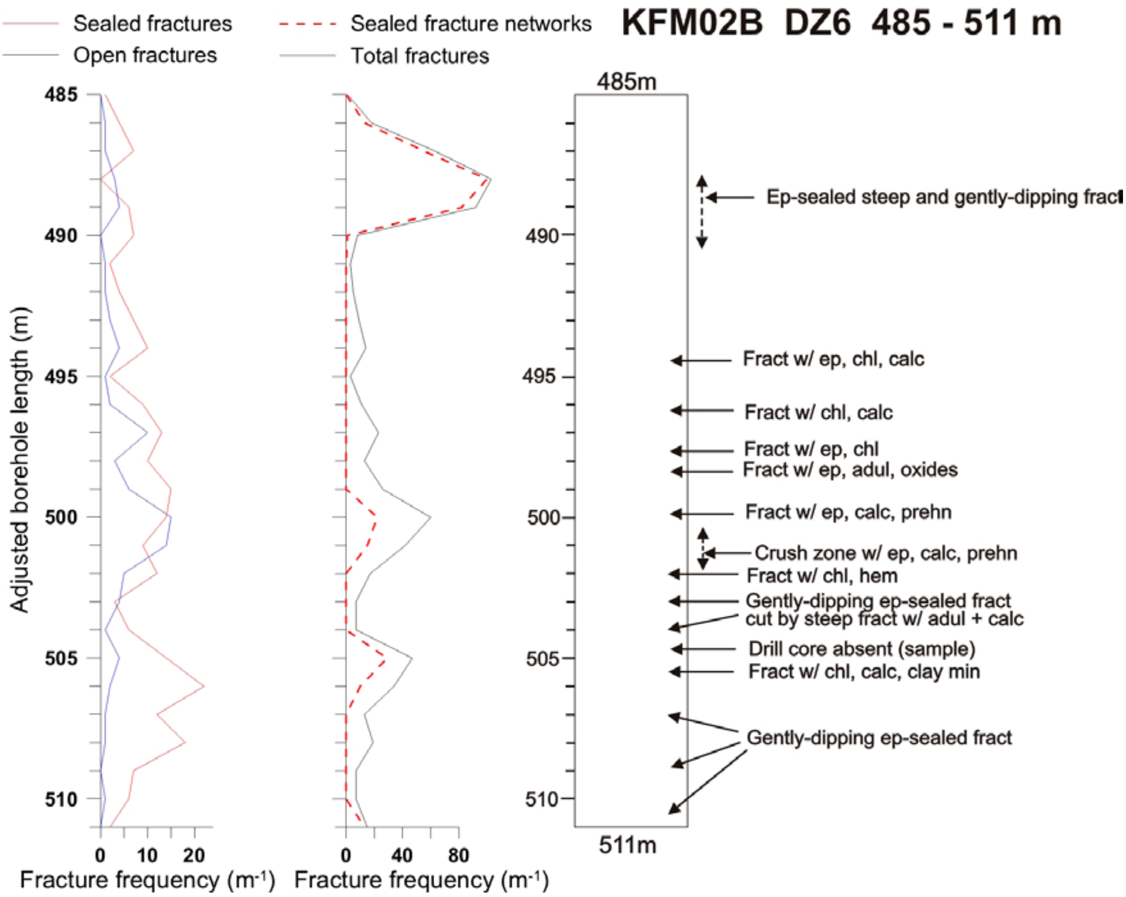


Figure 5-11. *Simplified drawing of DZ6 showing the most prominent brittle structures. Abbreviations as in Figure 5-3.*

Figure 5-12. Photograph of drill core from the uppermost part of DZ6 of KFM02B (486.6–491.6 m). Steep fractures with epidote and some chlorite and gently dipping epidote-sealed thin fractures are present in the amphibolite.

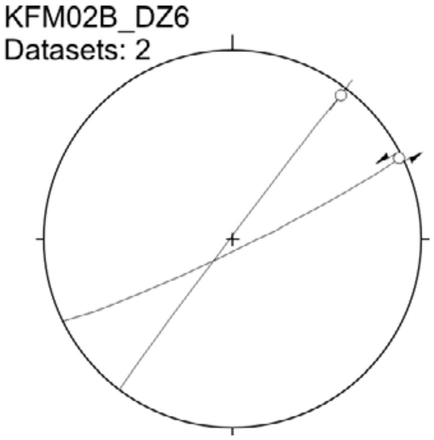


Figure 5-13. Stereonet of striated faults along DZ6 in KFM02B.

5.1.3 KFM08D

The drill site is located in the north-western part of the candidate area (Figure 5-1). The borehole has a length of 942.3 m and is oriented 100/55. The main rock type is a medium-grained metagranite-granodiorite that is partly altered (albitized) with subordinate occurrences of pegmatitic granite, metadiorite and amphibolite /Carlsten et al. 2007b/. Four deformation zones with a combined length of 100 m were investigated (DZ3, DZ5, DZ7, DZ12).

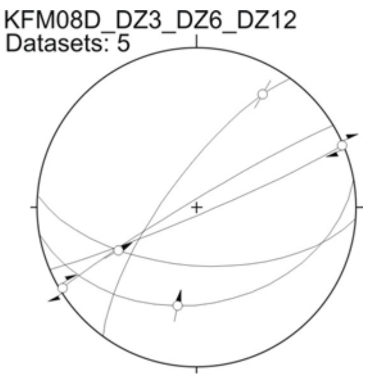


Figure 5-14. Stereoplot showing all the fault slip data collected along all the studied possible deformation zones in drill core KFM08D.

KFM08D: 371–396 m – DZ3

The rock types along DZ3 are medium-grained metagranite-granodiorite with subordinate occurrences of pegmatitic granite. Some metadiorite occurs in the lowermost part of the DZ3 (392–396 m). The zone shows some increase in the frequency of mainly sealed fractures. Steep fractures oriented NE-SW are common. However, gently dipping and steeply SW-dipping fractures also occur. The fractures are filled and/or coated mainly by chlorite, calcite and adularia. Below 386 m, fracture frequencies are fairly low and only marginally above background level (Figure 5-15 and Figure 5-16). The DZ3 is considered a transition zone according to /Munier et al. 2003/.

Only one, steep ENE-trending fault has been measured along DZ3 in KFM08D. It displays dextral slickensides on hematite and chlorite (Figure 5-17).

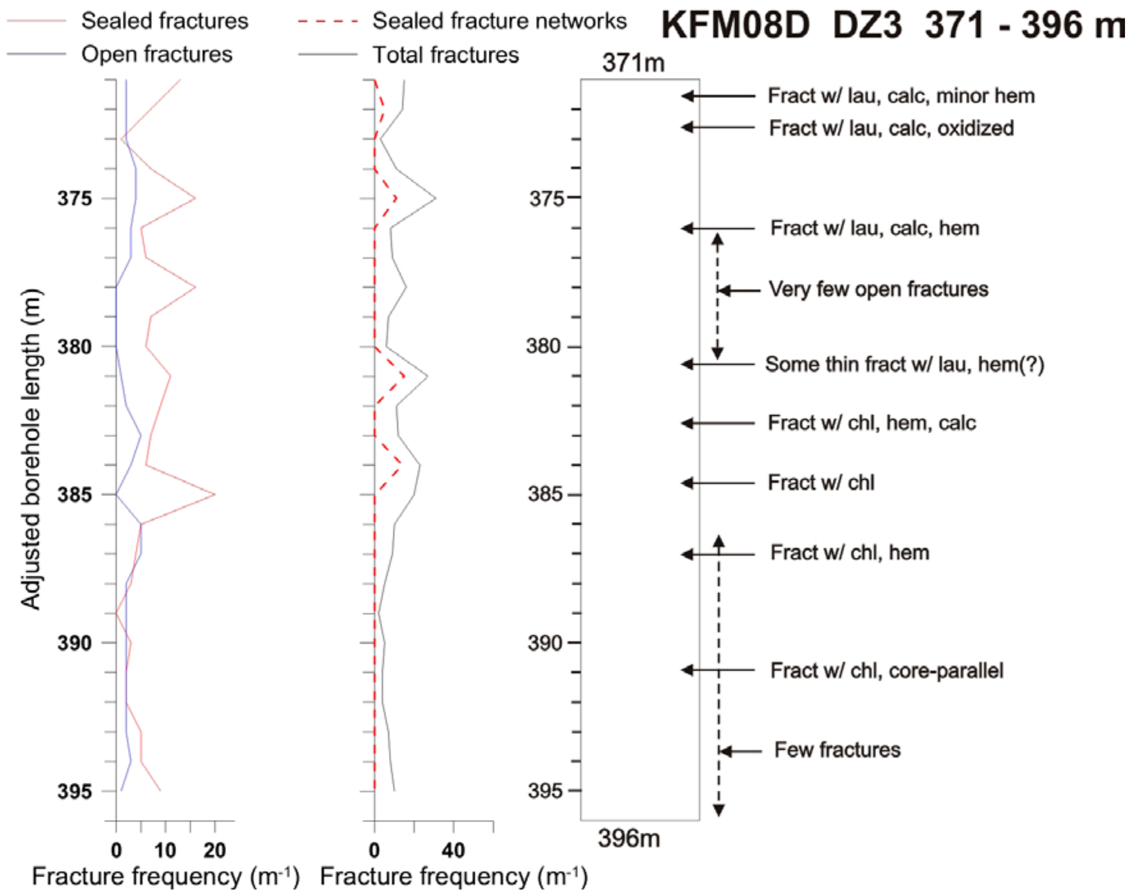


__Figure 5-15.__ Simplified drawing of DZ3 showing the most prominent brittle structures; see also Figure 5-16. Abbreviations as in Figure 5-3.

Figure 5-16. Photo showing weakly oxidized metagranite-granodiorite with some pegmatite from the central part of DZ3. Brittle deformation products are mainly represented by some sealed fractures.

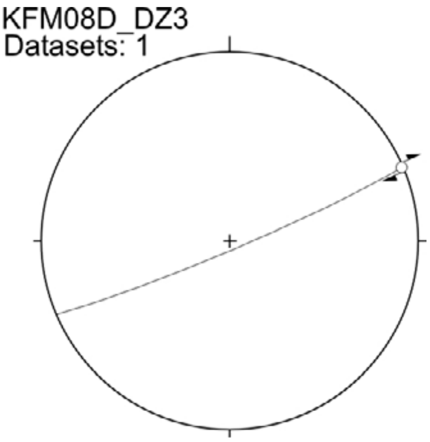


Figure 5-17. Stereoplot of fault slip data in DZ1 (KFM08D).

KFM08D: 546–571 m – DZ5

Deformation zone DZ5 occurs in pale grayish white (albitized), medium-grained metagranite-granodiorite with subordinate occurrences of pegmatitic granite. The zone exhibits an increased frequency of mainly sealed fractures that are predominantly NW-dipping. The fractures are sealed or coated with laumontite, calcite, chlorite, hematite, adularia and clay minerals. At ca 560 m, there is a ca 2.5 metres wide zone with fairly abundant fractures sealed with laumontite and some calcite. The fractures occur in parallel sets forming local fracture networks (Figure 5-18, Figure 5-19). The DZ is considered a transition zone according to /Munier et al. 2003/. No fault slip data have been identified in the zone.

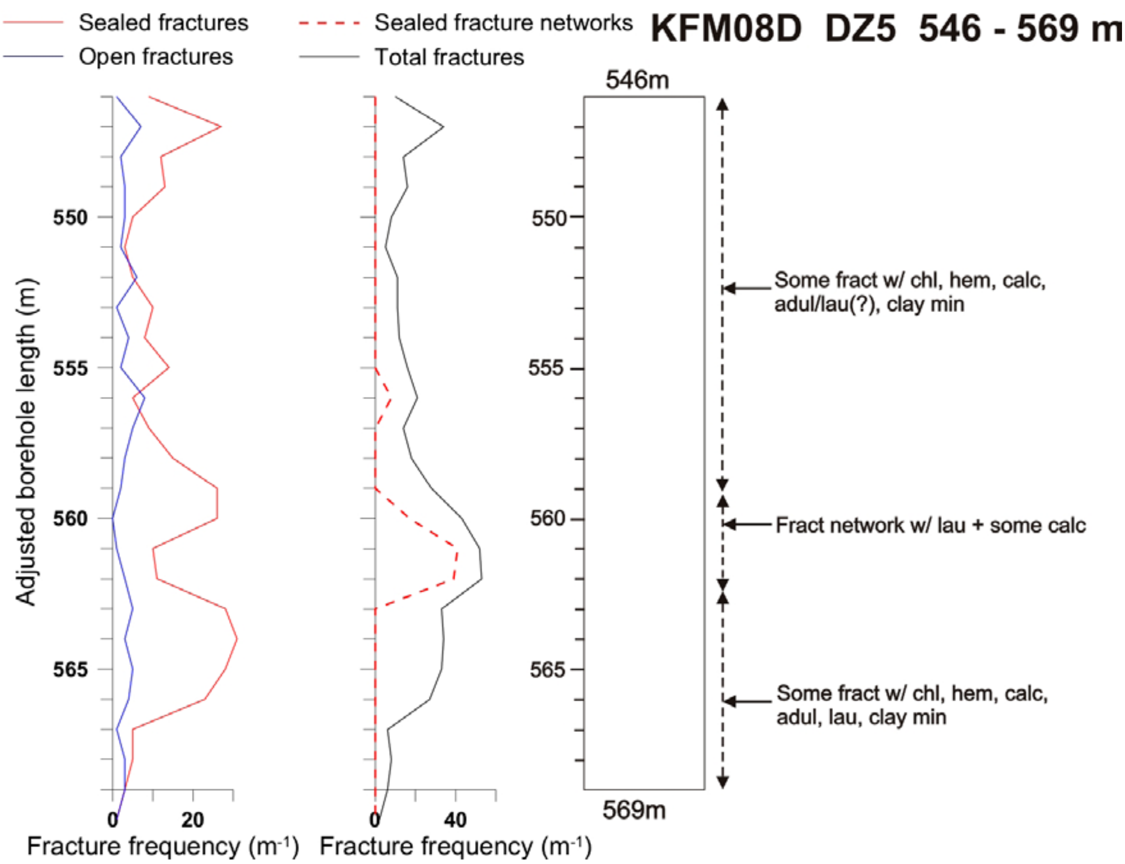


Figure 5-18. *Simplified drawing of DZ5 showing the most prominent brittle structures. Abbreviations as in Figure 5-3.*

Figure 5-19. *Photo showing pale greyish white (weakly oxidized) metagranite-granodiorite with some pegmatite from the central part of DZ5. Note occurrence of sealed fracture network at ca 560 m.*

KFM08D: 621–634 m – DZ7

Deformation zone DZ7 occurs in fine- to medium-grained metatonalite and pegmatitic granite. The lower part of the zone is characterized by a raised frequency of sealed fractures including some sealed fracture networks (Figure 5-20, Figure 5-21). The fractures are generally steep and oriented NNE-SSW. Above ca 627 m, the main brittle deformation is expressed as spaced open fractures. Weak oxidation has occurred locally. The fractures are sealed or coated with calcite, chlorite, hematite, and minor adularia and clay minerals. The DZ is considered a transition zone according to /Munier et al. 2003/.

A steep NE-SW fault has been measured along DZ7 in KFM08D (Figure 5-22). The fault shows dextral movement based on chlorite striations and calcite steps.

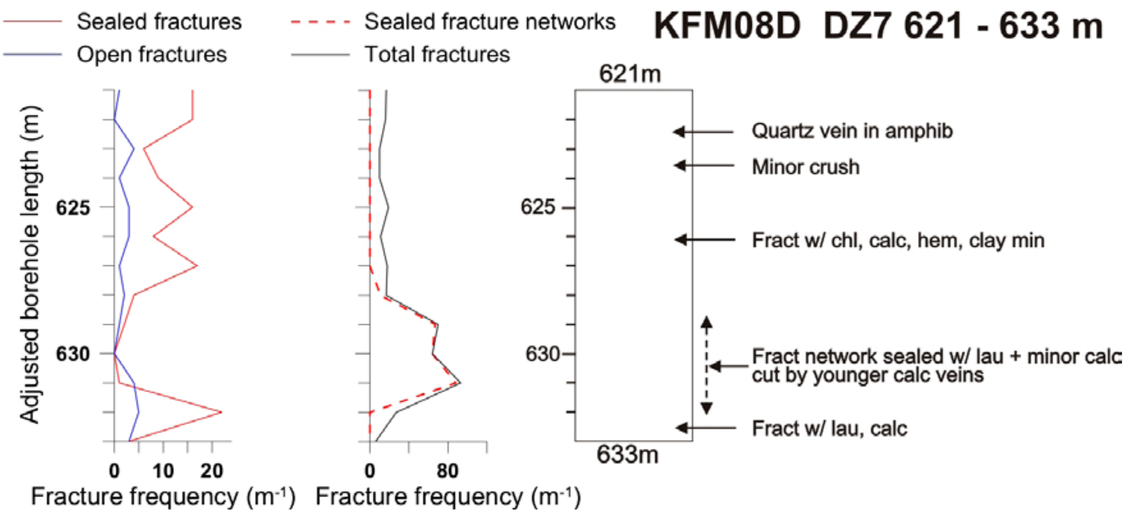


Figure 5-20. *Simplified drawing of DZ7 showing the most prominent brittle structures. Abbreviations as in Figure 5-3.*

Figure 5-21. *Photo showing the lower part of DZ7. Note occurrence of sealed fracture networks sealed mainly by laumontite and cut by younger calcite veins.*

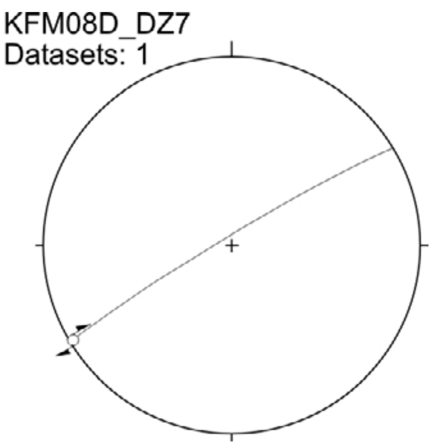


Figure 5-22. *Stereoplot of fault slip data in DZ7 (KFM08D).*

KFM08D: 903–941.15 m – DZ12

DZ12 consists of metadiorite, amphibolite, fine- to medium-grained granite, and albitized(?) medium-grained metagranite-granodiorite. The zone exhibits an increased frequency of sealed and open fractures (Figure 5-23). The most frequent fracture filling minerals are calcite, chlorite, clay minerals and oxides.

At ca 905.5 m, there is a ca 70 cm wide variably crushed zone with some chlorite and clay mineral coating on fractures. Few fractures occur in amphibolite with some pegmatite in the interval 906–919 m. The fractures are coated with chlorite, clay minerals and minor oxides. Some veins sealed with calcite are also present in the amphibolite. Fine-grained, weakly oxidized metagranite (919–924 m) contain few fractures (Figure 5-24).

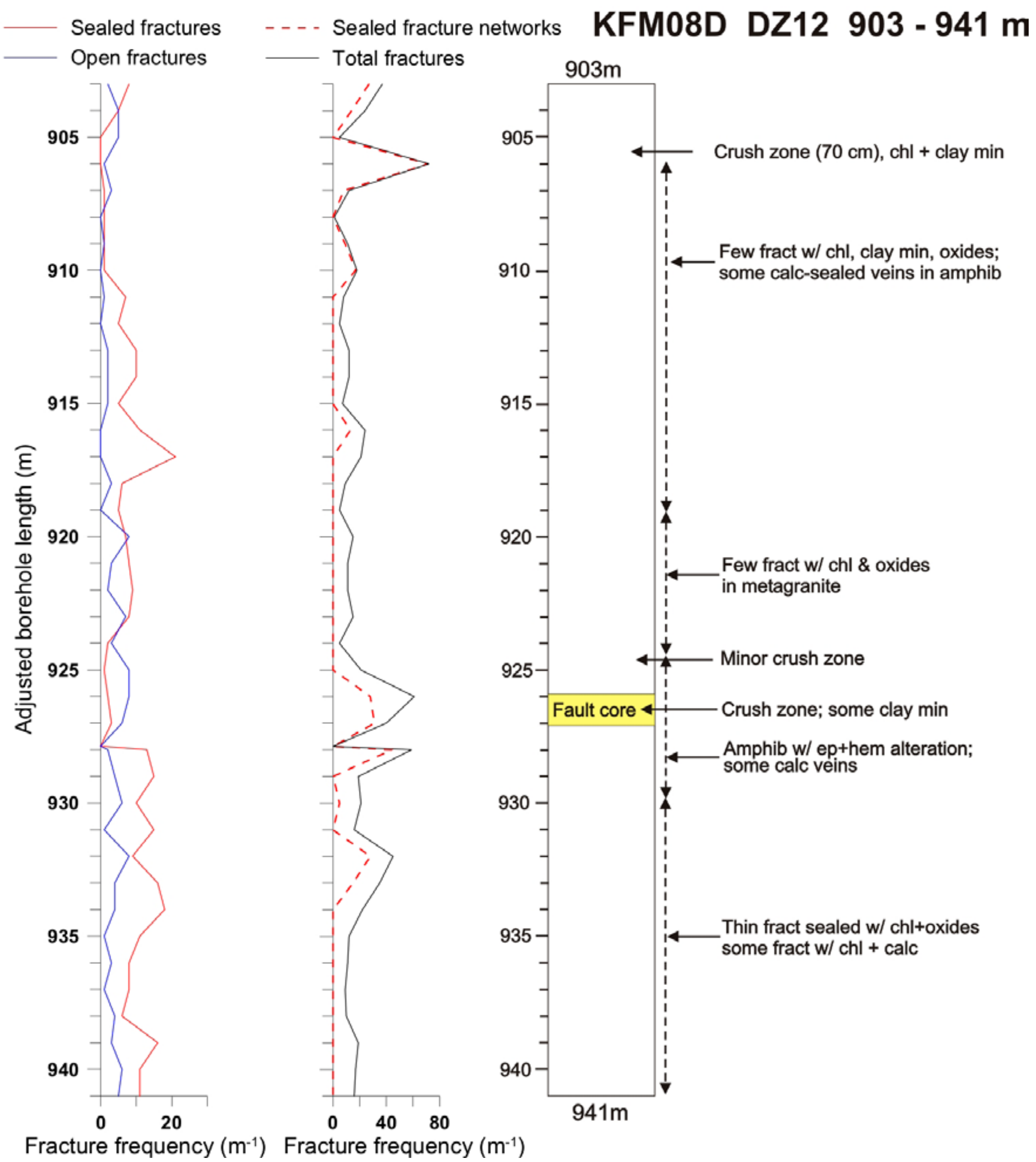


Figure 5-23. *Simplified drawing of DZ12 showing the most prominent brittle structures in the zone. Abbreviations as in Figure 5-3.*

***Figure 5-24.** Photograph showing the central part of DZ12.*

Along the interval 925–929.5 m, there is amphibolite with epidote and hematite alteration. Some calcite veins also occur. A crush zone with some clay mineral coating at ca 925–926 m is considered a fault core (Figure 5-23, Figure 5-24).

In the lower part of the DZ (929.5–941 m), there are some hairline veins sealed with chlorite + oxides. There are also some fractures with chlorite + calcite.

Apart from the fault core defined by strong crushing at ca 925–926 m, DZ12 is generally characterized by moderate fracture frequencies and is considered a transition zone according to /Munier et al. 2003/.

Three faults provided kinematic information along DZ12 in KFM08D (Figure 5-25). Two chlorite-striated faults that dip gently to moderately to the south show reverse movement based on calcite steps on the fault surface. A SSW-trending fault dipping steeply to the WNW has striations of chlorite plunging gently to the north. The sense of shear could not be determined.

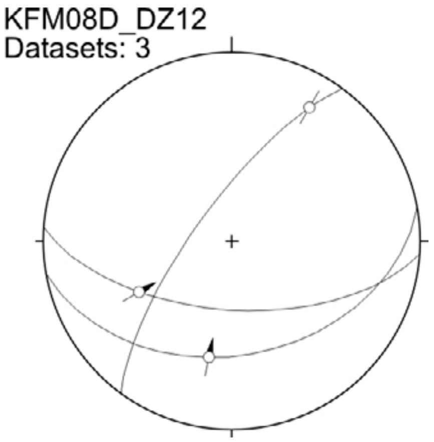


***Figure 5-25.** Stereoplot of fault slip data in DZ12 (KFM08D).*

5.1.4 KFM11A

This drill hole is located in the northeast part of the investigation area (Figure 5-1). The drill hole is oriented 040/60 and has a length of 852 m /Carlsten et al. 2007c/. One long deformation zone (DZ1) has been defined along the interval 245–824 m. For this study, only the central part of the DZ1 (498–630 m) was investigated. The main purpose of borehole KFM11A is to penetrate and provide data from the regional Singö deformation zone that runs approximately parallel to the coastline immediately offshore to the northeast of the Forsmark area.

KFM11A: 498–630 m – Part of DZ1

The investigated part of DZ1 consists mainly of medium to strongly foliated felsic to intermediate metavolcanic rocks, with subordinate pegmatitic granite, medium-grained metagranodiorite, amphibolite and medium-grained metagranite-granodiorite. In the lower part of the section (below 585 m), aplitic metagranite is the most prominent rock type /Carlsten et al. 2007c/.

From 498 m to 515 m, the fracture frequency is more than 40 fractures m^{-1} (Figure 5-26). Two peaks of very high fracture frequency are observed at ca 502 m and from 511 m to 515 m, respectively. They correspond to crush zones, breccias and cataclasites, all sealed by laumontite (Figure 5-28). The lowest highly fractured part begins at 511 m, with numerous core-parallel chlorite-clay coated fractures that are cut by irregular laumontite-sealed veins and terminates with numerous fractures coated with chlorite-clay minerals-hematite and sericite. A number of faults are present. The two peaks are separated by a zone of pegmatite in which calcite and laumontite veins cut quartz veins (Figure 5-29)

From 515 m to 521 m, the fracture frequency drops to less than 40 fractures m^{-1} (Figure 5-26). Laumontite is almost absent in this interval and the faults and fractures are coated with chlorite, talc and hematite. Three thin crush zones are present.

From ca 523 m to ca 528 m, the fracture frequency is high with abundant laumontite-sealed fractures (Figure 5-26). A number of faults are present with striated chlorite and hematite, and laumontite steps.

From 528 m to 540 m, the fracture frequency is moderate. The minerals coating the fractures are clay minerals, hematite, chlorite and rarely laumontite. The faults display laumontite steps in addition to striae on chlorite and hematite.

At 540 m, a nearly 1 m thick crush zone is observed in a pegmatitic host rock.

From 543 to 545 m, the fracture frequency is slightly elevated compared to the adjacent drill core. Two thin crush zones are present.

From 545 m down to 574 m, the fracture frequency is moderate (Figure 5-26 and Figure 5-27). This part begins with a thin crush zone. The fractures are parallel to the foliation and coated with clay minerals, chlorite, hematite, mica flakes and epidote. Late laumontite-sealed fractures are observed. At ca 564 m, the frequency of open fractures reaches 20 m^{-1} and from this level down to 574 m, there are few fractures with chlorite, clay minerals and laumontite. Some faults are also present.

At 574 m, there is a marked increase in the fracture frequency, especially laumontite-sealed fractures and fracture networks. Apart from some laumontite-sealed networks and crush zones, the fracture frequency remains moderate down to ca 590 m (Figure 5-27).

From 590 m down to the base of DZ1 at 629 m, the drill core is strongly fractured with a predominance of laumontite and a notable reddish oxidation (Figure 5-27). Crush zones and laumontite-sealed cataclasites and networks are common, e.g. at ca 600 m. Other fracture minerals are chlorite, hematite, clay minerals and calcite. Cross-cutting relationships show that late fracturing was accompanied by calcite and a secondary laumontite mineralization (Figure 5-29). These late calcite-laumontite-filled fractures are commonly core-parallel.

The studied interval of DZ1 is part of a long and complex deformation zone without a well-defined transition zone flanking a fault core containing fault rocks. Taken together, the interval can be broadly split into three sub-zones: 498–528 m, 528–574 m and 574–629 m. Apart from crush zones at 540 and 545 m, the central sub-zone contains a strongly foliated metagranodiorite with moderate fracture frequency and minor fault rocks. Following the definition of /Munier et al. 2003/, this sub-zone may be regarded a transition zone, possibly with host rock preserved. The upper and lower sub-zones have markedly higher fracture frequencies, fairly abundant crush zones are present, the rocks are more oxidized and short intervals of fault rocks (breccias, cataclasites) are observed at different depths. Still, short sections of virtually intact host rock are present. Given the spatial frequency of the brittle features, and the impossibility to subdivide the sub-zones into distinct and meaningful fault cores and transition zones, we assign the upper (498–528 m) and lower (574–629 m) sub-zones to separate fault cores. On a regional scale, the fault core intervals separated by a transition zone may represent the anastomosing geometry of the larger Singö deformation zone.

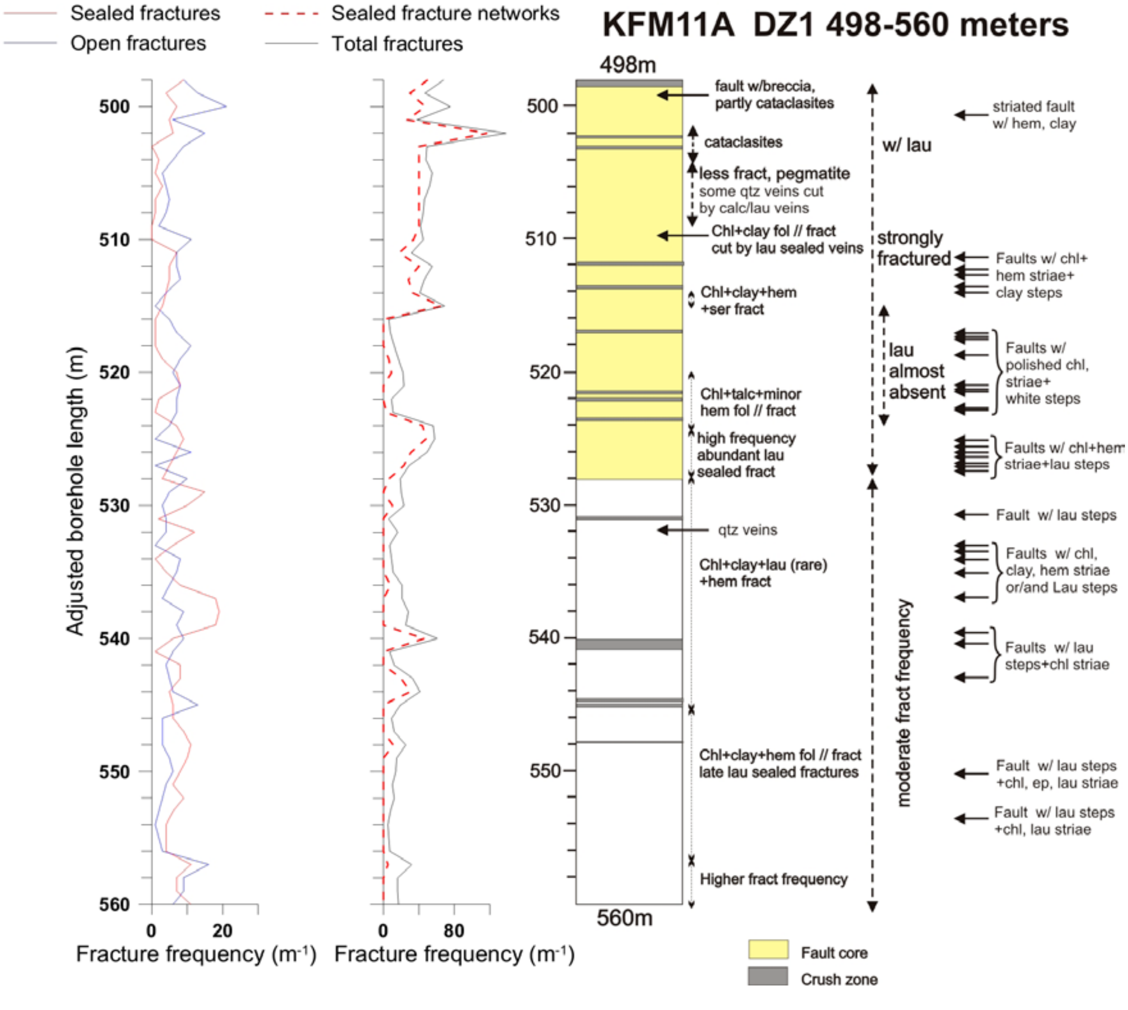


***Figure 5-26.** Simplified drawing of the upper part of the interval 498–630 m along DZ1 (KFM11A) showing the most prominent occurrences of brittle structures. Abbreviations as in Figure 5-3.*

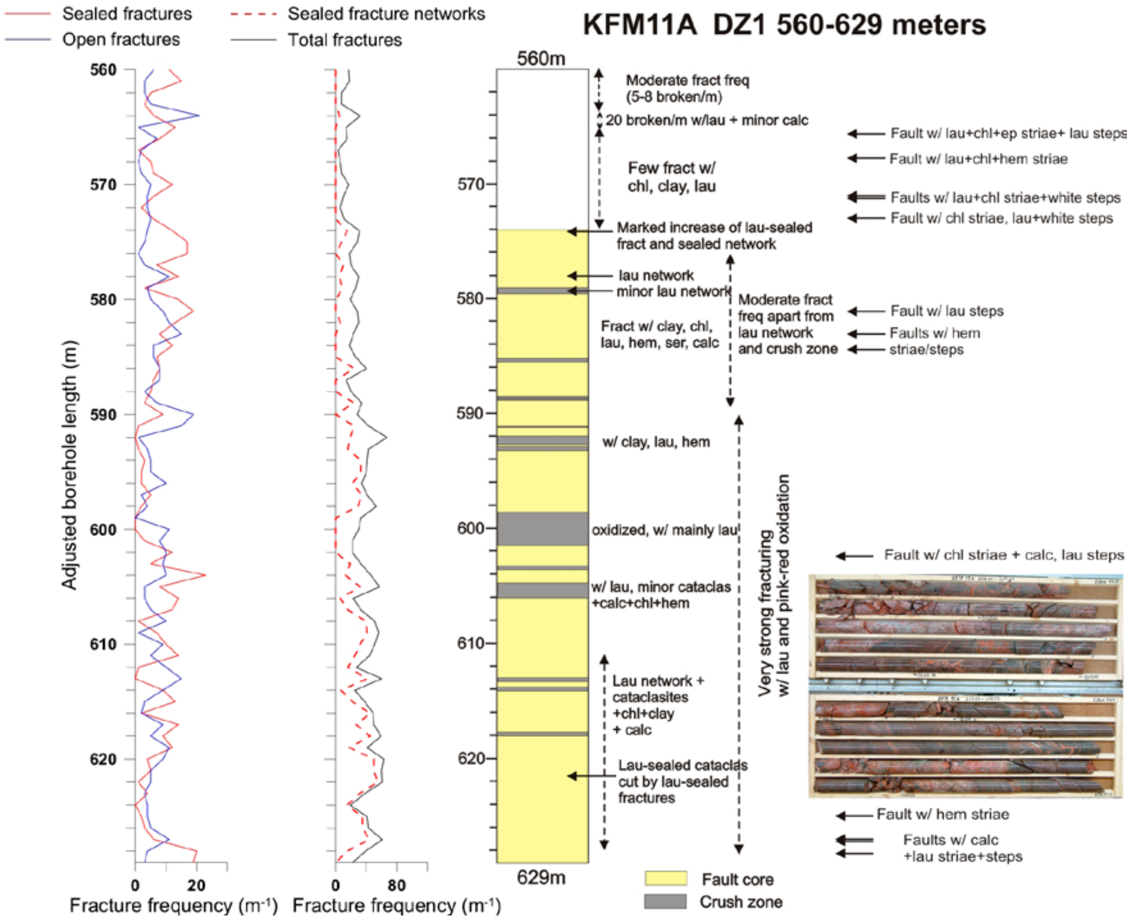


Figure 5-27. Simplified drawing of the lower part of the interval 498–630 m along DZ1 (KFM11A) showing the most prominent occurrences of brittle structures. The inserted photograph shows the high frequency of laumontite-sealed fractures, fracture networks and cataclasites in the lower part of the studied drill core. Abbreviations as in Figure 5-3.

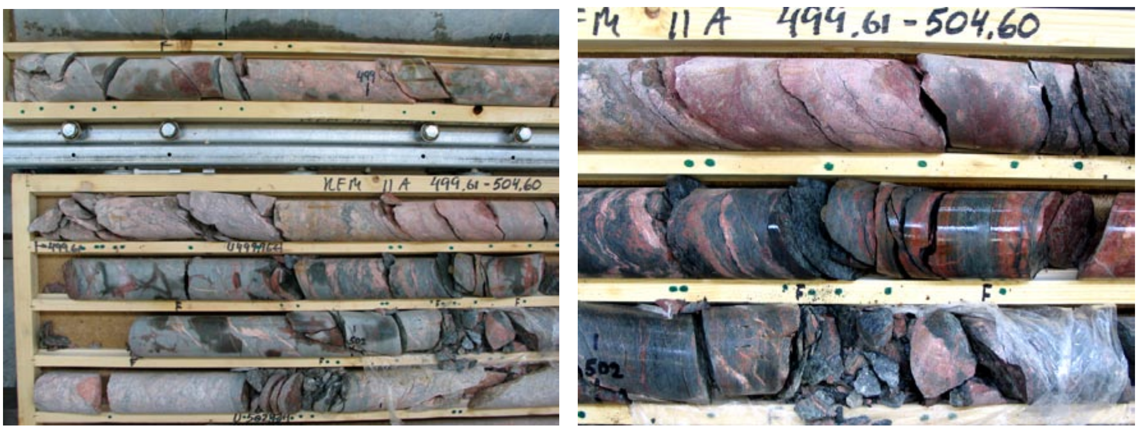


Figure 5-28. Left: Photograph of the upper part of the studied drill core showing the abundant occurrences of faults with laumontite-sealed breccia and cataclasite. Right: Close-up of the laumontite-sealed cataclasites. (DZ1 in KFM11A).

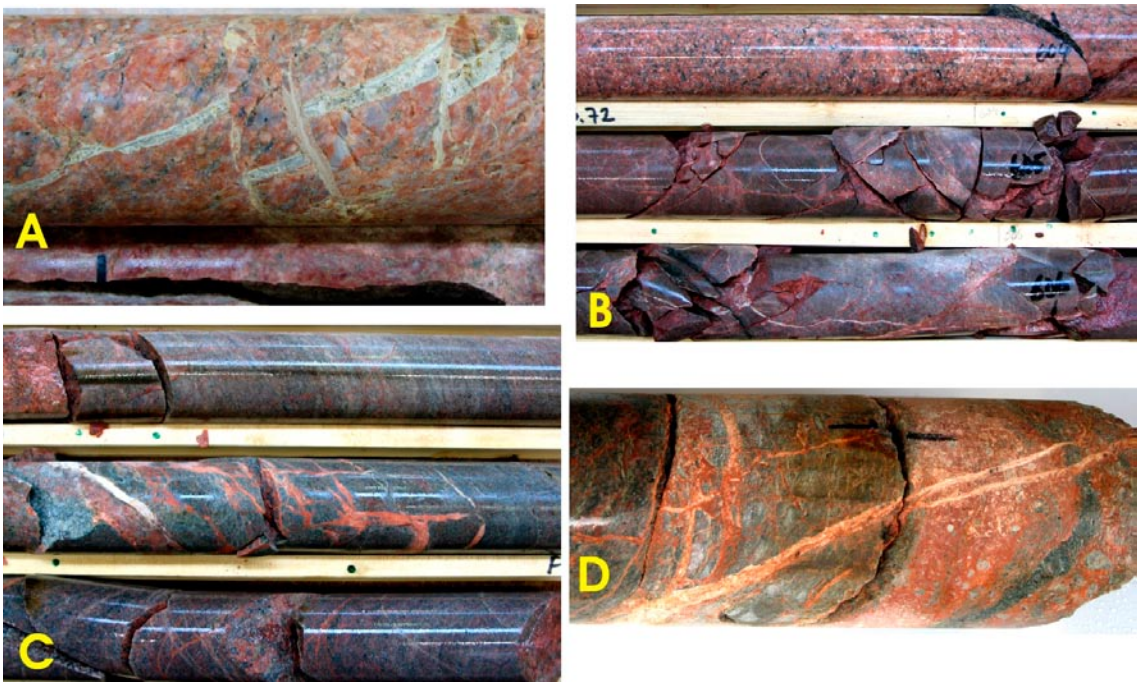


Figure 5-29. *Photographs illustrating some cross-cutting relationships between brittle structures in DZ1 (KFM11A). A: white quartz veins cut by veins with calcite in their core and an uncertain mineral at their margins. B: crush zone and laumontite-sealed cataclasites and vein network cut by calcite veins. C: dense laumontite-sealed network later reactivated with calcite infill at 616.50 m. D: laumontite-sealed cataclasite cut by a second generation of laumontite-sealed fractures at 621.60 m.*

A total of 46 fault slip data were collected along DZ1 of the drill core KFM11A (Figure 5-30). Most of the fault slip data were obtained at depths between 510 and 540 m and close to the bottom of the studied drill core (625–629 m). Few striated faults were observed from 540 to 585 m, and they rarely occur along the rest of DZ1. Notably, the abundance of striated faults is not highest where the fracture frequency is high.

As a first attempt to analyse the fault slip data set, the faults have been discriminated according to the minerals on the fault surfaces. This is justified by the observation that the chlorite- and/or hematite-coated fractures are cut by late laumontite- and calcite-sealed fractures (see section above). Note that epidote was not observed on any of the measures faults. 50% of the faults display striations on only chlorite and hematite and in some cases polished chlorite, clay minerals and talc (stereonet B on Figure 5-30). One some of the faults there are steps that reveal the sense of movement along the fault (Figure 5-31A). Shear indicators observed on a few steep NW-SE faults exhibit both dextral and sinistral sense of movement. Gently-dipping ENE-WSW to ESE-WNW faults show reverse movement in two cases, but most of these faults are predominantly strike-slip with undetermined shear sense.

In addition to chlorite, hematite, and/or talc and clay minerals, the remaining 50% of the faults have steps defined by laumontite or calcite (C on Figure 5-30). These data provide very good kinematic indicators and allow exact determination of the sense of shear; see examples of fault surfaces on Figure 5-31. The faults have the same general orientation as those without laumontite or calcite and exhibit variable sense of movement. The steep set of WNW-ESE to NW-SE faults display opposing dextral and sinistral kinematics. Some variably oriented gently-dipping faults show reverse and normal-oblique relative movement.

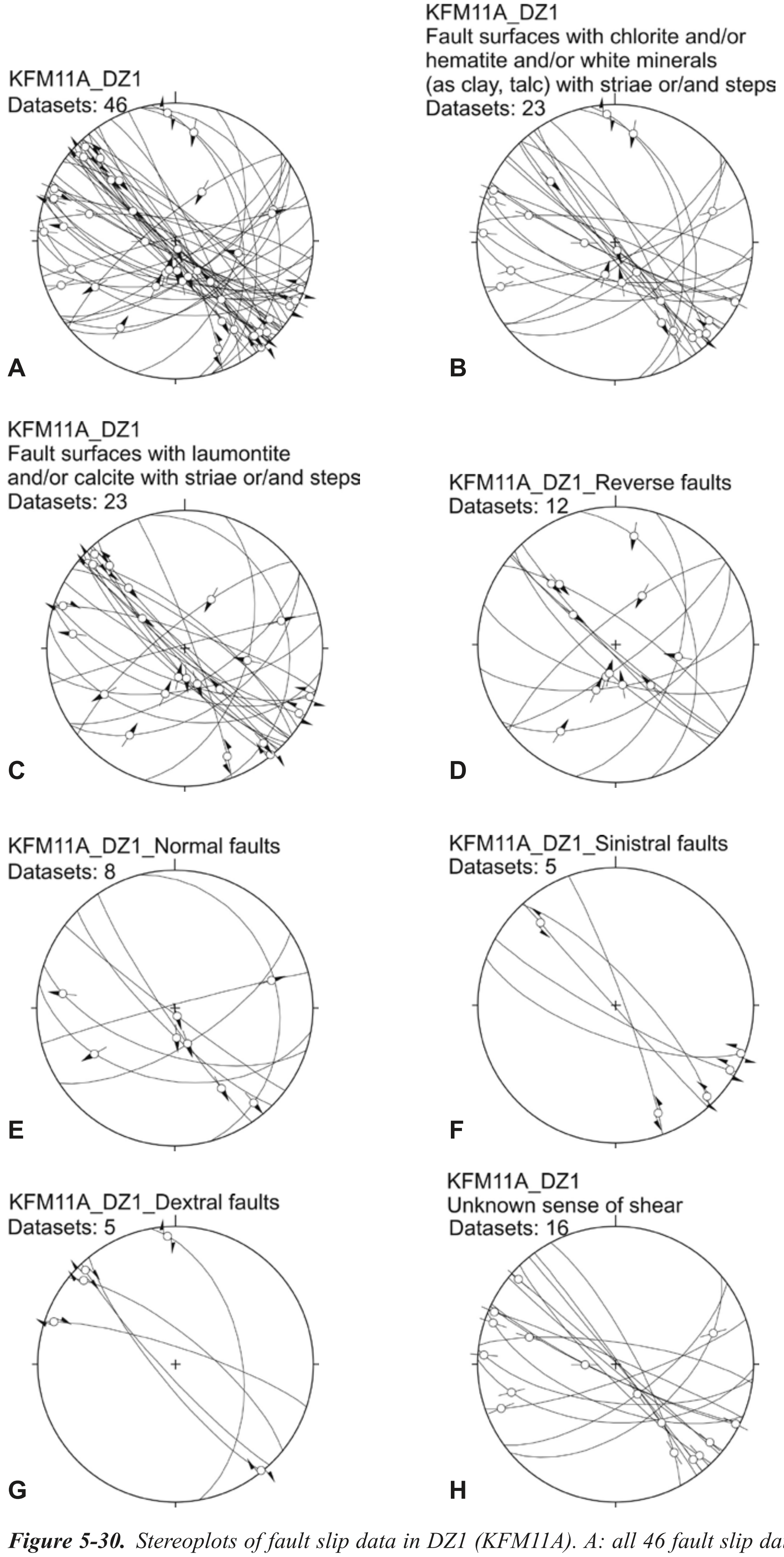


Figure 5-30. *Stereoplots of fault slip data in DZ1 (KFM11A). A: all 46 fault slip data; B: 23 faults with laumontite and/or calcite in addition to chlorite and/or hematite and/or clay minerals/talc; C: 23 striated and/or stepped faults with chlorite and/or hematite and/or clay minerals/talc; D: 12 reverse fault slip data; E: 8 normal fault slip data; F: 5 sinistral fault slip data; G: 5 dextral fault slip data; H: 16 fault slip data with unknown sense of shear.*

Figure 5-31. *Photographs illustrating fault surfaces observed in DZ1 of KFM11A. A: reverse fault surface (518.59 m, strike/dip and pitch: 53/78–74) with slickensides and steps defined by chlorite, hematite and clay minerals. B: reverse fault surface (525.60 m, strike/dip and pitch: 305/76–42) with chlorite slickensides and laumontite steps. C: normal fault surface (525.95 m, strike/dip and pitch: 135/78–77) with slickensides and steps with chlorite and laumontite. D: reverse fault surface (571.14 m, strike/dip and pitch: 17/52–86) with slickensides and steps defined by chlorite, laumontite and clay minerals.*

The fault slip data sorted according to their recorded kinematics are shown in stereonets D (reverse to oblique), E (normal to oblique), F (sinistral), and G (dextral) on Figure 5-30. In each of these four groups there are faults with and without laumontite and/or calcite. Thus, there is no clear difference in the kinematics revealed by the two fault populations shown in Figure 5-30B and C. Both fault populations have similar orientations and similar slip directions are observed on their surface. This may suggest that the faults initially developed under fairly similar brittle conditions (depth, temperature, fluid transport) facilitating growth of chlorite and hematite on the fault surfaces. Later reactivation allowed for the growth of laumontite and calcite under conditions that differed from those that applied during earlier fault development. The lack of laumontite and calcite on some fault surfaces may be due to local variation along the faults during fault movement, fluid flow and mineral growth.

The predominant set of faults trends NW-SE parallel to the regional Singö Deformation Zone (Figure 5-30A). Strike-slip faults exhibit opposite shear sense, and both reverse and normal oblique-slip faults are present. A number of mainly strike slip faults with undetermined shear sense are also recorded along this trend (Figure 5-30). Taken together, these observations would imply that movement along the Singö Deformation Zone took place under successive and somewhat contrasting tectonic stress regimes. However, the data on kinematics from the investigated faults in KFM11A do not allow us to determine the relative chronology of the successive stress regimes. Reactivation of faults may also have occurred as a result of relative adjustments between crustal compartments during later loading and/or exhumation of the crust.

5.1.5 KFM12A

This inclined borehole is oriented 036/61 starting from a location to the southwest of the investigation area (Figure 5-1). The borehole has a length of 601.4 m /Carlsten et al. 2007d/. Three deformation zones (DZ1, DZ2 and DZ3) with a total length of 275 m were investigated. Borehole KFM12A penetrates the regional WNW-ESE-oriented Forsmark deformation zone that runs sub-parallel to and some distance to the southwest of the Eckardfjärden deformation zone.

A total of 43 striated faults were observed along DZ1 and DZ2. The results show that there is a predominant set of steep faults oriented NW-SE to WNW-ESE, parallel to the Forsmark deformation zone. Faults dipping to the east and southeast are also present (see below for details).

KFM12A: 125–158 m – DZ1

DZ1 consists of porphyritic and equigranular metagranodiorite with subordinate fine- to medium-grained granite, metagabbro/diorite, amphibolite and aplitic metagranite. In general, the rocks are strongly foliated. The zone shows increased frequency of sealed fractures, sealed fracture networks and, to some extent, open fractures. Steep NE-striking fractures and fractures that have variable, gentle dips are present. Fracture minerals include epidote, quartz, chlorite, clay minerals, calcite, laumontite and hematite. The highest fracture frequencies are associated with fracture networks with epidote, quartz and some chlorite (Figure 5-33). Epidote-sealed fractures are cut by calcite-sealed fractures and by fractures with chlorite, clay minerals and calcite. Locally, minor brecciation is observed along the epidote-sealed fractures (Figure 5-34). Laumontite-sealed fractures appear in the lower part of the zone. The DZ is considered to be a transition zone according to /Munier et al. 2003/.

Kinematic data were obtained from 10 striated faults along DZ1 in KFM12A (Figure 5-35). The faults are coated with chlorite, clay minerals, hematite and calcite. Calcite and laumontite steps are very common on fault surfaces and allow determination of the sense of shear. Striations are marked on all minerals. A predominant set of strike-slip faults strike NW-SE, sub-parallel to the Forsmark deformation zone. Two of these show sinistral strike-slip, and one fault shows dextral normal (oblique) sense of movement. Strike-slip faults striking NE-SW to ENE-WSW and with variable dip show both sinistral and dextral sense of movement. A gently SSE-dipping reverse fault is also present.

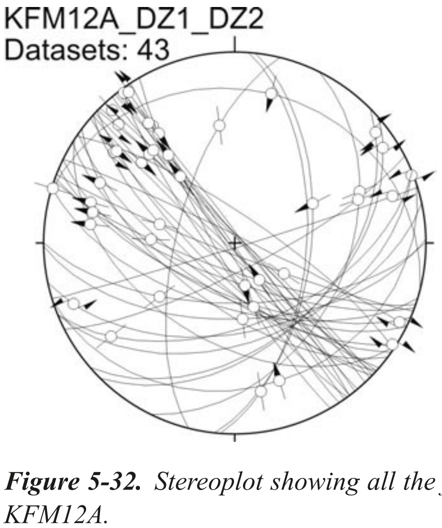


Figure 5-32. Stereoplot showing all the fault slip data collected along all the studied DZ in drill core KFM12A.

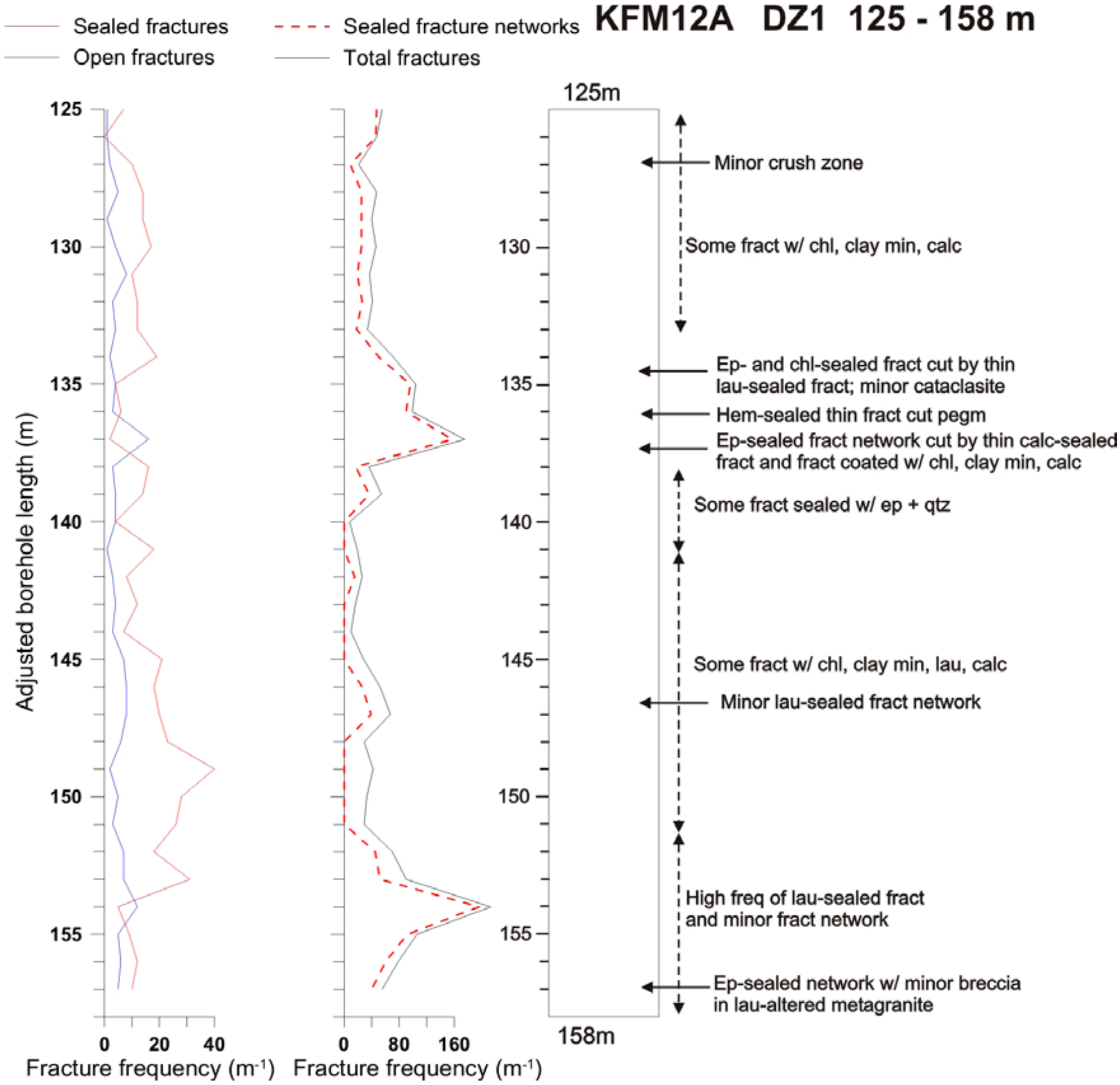


Figure 5-33. *Simplified drawing of DZ1 showing the most prominent brittle structures in the zone. Abbreviations as in Figure 5-3.*

Figure 5-34. *Photo (ca 157 m) showing the minor brecciation associated with epidote fracture network.*

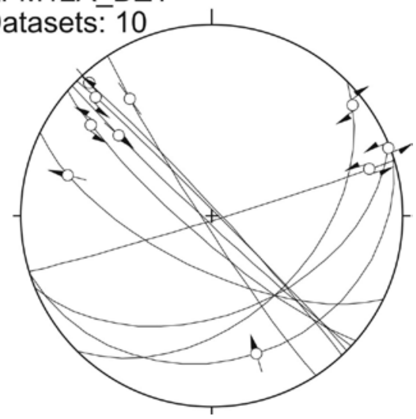


Figure 5-35. *Stereoplot of fault slip data in DZ1 (KFM12A).*

KFM12A: 170–402 m – DZ2 (The Forsmark zone)

The rock types in this zone are foliated metagranodiorite, pegmatitic granite, metagabbro/diorite, amphibolite and fine- to medium-grained metagranitoid. The zone exhibits increased frequencies of sealed fractures, sealed fracture networks and open fractures. The fractures are mainly oriented NW-SE with steep dips to the SW. Variably oriented fractures with gentle to moderate dips are also common. Brittle deformation products are less common below ca 338 m.

The log and the description of the DZ are split into three sections: 170–240 m, 240–300 m and 300–402 m.

The upper part of DZ2 (170–240 m) is shown in Figure 5-36.

170–180 m: Strongly oxidised metagranite with thin laumontite-sealed fractures containing minor calcite and some chlorite. The fractures may be parallel to or cross-cut the foliation in the host rock. Minor cataclasite occurs locally. At 176–177 m, there are networks of epidote-sealed fractures cut by laumontite- and calcite-sealed fractures.

180–ca 198 m: Amphibolite and oxidised metagranite with numerous fractures sealed with laumontite (predominant), chlorite, clay minerals, calcite and hematite. Epidote and quartz occur sporadically. From ca 188 m, there is some increase in the abundance of thin, laumonite-sealed fractures. A minor E-dipping normal fault with dip slip movement occurs at ca 192.5 m (Figure 5-37).

The interval from 198 to 220 m is characterized by fractures sealed with chlorite, clay minerals, calcite, laumontite and oxides and some sporadic occurrences of fault rocks (Figure 5-36). At ca 202–203 m, sealed fracture networks with epidote and chlorite are cut by fractures sealed with calcite and laumontite (Figure 5-38). A thin section (sample KFM12A_202.9) was studies from a fault rock at ca 203 m (Figure 5-39). The foliated metagranite exhibits several generations of deformation products. Dark greenish, chlorite-rich, foliated shear zones/cataclasite in metagranite are cut at high angles by discrete fractures, some of which are sealed with chlorite. Irregular fractures sealed with feldspar (?) and some thin hairline veins postdate other brittle deformation products.

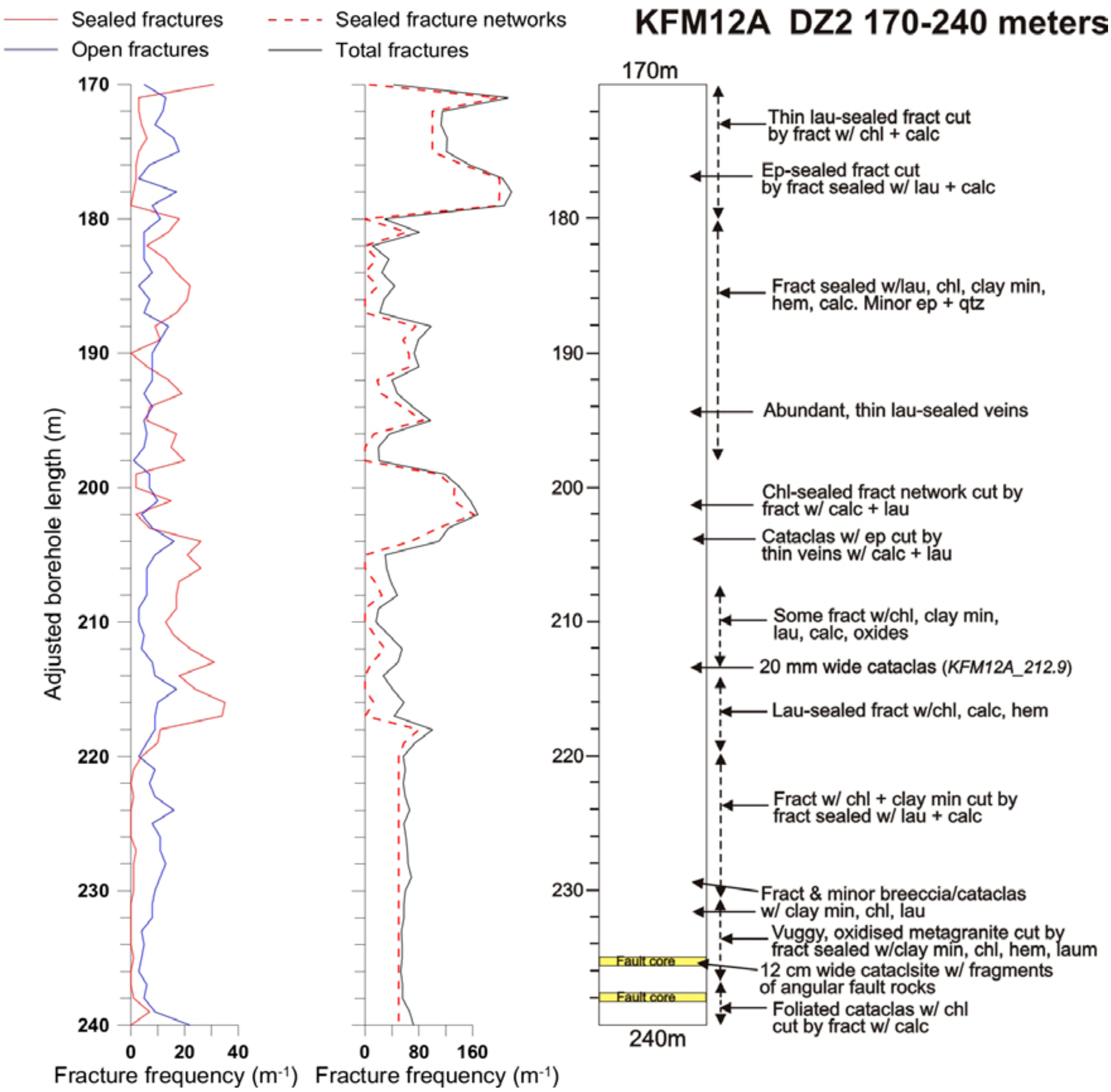


Figure 5-36. *Simplified drawing of the upper part of DZ2 (170–240 m) showing the most prominent brittle structures in the zone. Abbreviations as in Figure 5-3.*

Two generations of fault rock that cut fine-grained reddish metagranite occur at ca 205 m (sample KFM12A_204.9; Figure 5-40). A dark greenish, foliated shear zone rich in chlorite is associated foliated to mylonitic metagranite. The shear zone has been reactivated and the central part is a fine-grained ultra-cataclasite with angular fragments of the mylonite.

At 212.9 m, a 20 mm wide, multi-generation, dark cataclasite occurs in reddish metagranite (sample KFM12A_212.9; Figure 5-41). The thin section shows foliated metagranite that is variably deformed and converted to cataclasite. The lower part of the thin section shows angular clasts of cataclasite with some dark elongate fragments enriched in hematite. Pale vein-like features that post-date the cataclasite are sealed with euhedral quartz.

The interval 220–230.5 m is characterised by fractures sealed with chlorite and clay minerals and minor hematite that are cut by sealed fractures with laumontite and calcite (Figure 5-36). Sample KFM12A_223.95 (Figure 5-42) shows a foliated host rock affected by complex development of different types of cataclasite post-dated by fractures and veins sealed with oxides, chlorite, quartz and laumontite.

Figure 5-37. *Close-up of drill core showing a small fault that cuts lithological boundaries at ca 192.5 m. The normal fault has dip slip movement and is oriented 358/39.*

Figure 5-38. *Close-up of drill core at ca 203 m showing different types of sealed fractures and cataclasites. Thin, chlorite- and epidote-sealed shear zones and fractures are cut by thin veins sealed with calcite and laumontite (for details, see Figure 5-39).*

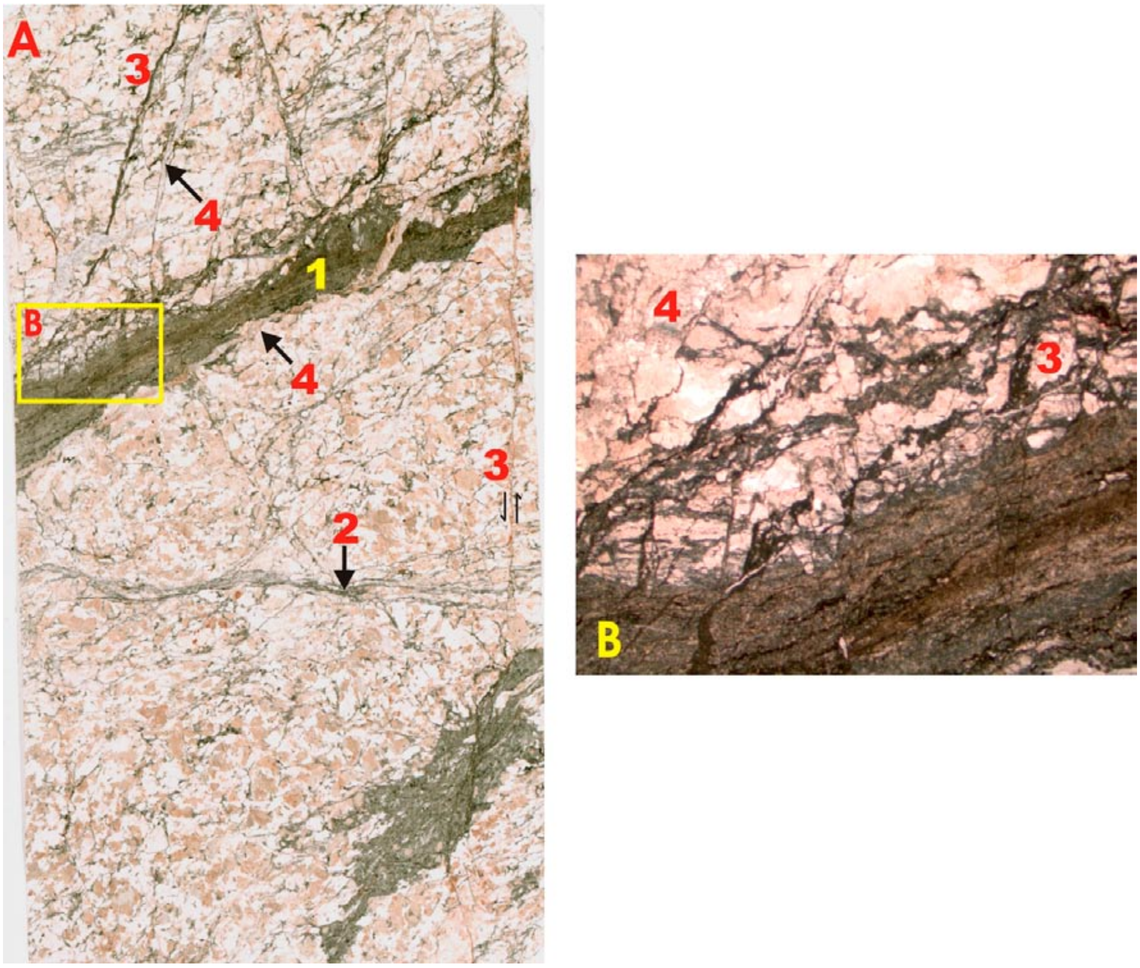


Figure 5-39. Scanned thin section (A) and photomicrograph (B) of sample KFM12A_202.9. The thin section (height of view is 38 mm) shows altered and partly proto-mylonitic metagranite cut by dark greenish, foliated shear zones rich in chlorite and epidote (1) and a thin shear zone in metagranite (2) which is cut at high angles by discrete shear zones/cataclasites (3), some of which contain chlorite. Irregular fractures (4) sealed with feldspar (?) and some thin hairline veins (visible in B) postdate other brittle deformation products.

Vuggy, oxidised metagranite occurs in the interval 230.5–239.5 m (Figure 5-36). Fractures and local minor breccia/cataclasite are sealed with abundant clay minerals, some chlorite and hematite, and minor laumontite. At ca 235 m, the drill core contains a 12 cm wide pale green cataclasite with fragments of reddish fault rock (Figure 5-43) defining the central part of a ca 0.5 m wide fault core. Another core section with high density of minor faults and sealed fractures with local fault rock development define a ca 0.5 fault core at ca 238 m. At ca 239 m, foliated chlorite-rich cataclasites are cut by late fractures sealed with calcite.

The interval 170–240 m is generally considered a transition zone /Munier et al. 2003/ with fairly uniform fracture frequency and local occurrences of minor fault rocks. Two 0.5 m wide intervals at ca 235 and 238 m, respectively, are considered fault core.

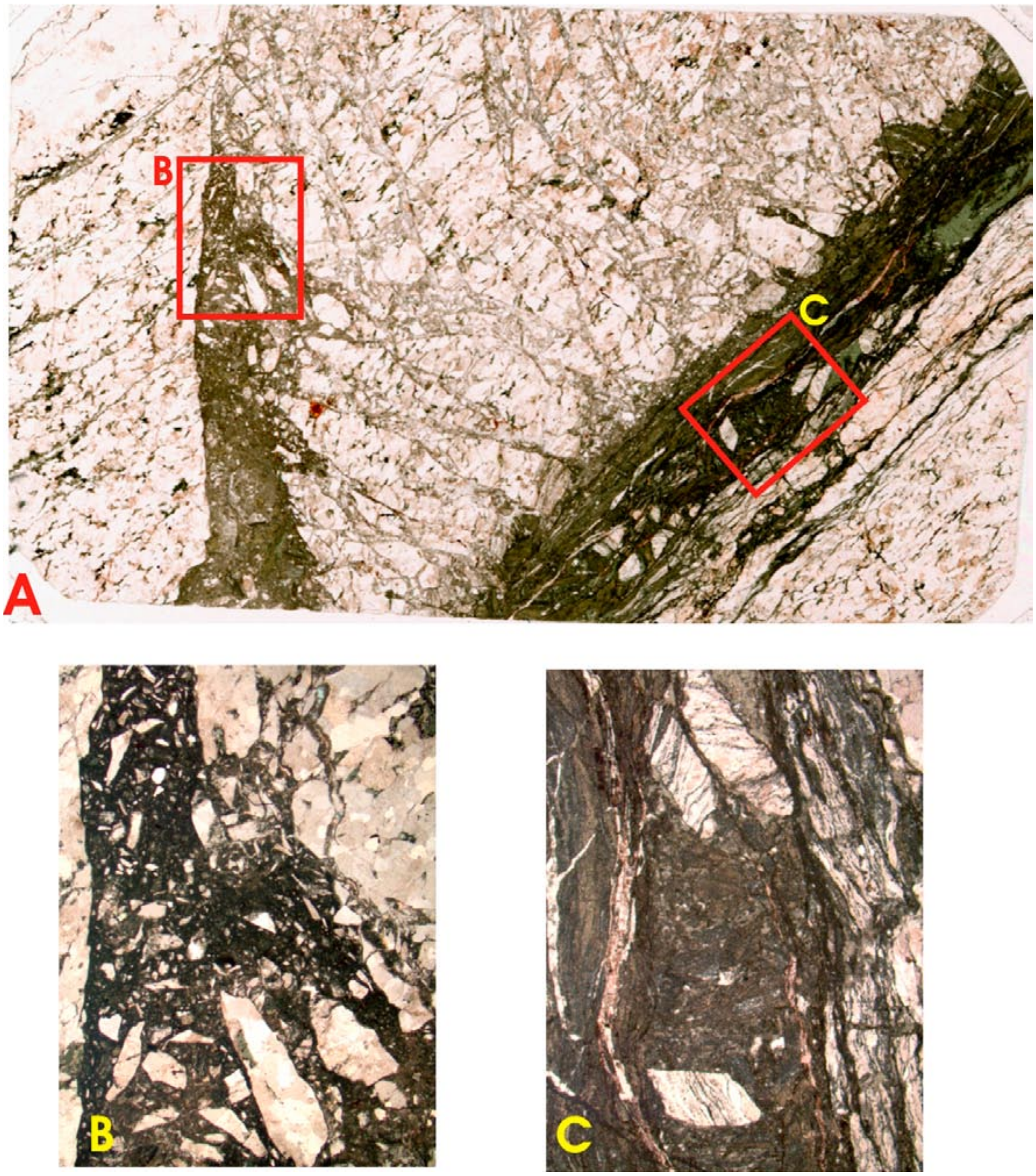


Figure 5-40. *Scanned thin section (A) and photomicrographs (B and C) of sample KFM12A_204.9. The thin section (width of view is 38 mm) shows foliated metagranite cut by dark greenish, foliated shear zone rich in chlorite (right). The metagranite adjacent to the shear zone has a mylonitic texture. The shear zone has been reactivated and the central part is a fine-grained ultra-cataclasite with angular fragments of the mylonite (C). The cataclasite shown in B is chlorite-rich with angular fragments of the metagranite. The metagranite between the shear zone/cataclasites is riddled with thin fractures with minor development of cataclasite.*

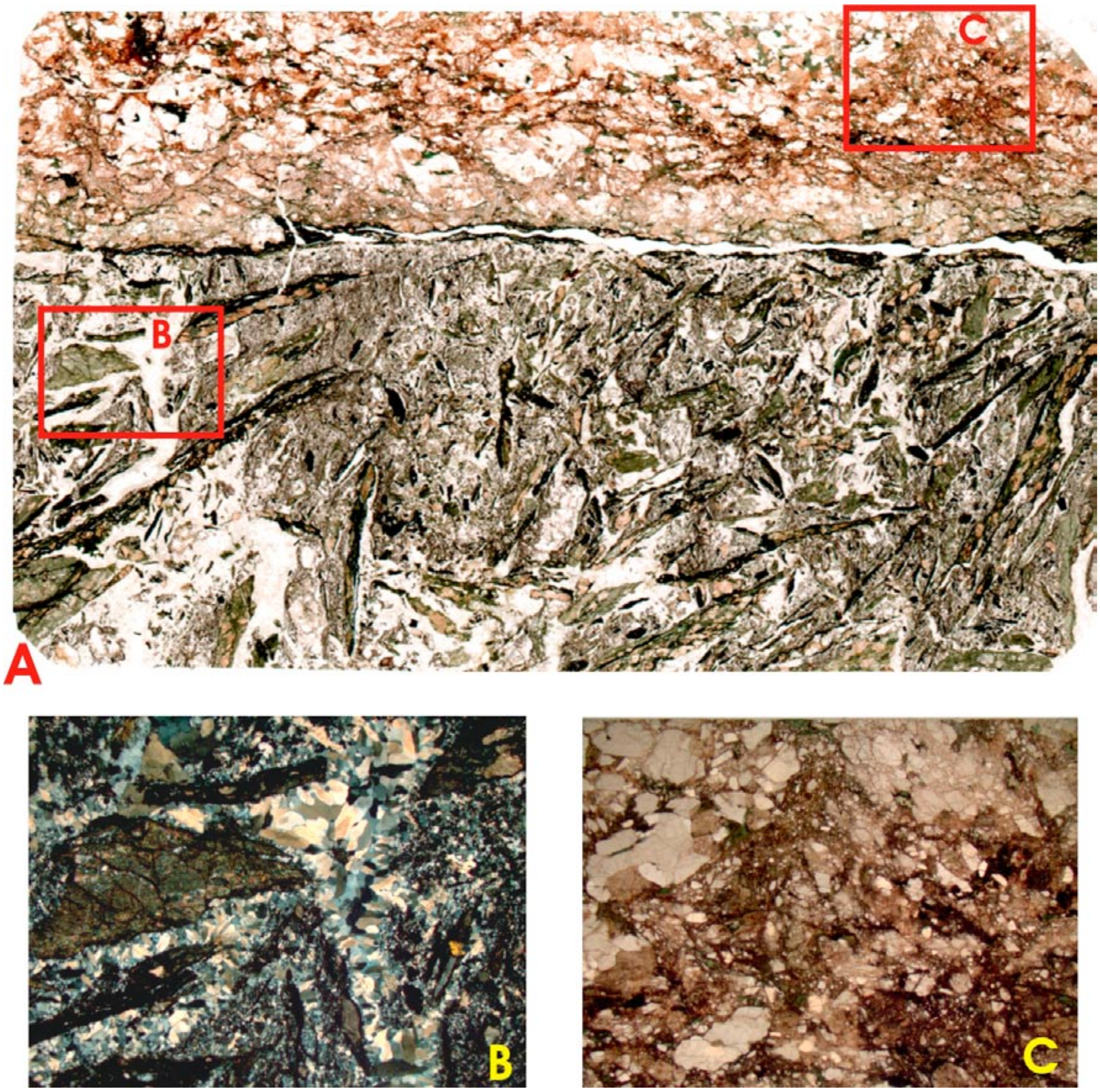
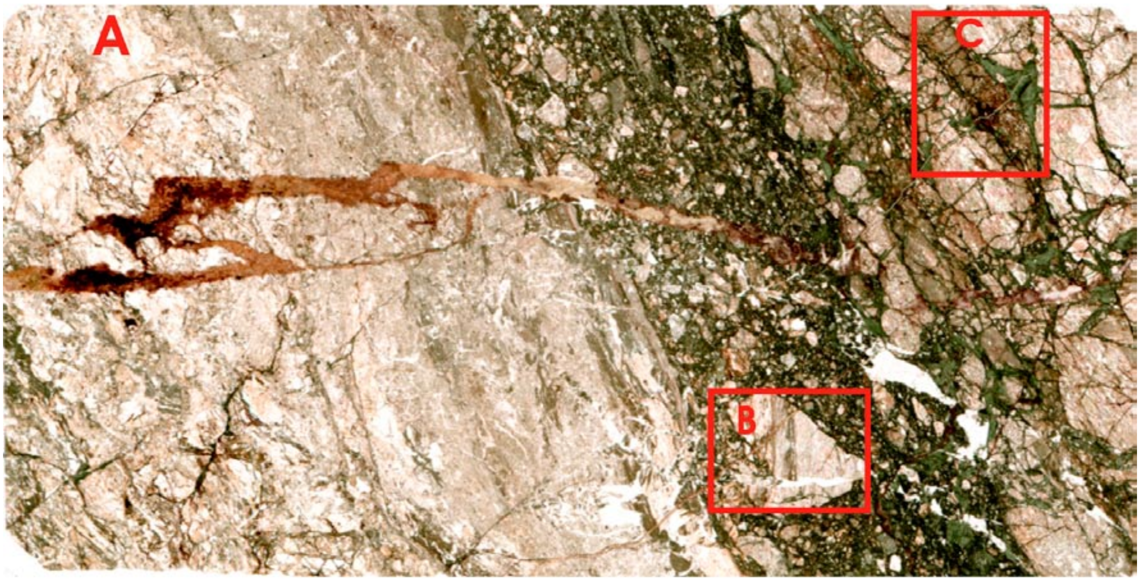


Figure 5-41. *Scanned thin section (A) and photomicrographs (B and C) of sample KFM12A_212.9. The thin section (width of view is 35 mm) shows foliated metagranite (above) that is variably deformed and converted to cataclasite (C). The lower part of the thin section shows angular clasts of cataclasite with some dark elongate fragments enriched in hematite. Pale vein-like features are sealed with euhedral quartz that appears to have grown on the walls of open fractures and voids in the fault rock (B).*



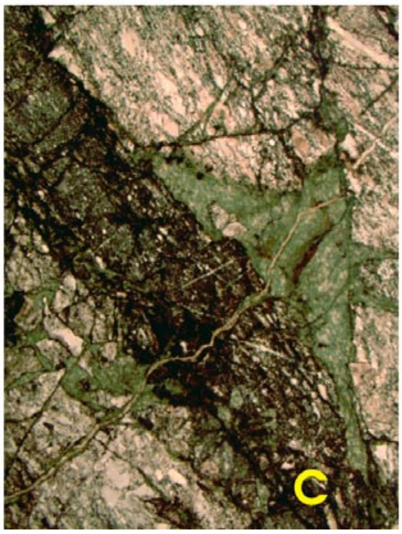


Figure 5-42. *Scanned thin section (A) and photomicrographs (B and C) of sample KFM12A_223.95. The thin section (width of view is 39 mm) shows a variety of proto-cataclasites, cataclasites and ultra-cataclasites that are cut by laumontite-rich veins (left-hand part of A). In the central-right part, the sample consists of a second-generation cataclasite that contains fragments of proto-mylonite and an earlier formed cataclasite in a dark greenish, fine-grained groundmass. The enlarged view (B) shows angular fragments in fine-grained cataclasite cut by pale quartz vein and a late vein with laumontite (L). In the right-hand part of the thin section, the host rock is mylonitic with thin fractures sealed with oxides (?) that are post-dated by fractures sealed with green chlorite (C). Chlorite-sealed fractures are cut by a hairline vein (C).*

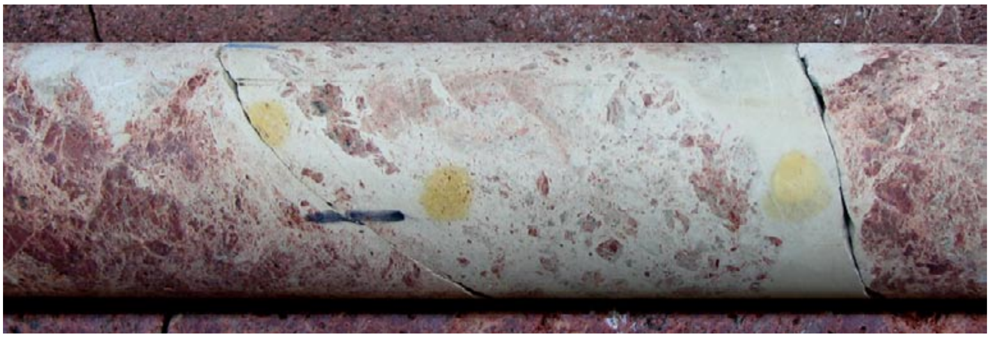


***Figure 5-43.** Photograph of drill core KFM12A, DZ2, at ca 232.2 m showing a 12 cm wide pale green cataclasite with fragments of reddish fault rock.*

The central part of DZ2 (240–300 m) is illustrated in Figure 5-44. From about 240 m, the fracture frequency shows once again generally higher values, although short intervals of drill core have less abundant fractures (Figure 5-44). This pattern persists through the following 100 m of drill core KFM12A. The entire interval from 240 to 300 m contains fractures with laumontite and calcite, in some cases associated with minor development of fault breccia and cataclasite. The breccias are usually narrow (10–40 mm), e.g. at ca 252–256 m (Figure 5-45), at 273.5 m and ca 278 m. These sealed fractures post-date fractures coated and/or sealed with chlorite, clay minerals and hematite. A steep SE-striking fault with chlorite striation and laumontite steps occurs in this interval (Figure 5-46). A crush zone with chlorite and clay mineral coating occurs at 274–275.5 m (Figure 5-47). This zone constitutes a fault core (Figure 5-44). Some minor crush zones (< 5–10 cm) are also present.

At ca 283 m there is a shift in rock types and appearance of the drill core. Below this level, there are mainly fine-grained mafic to intermediate rocks with local reddish alteration. Epidote commonly occurs as a metamorphic mineral or alteration product.

At 287 m, reddish green breccia and cataclasite with chlorite are cut by fractures filled or coated with chlorite, clay minerals and calcite (Figure 5-48). At 293–294 m, there are several narrow, fractured zones with some dark greenish cataclasite that contain angular reddish clasts. Epidote alteration is pronounced at ca 299 m.

Considered as a whole, the interval 240–300 m is a transition zone with a pronounced crush zone at 274–275.5 m that represents fault core.

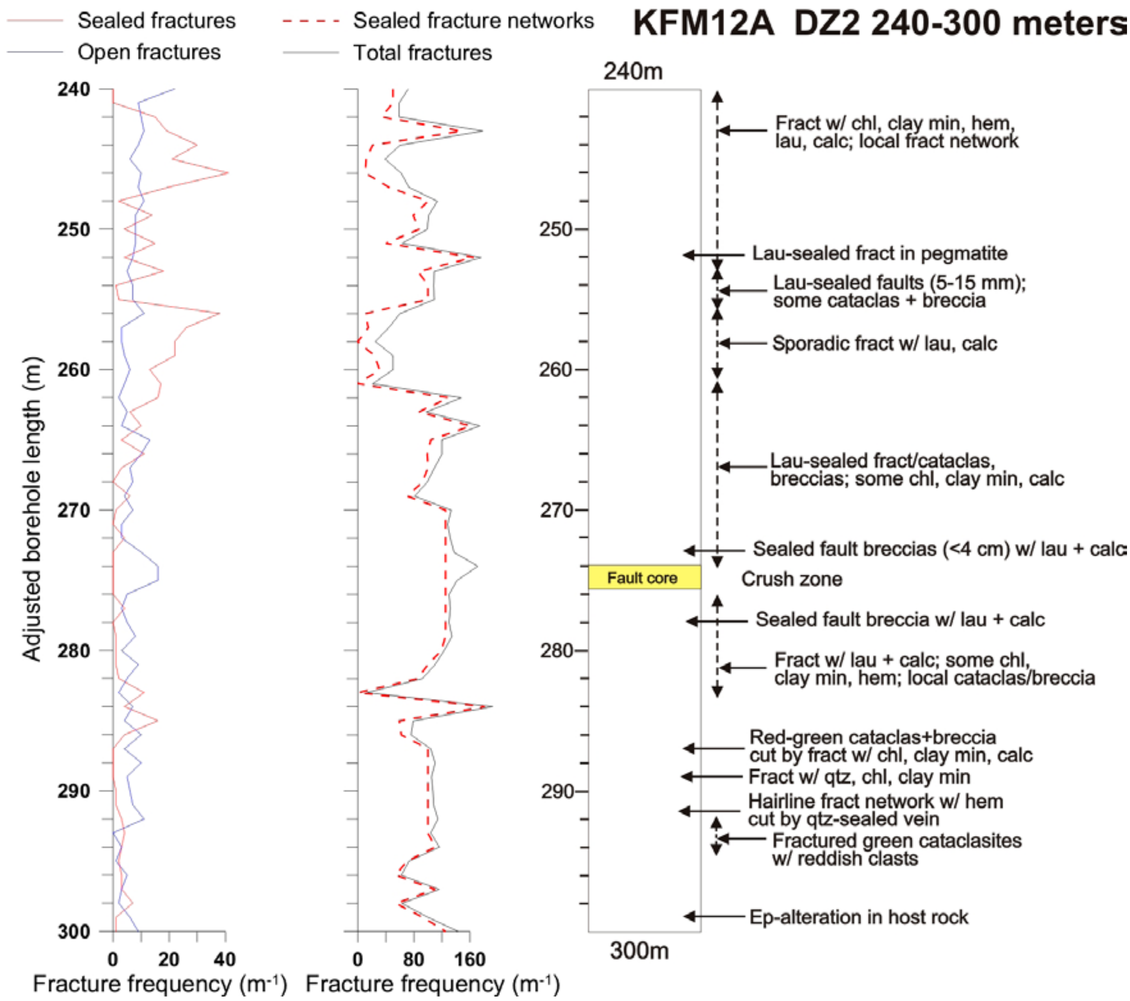


***Figure 5-44.** Simplified drawing of the lower part of DZ2 (240–300 m) showing the most prominent brittle structures in the zone. Abbreviations as in Figure 5-3.*

***Figure 5-45.** Example of drill core from DZ2 of KFM12A (ca 252–254 m). Faults sealed with laumontite and calcite are present. In general, these brittle structures post-date fractures coated and/or sealed with chlorite, clay minerals and hematite.*

Figure 5-46. *Photograph illustrating fault surface observed in DZ2 of KFM12A. Chlorite striation and steps with laumontite provides kinematic data (253.78 m, strike/dip and pitch: 132/85–72).*

Figure 5-47. *Photograph showing oxidized pegmatite and metagranite from DZ2. A significant crush zone forming a fault core is present at 274–275.5 m. The fractures are coated with chlorite and clay minerals.*

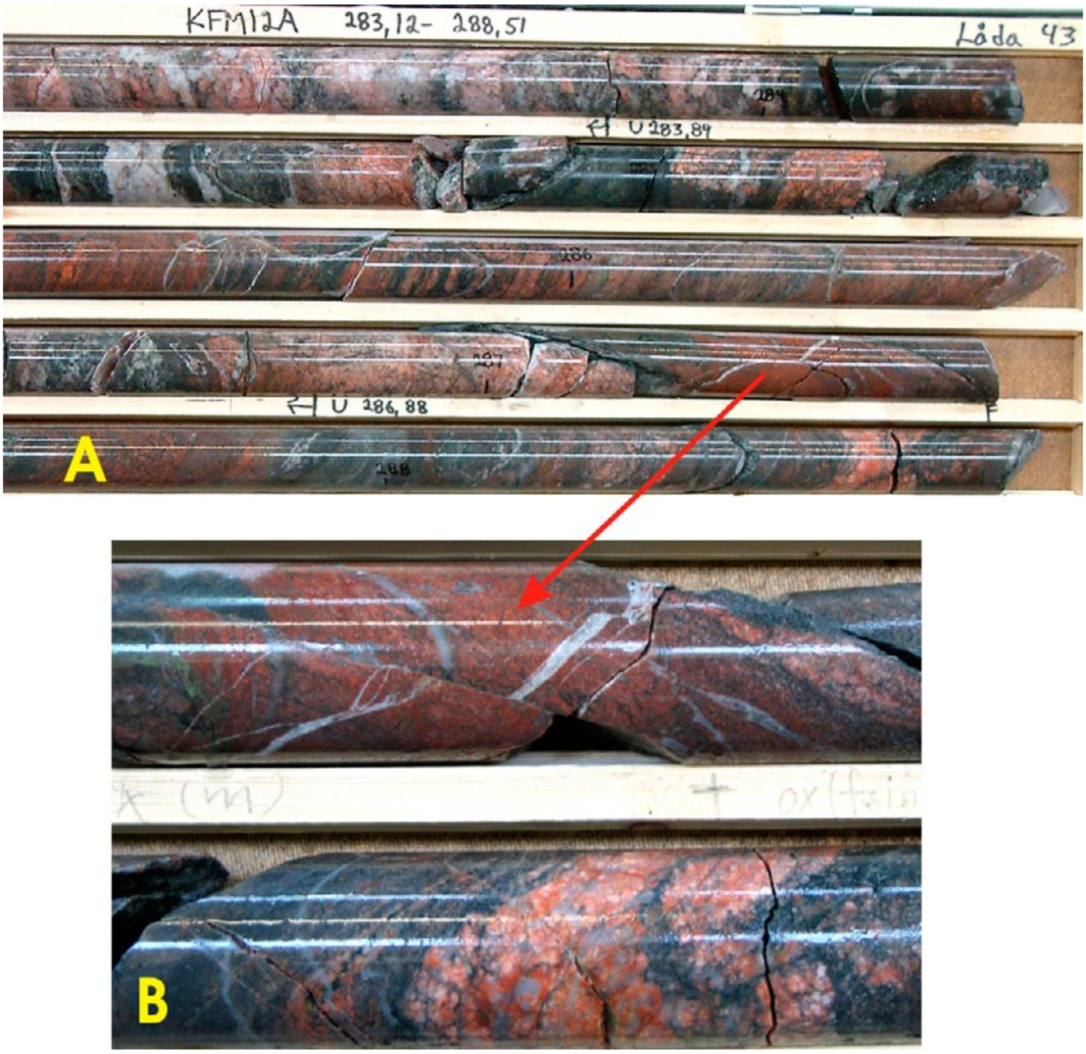


Figure 5-48. *Photograph showing drill core from DZ2 at ca 285–290 m (A). At ca 287.3 m (B) reddish green breccia and cataclasite with chlorite are cut by veins sealed with quartz and calcite (white). These veins are offset by fractures coated with chlorite, clay minerals and minor calcite.*

The lower part of DZ2 (300–402 m) is illustrated in Figure 5-49. The upper part of this section (300–312 m) is a transition zone /Munier et al. 2003/.

302–305.5 m: Reddish to greenish host rock alteration; fracture network and (proto)-cataclasite sealed with epidote + chlorite, and cut by hematite- and calcite-sealed fractures. Few broken fractures are present.

308–310.5 m: Occurrences of epidote-sealed proto-breccia with local cataclasite containing some chlorite that are cut by hairline veins sealed with hematite + quartz. Chlorite, clay minerals, quartz and pyrite are present on broken fractures.

312–ca 314 m: Oxidised host rock with proto-breccia, in places dense sealed fracture network with epidote, chlorite and some quartz; locally hematite-altered sheared fault rock and gouge (up to 1 cm wide).

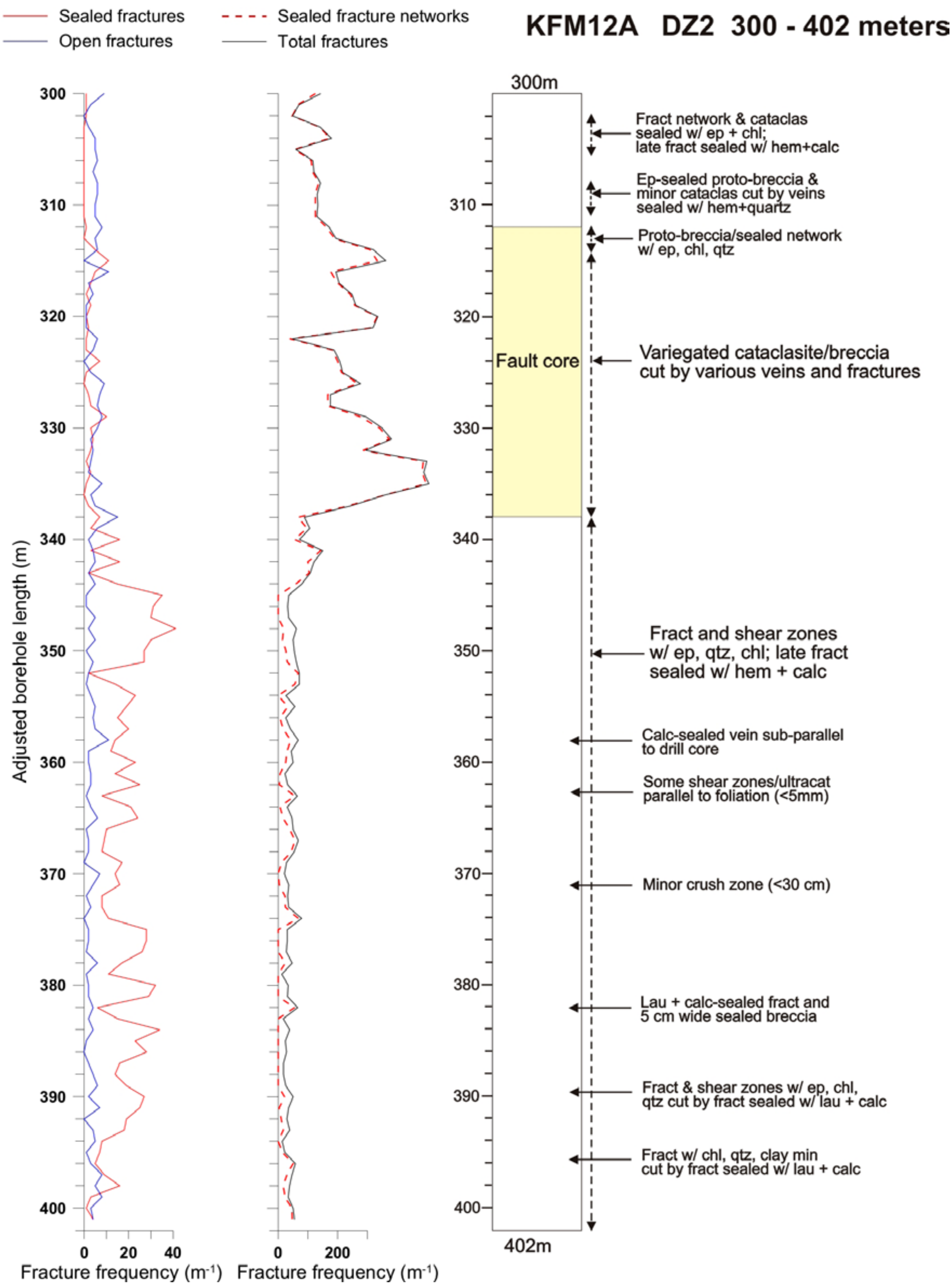


Figure 5-49. *Simplified drawing of the lower part of DZ2 (300–402 m) showing the most prominent brittle structures in the zone. Abbreviations as in Figure 5-3.*

The interval 314–338 m consists of virtually 100% proto-cataclasite, cataclasite, fault breccia and minor ultra-cataclasite occurring in up to 20 mm wide zones (Figure 5-51). Colors are variable in shades of pale green, pink, grey and reddish. Strong oxidation and epidote-alteration combined with pronounced grain-size reduction generally prevents recognition of the original host rock. The fault rocks are cut by later veins and fractures, including local networks of quartz veins, veins sealed with laumontite and calcite, and fractures with chlorite, clay minerals, hematite, calcite and pyrite. Greenish ultra-cataclasite and cataclasite cut by calcite-sealed veins occurs at ca 314 m (sample KFM12A_314.0; Figure 5-50).

The entire section from 312 to 338 m is dominated by fault rocks (Figure 5-51) and is defined as a fault core /Munier et al. 2003/. Four striated faults were recorded in this interval. At ca 338 m there is a quite abrupt transition to a strongly foliated, interlayered complex of metagranite, amphibolite and pegmatite that continue to the base of the DZ. Brittle deformation products are notably less abundant and fairly evenly distributed (Figure 5-49). Sealed fractures predominate.

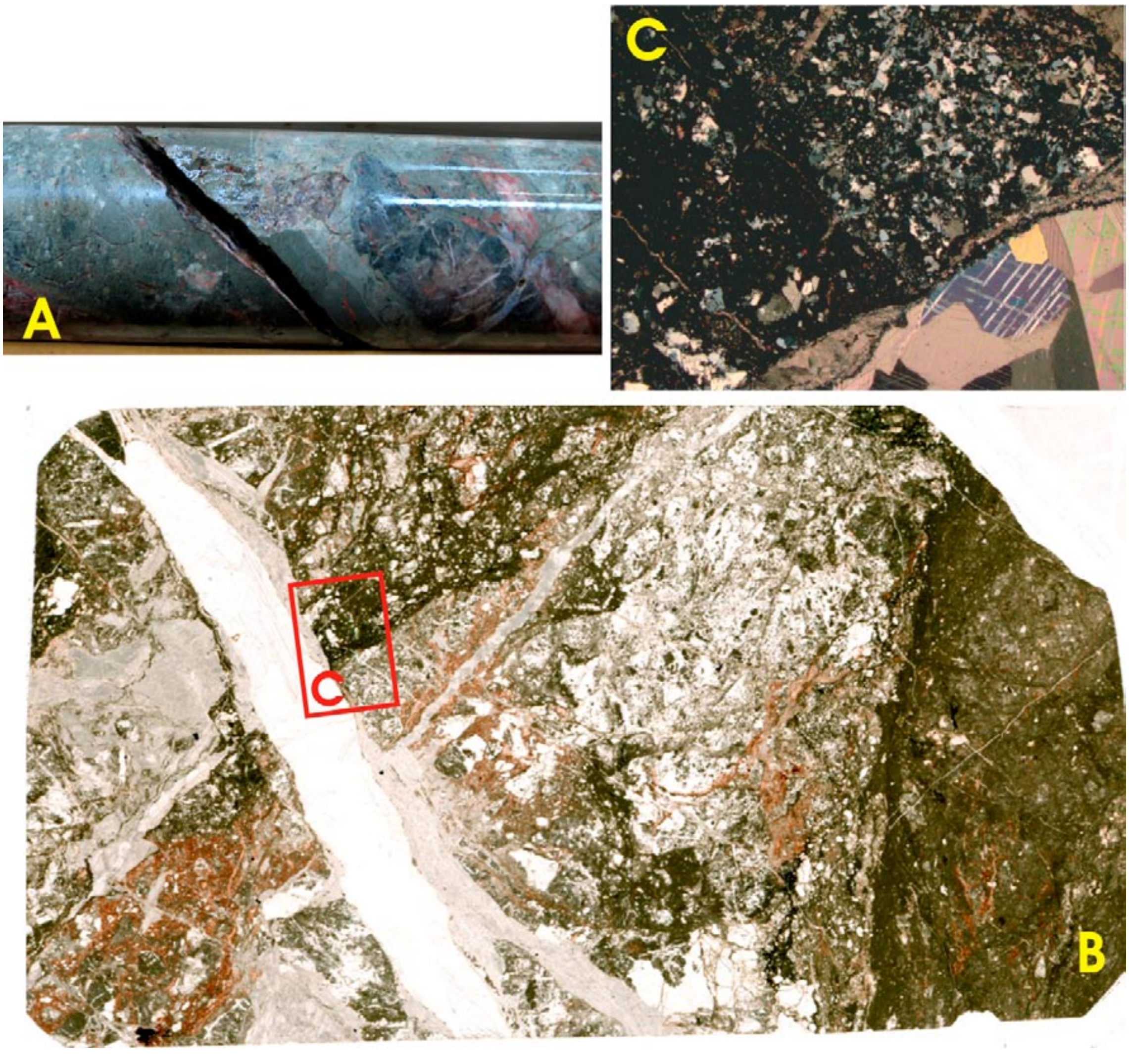


Figure 5-50. *Section of drill core (A), scanned thin section (B) and photomicrographs (C) of sample KFM12A_314.0. The drill core and thin section (width of view is 38 mm) shows different types of cataclasite that are cut by two generations of calcite veins. The first generation is deformed (grey in B), and is cut by a vein with euhedral, undeformed calcite (A, B and C).*

Figure 5-51. *Photograph showing drill core from DZ2 at ca 315–326 m. The drill core consists of greenish, reddish and grey proto-cataclasite, cataclasite and fault breccia. Minor ultra-cataclasite occurs in up to 20 mm wide zones.*

Locally, there are some thin (< 5 mm) shear zones and ultra-cataclasites that are oriented parallel to the foliation in the host rock. Fractures and some shear zones with epidote, chlorite and quartz are cut by fractures sealed with mainly laumontite and calcite. A minor crush zone occurs at ca 370.5 m. The interval 338–402 m is considered a transition zone according to the definition of /Munier et al. 2003/.

33 fault slip data were collected along DZ2 in drill core KFM12A (Figure 5-52). Chlorite, hematite and clay minerals on the fault surfaces are striated or/and polished. Laumontite and calcite steps are present in some cases and allow determination of the sense of shear.

A major set of faults is oriented NW-SE parallel to the trend of the Forsmark deformation zone (A on Figure 5-52). Shear zones along this trend exhibit variable sense of movement. Normal to highly oblique normal faults (B on Figure 5-52), and less abundant reverse to highly oblique reverse faults are present (C on Figure 5-52). A smaller population of dextral and sinistral faults also occurs (D and E on Figure 5-52). The variation in shear sense probably records periodic reactivation along the regional fault and shear zone. Some E-W trending gently-dipping fault planes are present; one north-dipping with reverse striae (C on Figure 5-52), and some south-dipping fault planes with undetermined sense of shear (G on Figure 5-52).

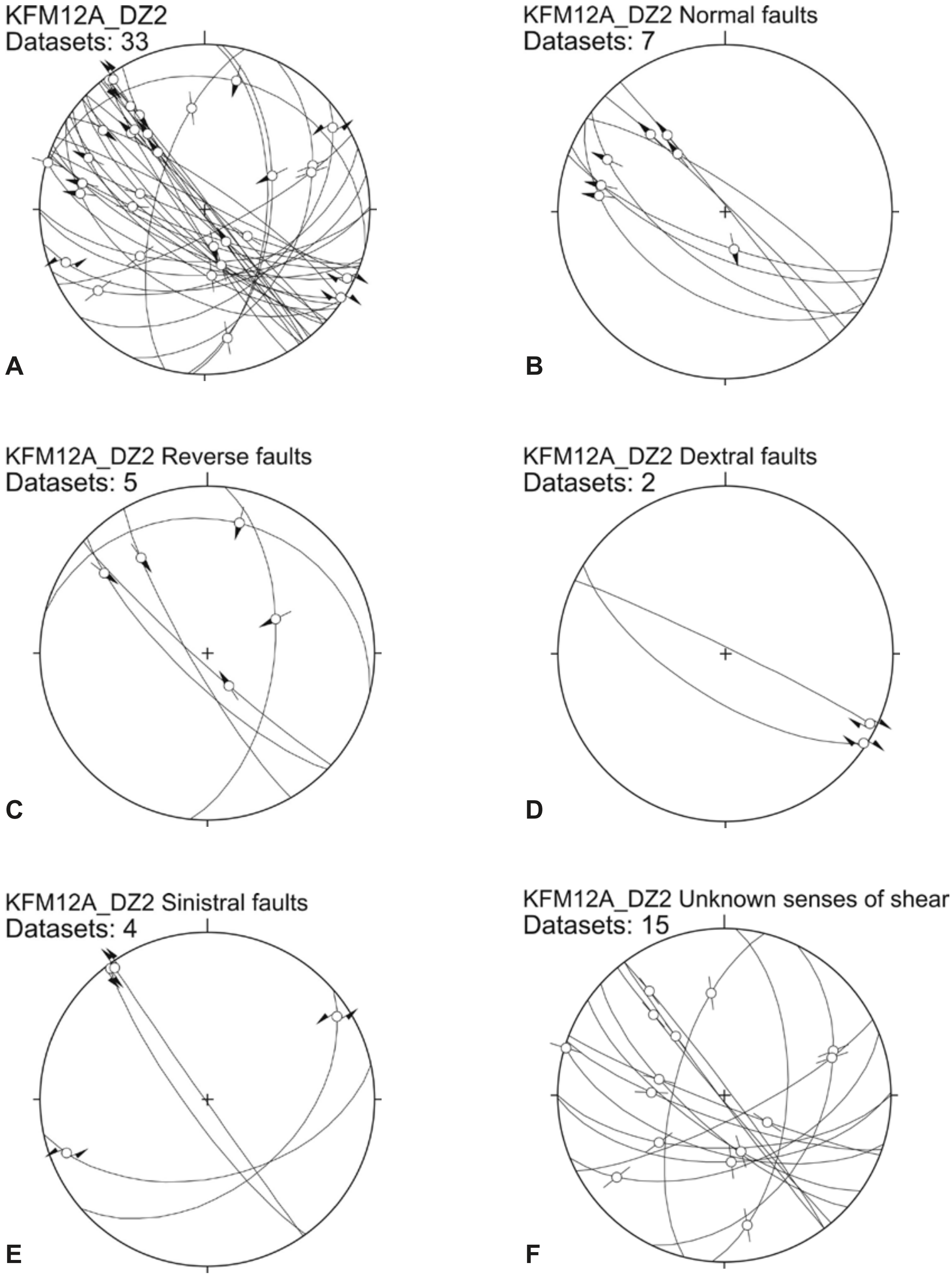


Figure 5-52. *Stereoplots of fault slip data in DZ2 (KFM12A).*

KFM12A: 513–523 m – DZ3

The rock types in this zone are fine- to medium-grained granite and metagranodiorite. The zone exhibits increased frequency of sealed and open fractures. The factures dip moderately to the south to southwest, however, flat to gently dipping fractures are also present. A crush zone occurs in the upper part of the zone at ca 515 m (Figure 5-53). The most frequent fracture-filling minerals include chlorite, calcite and some hematite and adularia. DZ3 is a transition zone according to the definition of /Munier et al. 2003/. Striated faults were not observed in DZ3.

5.1.6 Ductile deformation

The candidate investigation area at Forsmark (Figure 5-1) constitutes a tectonic lens with marginal belts high-strain belts that exhibit stronger ductile deformation /Stephens et al. 2007, Hermansson et al. 2007/. An attempt was made to study the strong ductile deformation in the interval 60–145 m in KFM12A based on the nature and orientation of the fabric observed in the drill core. The drill core in the interval is oriented 036/60. The rock type is metagranodiorite-metatonalite with pink, augen-shaped K-feldspar megacrysts that are aligned within the penetrative, ductile planar fabric. Flattened and recrystallized grains of feldspar, quartz and oriented flakes of biotite define the fabric, which is ubiquitous and fairly uniform throughout the studied core section. It is clear that the fabric is of LS-type with a well-defined direction of elongation. The general attitude of the fabric can be deduced using thin bands of foliation-parallel amphibolite that are easily recognized on the BIPS-image. Some measurements obtained in the interval 90–120 m (117/80, 120/75, 120/80) show that the fabric is dipping steeply to the SSW. The lineation direction is approximately down dip; i.e. the lineation plunges steeply to the south. Some evidence of shear (rotational strain) is locally observed (Figure 5-54), however, the general asymmetry of megacrysts and poorly defined shear bands are uncertain and does not allow the sense of shear to be determined.

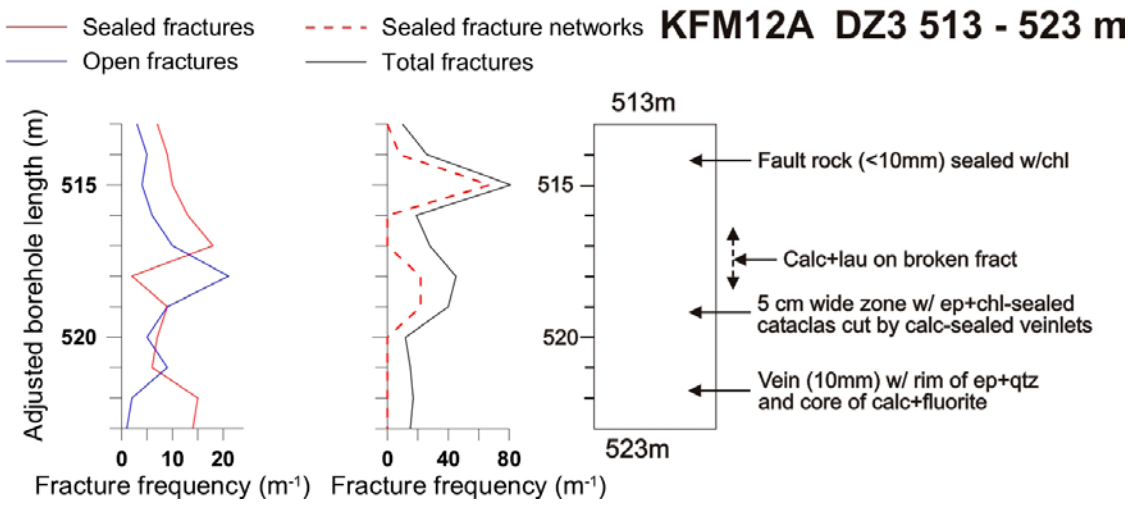


Figure 5-53. *Simplified drawing of DZ3. Abbreviations as in Figure 5-3.*

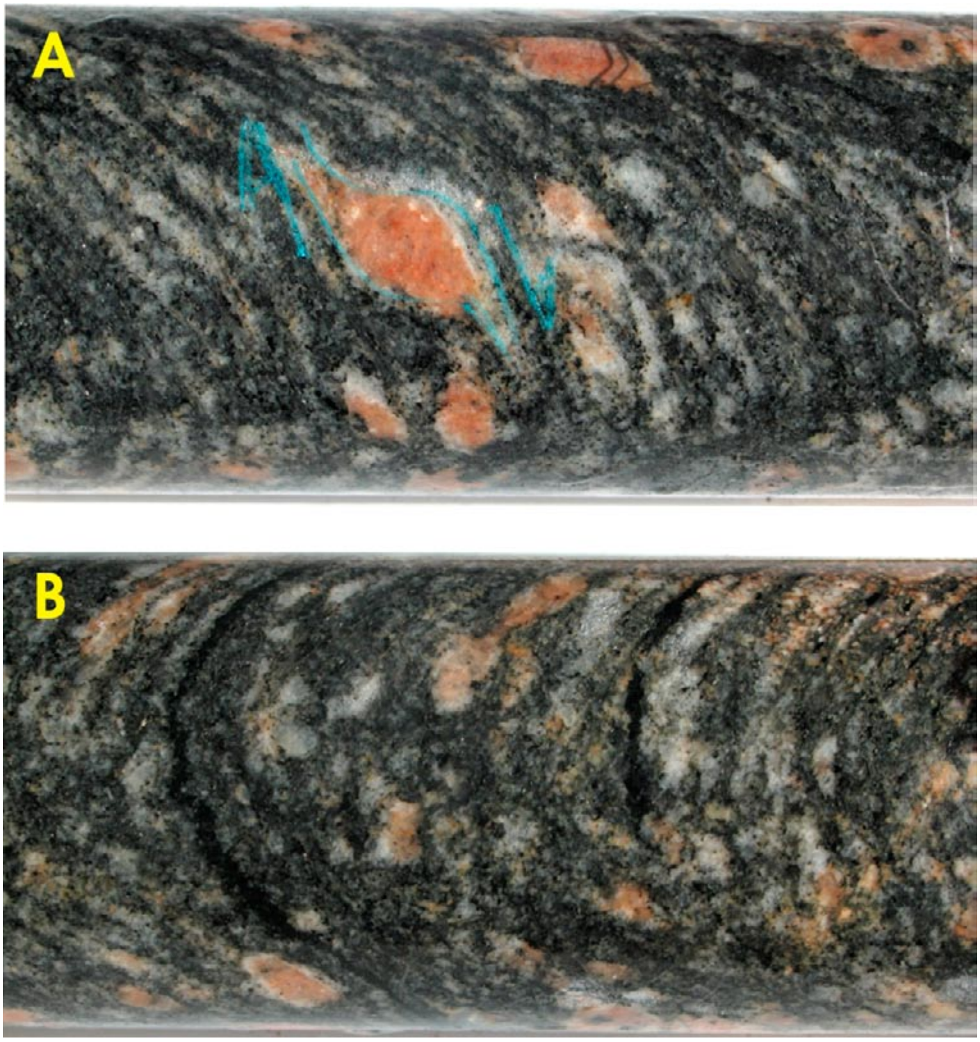


Figure 5-54. *Photographs of drill core KFM12A. A) Section normal to the foliation and parallel to the lineation. The asymmetry K-feldspar augen suggests rotational strain. B) Section at 90 degrees to that shown in A. Note the contrasting nature of the fabric providing evidence of a marked lineation in the rock.*

5.2 Summary of the results of the borehole data

Four boreholes (KFM02B, KFM08D, KFM11A and KFM12A) have been investigated. KFM02B and KFM08D are situated in different geographic locations within the investigation area (Figure 5-1). KFM11A is directed towards the northwest with the aim of obtaining data on the regional Singö deformation zone. KFM12A is located to the southwest of the investigation area and penetrates the regional Forsmark deformation zone. Both the Singö and Forsmark deformation zones are oriented approximately WNW-ESE; i.e. at a small angle to to the Eckardfjärden deformation zone that runs sub-parallel and adjacent to the southwestern boundary of the investigation area.

Relatively few kinematic data were obtained from KFM02B and KFM08D. In both drill cores, a population of NE-SW, steep to gently SE-dipping faults are present. Slickensides on these faults show strike-slip, oblique-slip and dip-parallel movement. A couple of gently south-dipping faults (KFM08D) exhibit reverse sense of shear. With the exception of short interval of fault core in DZ12 of KFM08D, all the inspected deformation zones in KFM02B and KFM08D are considered transition zones.

In KFM11A (the Singö deformation zone), kinematic data were obtained from 46 faults were observed within the part of DZ1 that was investigated. By far the most abundant fault population strikes NW-SE to WNW-ESE. Strike-slip faults parallel to the Singö deformation zone show both dextral and sinistral sense of movement. Dip-slip and oblique-slip faults that exhibit reverse and normal movement are present. In addition, faults with undetermined shear sense are recorded along this trend. Taken together, these observations would imply that the Singö deformation zone was reactivated under successive and contrasting stress regimes. In KFM11A there are also some variably oriented, gently-dipping fault planes that show reverse movement. The striations on these faults are oriented close to N-S and may thus record a N-S compression event. A few variably oriented normal faults show disparate orientations. The upper (498–528 m) and lower (574–629 m) sections of the investigated part of DZ1 are classified as fault core separated by a central transition zone (578–574 m). On a regional scale, the fault core intervals separated by a transition zone may represent the anastomosing geometry of the larger Singö deformation zone.

The steep NW-SE- to WNW-ESE-striking set of faults is also observed in DZ1 and DZ2 of drill core KFM12A (the Forsmark deformation zone). Faults along this trend again reveal variable sense of movement. Normal to highly oblique normal faults, and less abundant reverse to highly oblique reverse faults are present. A smaller population of dextral and sinistral faults also occurs. The variation in shear sense probably records periodic reactivation along the regional fault and shear zone. Some faults dip to the east, southeast and south and have variable shear sense. Short intervals of fault core are present within the upper parts of DZ2. A prominent fault core composed of variegated cataclasite and fault breccia cut by a variety of veins and fractures is intersected at 312–338 m. The remaining part of DZ2 and the entire intervals of DZ1 and DZ3 are considered transition zones.

The predominant set of NW to WNW steep faults has also been documented in several boreholes during the earlier phases of the study /Nordgulen and Saintot 2006, Saintot and Nordgulen 2007/. Thus, the data obtained from KFM11A and KFM12A support the regional significance of this fault system; see also /Stephens et al. 2007/.

A minor population of gently dipping faults trending E-W to NE-SW occur in some of the studied deformation zones. They are reminiscent of the important population of reverse faults identified during the first phase of the study, especially in KFM02A /Nordgulen and Saintot 2006/. As such, they may also represent faults similar to those imaged as the large seismic reflectors interpreted as thrusts by /Juhlin and Stephens 2006/.

Among the oldest observed fractures are the epidote- and quartz-sealed fractures and fracture networks with some chlorite. Striated fault surfaces are commonly coated with chlorite and hematite, and steps defined by calcite and laumontite allow determination of the sense of movement on many faults. Chlorite- and hematite-coated faults are commonly reactivated and/or cut by faults and fractures with laumontite, calcite, and less commonly adularia and prehnite. In some cases, these minerals have sealed breccias and cataclasites. Late fracture minerals include quartz, calcite, prehnite, pyrite and clay minerals. These observations corroborate the findings from the earlier phases of this study and provide further evidence that the main faults and fracture systems have been reactivated and coated/filled with a variety of minerals in response to changes in hydrothermal regime and stress conditions.

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Appendix 1

ID	Adjusted secup	Possible DZ	Sample
KFM12A	202.9	DZ2	Metagranite cut by shear zones and cataclasites
KFM12A	204.9	DZ2	Metagranite cut by cataclasites
KFM12A	212.9	DZ2	Metagranite cut by cataclasites
KFM12A	223.95	DZ2	Cataclasite cut by laumontite vein
KFM12A	314.0	DZ2	Greenish cataclasite with calcite vein