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Fracture mineralogy

Results from drill core KLX15A

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Keywords: Fracture minerals, Laxemar, Sequence of mineralization, Relative dating, SEM-EDS.

Abstract

The drill core KLX15A from the Laxemar subarea has been sampled for studies of the fracture mineralogy. Earlier studies in the Laxemar subarea have been carried out on cored boreholes KLX02 /e.g. Drake and Tullborg 2005/, KLX03, KLX04, KLX06, KLX07A, KLX08 and KLX10 /Drake and Tullborg 2007/. Of these, only KLX03 and KLX10 are drilled in the focused area for the final repository of spent nuclear fuel within the Laxemar subarea /SKB 2006/. The aim of the current study is to obtain more information of the fracture fillings present in the focused area, in which KLX15A is drilled, and to compare the features and characteristics of these fracture fillings to the results from the earlier investigated bore holes within the subarea.

In order to investigate the features of the fracture fillings and their relative relations 5 thin sections and 4 fracture surface samples have been analysed using petrographic microscope and scanning electron microscope (SEM-EDS). Additional samples were investigated using hand lens and stereo microscope.

The relative sequence of fracture fillings in KLX15A is very similar to earlier reported results from the Laxemar subarea /Drake and Tullborg 2005, 2007/. In /Drake and Tullborg 2007/ a subdivision of the fracture fillings into major fracture filling generations was made. Minerals representing these generations are present in KLX15A, although the abundance of each generation differs between KLX15A and the other boreholes. Generation 4 fractures have been difficult to distinguish since isotopic data are lacking.

The general sequence of fracture fillings in KLX15A, in common with the other studied boreholes are as follows: Epidote– and quartz-rich mylonite is oldest and is often re-activated by cataclasite and later formed brittle fractures. The formation temperatures of the different generations of fracture fillings are successively lower with time, indicated by early formed epidote followed by minerals of lower formation temperature like prehnite and even later zeolites (laumontite and later harmotome). The earliest deformation in the area (mylonites – Generation 1, cataclasites – Generation 2 and fractures filled with epidote, calcite, quartz, fluorite, prehnite and early formed laumontite – Generation 3) are Pre-Cambrian (older than 1,400 Ma, /Drake et al. 2007/). Red-staining adjacent to these fractures is common (but not as common in KLX15A as in e.g. KLX04 and KLX10). Discrete mylonite zones and/or cataclasite zones (< 1 dm wide) are quite common in KLX15A. Generation 4 fractures (e.g. calcite) are also Pre-Cambrian. The fracture mineralization of calcite, fluorite, pyrite, gypsum, barite, apophyllite and harmotome is Phanerozoic (mainly Paleozoic, Generation 5 /Drake et al. 2007/). Generation 5 fractures are less frequently observed in KLX15A, compared to other boreholes within the subarea and the minerals gypsum, harmotome, apophyllite and fluorite are less frequent in KLX15A than in other parts of the Laxemar subarea. Fracture minerals formed later than the Paleozoic (possibly until Quaternary) are mainly calcite, pyrite, clay minerals and Fe-oxyhydroxides in open fractures. This calcite has varying morphologies (scalenohedral, equant, needle shaped and nailhead shaped), which might reflect precipitation from fluids of different salinities.

Sammanfattning

Sprickmineralogiska undersökningar har utförts på prover från det djupa kärnborrhålet KLX15A, Laxemar. Sprickmineralstudier har tidigare bedrivits på prover från borrhål KLX02 /t ex Drake och Tullborg 2005/, KLX03, KLX04, KLX06, KLX07A, KLX08 och KLX10 /Drake och Tullborg 2007/. Av dessa borrhål är endast KLX03 och KLX10 borrade i det område som nu är i fokus för ett slutförvar av använt kärnbränsle /SKB 2006/. Syftet med denna studie är att utöka kunskapen om sprickfyllningar i det fokuserade området, i vilket KLX15A är borrat, och att jämföra resultaten med tidigare studier i delområde Laxemar.

Fem tunnslip från läkta sprickor och fyra sprickytor från öppna sprickor har undersökts med petrografiskt mikroskop och svepelektronmikroskop för att utröna karaktärsdrag och relativa relationer mellan olika sprickfyllningar. Ytterliggare ett antal prover har undersökts med stereomikroskop och lupp.

Den relativa sekvensen av sprickfyllnader i KLX15A är mycket lik den som tidigare rapporterats från delområde Laxemar /Drake och Tullborg 2005 2007/. I /Drake och Tullborg 2007/ delades sprickfyllningarna upp i ett antal huvudgenerationer. Mineral från alla dessa generationer har observerats i KLX15A (även om Generation 4 är svår att urskilja utan isotopdata). Mängden mineral i olika generationer i KLX15A skiljer sig dock något från en del av de andra borrhålen i delområde Laxemar. Den generella sprickmineralsekvensen i KLX15A och i övriga delområde Laxemar är som följer: Epidot– och kvartsrik mylonit är tidigast bildad och har ofta blivit reaktiverad av senare bildad kataklasit och senare spröda sprickor. De olika generationerna har successivt lägre bildningstemperaturer; från tidigt bildad epidot, som följs av mineral med lägre bildningstemperatur som prehnit och ännu senare zeoliter (laumontit och harmotom). Den tidigaste deformationen i området (mylonit – Generation 1, kataklasit – Generation 2, och sprickor läkta av epidot, prehnit och tidigt bildad laumontit – Generation 3) är med högsta sannolikhet prekambriska (äldre än 1 400 Ma /Drake et al. 2007/). Rödfärgning längs dessa sprickor är vanlig (men inte lika vanlig som i t ex KLX04 och KLX10). I KLX15A är det ganska vanligt med diskreta zoner av mylonit och/eller kataklasit med en bredd på ett par centimeter till ett par decimeter. Generation 4 är även den prekambrisk. Generationen av sprickor läkta av t.ex. kalcit, fluorit, pyrit, gips, baryt, apofyllit och harmotom är sannolikt paleozoisk /Drake et al. 2007/. Sprickor tillhörande Generation 5 är inte lika vanliga i KLX15A som i övriga borrhål i delområde Laxemar. Exempelvis är fluorit, gips, apofyllit och harmotom inte lika frekvent förekommande som i området i övrigt. Sprickmineral som bildats senare än paleozoikum (möjligen under kvartärtiden) är mestadels kalcit, pyrit, lermineral och ytnära Fe-oxyhydroxider i öppna sprickor. Denna kalcit har varierande morfologi vilket kan tyda på utfällning från vatten med varierande salthalt.

Contents

1 Introduction

The drill core KLX15A from the Laxemar subarea has been sampled for studies of the fracture mineralogy. Earlier studies in the Laxemar subarea have been carried out on cored boreholes KLX02 /e.g. Drake and Tullborg 2005/, KLX03, KLX04, KLX06, KLX07A, KLX08 and KLX10 /Drake and Tullborg 2007/, see Figure 1-1. Of these, only KLX03 and KLX10 are drilled in the focused area for the final repository of spent nuclear fuel within the Laxemar subarea /SKB 2006/. The aim of the current study is to obtain more information of the fracture fillings present in the focused area, in which KLX15A is drilled, and to compare the features and characteristics of these fracture fillings to the results from the earlier investigated bore holes within the subarea.

In order to investigate the features of the fracture fillings and their relative relations 5 thin sections and 4 fracture surface samples have been analysed using petrographic microscope and scanning electron microscope (SEM-EDS).

The work was carried out in accordance with activity plans SKB PS 400–06–132. In Table 1-1 the controlling documents for performing this activity are listed. Both the activity plan and the method description are SKB's internal controlling documents.

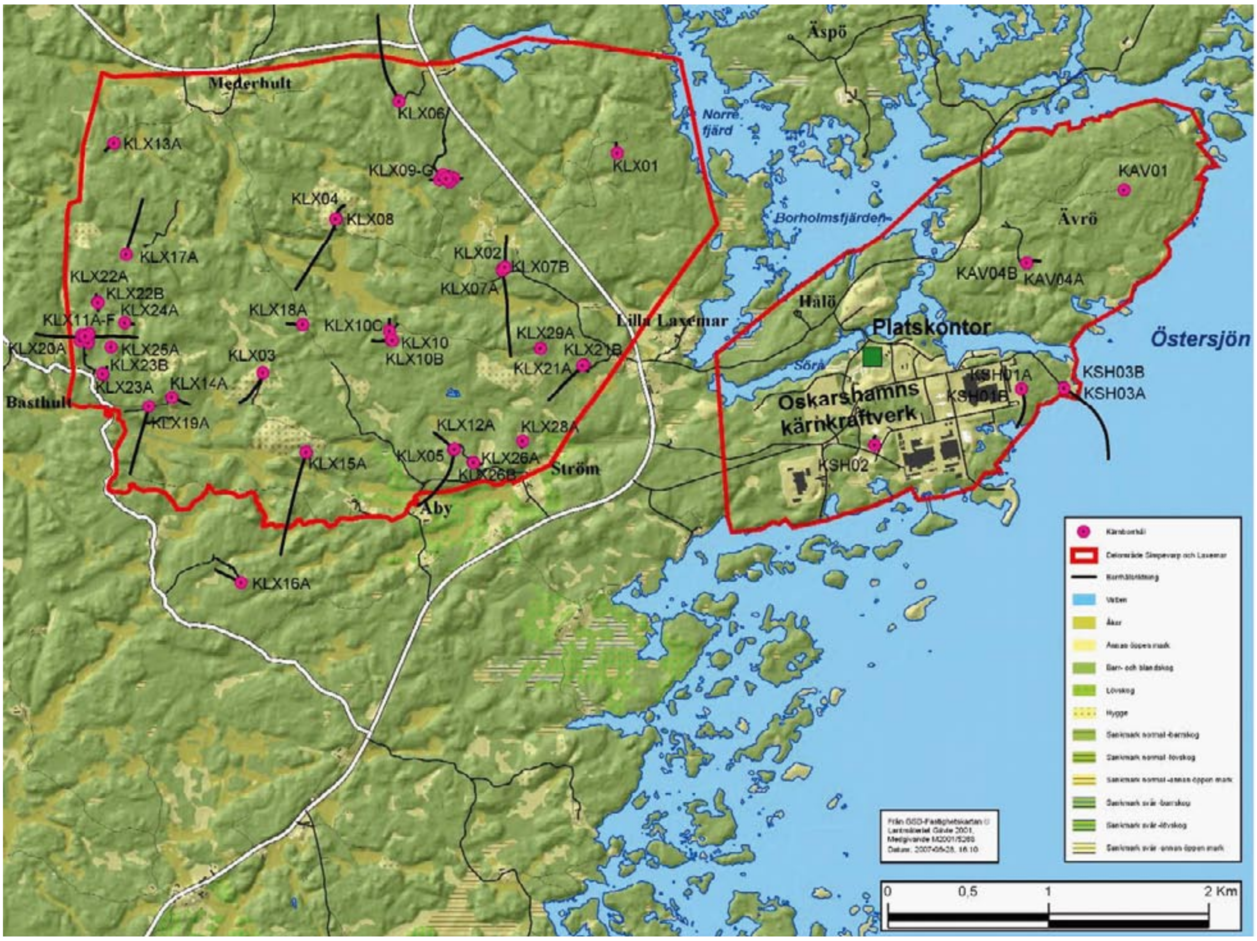

Figure 1-1. Map showing the location and projection of the cored boreholes in the Laxemar subarea (left) and the Simpevarp subarea (right).

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

Activity plan	Number	Version
Sprickmineralogiska undersökningar*	AP PS 400-06-132	1.0
Method descriptions	**Number**	**Version**
Sprickmineralanalys	SKB MD 144.001	1.0

*I KLX13A, KLX19A, KLX20A och KLX26A, samt i tillägg 1 och 2.

2 Objective and scope

The aim of this study is to obtain a detailed description, including mineralogy and mineral chemistry of fracture fillings from the cored borehole KLX15A (in the focused area), and to compare these features with results from other studies in the Laxemar subarea (mainly outside the focused area) /Drake and Tullborg 2005, 2007/.

3 Geological background

The bedrock in the Simpevarp/Laxemar area north of Oskarshamn is dominated by Småland granitoids and dioritoids of the Transscandinavian Igneous Belt (TIB) e.g. /Gaal and Gorbatschev 1987, Kornfält and Wikman 1987, Kornfält et al. 1997, Wahlgren et al. 2004/. The Småland granitoids in the Simpevarp/Laxemar/Äspö area belong to the TIB 1 suite /Larson and Berglund 1992, Åhäll and Larson 2000/ and have been dated with U-Pb-dating to 1,804 ± 4 Ma (zircon) /Kornfält et al. 1997/ and 1,802 ± 4 Ma (zircon), 1,793 ± 4 (titanite) and 1,800 ± 4 Ma (titanite and zircon) /Wahlgren et al. 2004/. Other intrusions are e.g. Götemar /Kresten and Chyssler 1976, Åberg et al. 1984/ and Uthammar. These coarse-grained granites were emplaced at c. 1.45–1.44 Ga /Åhäll 2001/. Dating and determination of a paleomagnetic pole of the "Äspö diorite" from Äspö, show that the rock has not been heated above 550–600ºC since its crystallization /Maddock et al. 1993/.

The bedrock surface in the Laxemar subarea is dominated by the Ävrö granite (80%) /Persson Nilsson et al. 2004/. Other rock types in the subarea are quartz monzodiorite, fine-grained dioritoid and diorite to gabbro (all of these are most common in the south part of the subarea). The Ävrö granite has been observed to mix and mingle with the equigranular quartz monzodiorite and gradual contact relationships indicate that the two rock types formed more or less synchronously /Persson Nilsson et al. 2004, Wahlgren et al. 2004, 2005, 2006/.

The rocks in the Laxemar subarea are generally well preserved. A week foliation is occasionally observed in the Ävrö granite and this foliation affects the matrix whereas the megacrysts of microcline show no or weak preferred orientation. Several local shear zones (mylonites, ductile shear zones and brittle-ductile shear zones) have been mapped /Persson Nilsson et al. 2004/. The width of these zones varies between a decimetre to several tens of metres. A characteristic phenomenon that affects all rock types in the Laxemar subarea is inhomogeneous red staining /Persson Nilsson et al. 2004/. The red-staining in the Simpevarp and Laxemar subareas has been studied in detail from drill cores KSH01A+B and KSH03A+B at Simpevarp /Drake and Tullborg 2006c/, and KLX04, at Laxemar /Drake and Tullborg 2006d/.

Earlier studies of the fracture minerals within the Simpevarp/Laxemar site investigations have been carried out by e.g. /Drake and Tullborg 2004, 2005, 2006a, 2007, Drake et al. 2007/. Other studies of fracture minerals in the region have been carried out by e.g. /Tullborg 1988, 1997, Alm and Sundblad 2002, Drake and Tullborg 2006b/.

4 The KLX15A drill core

Borehole KLX15A is a 1,000–meter long cored borehole, drilled within the site investigation program in the Laxemar subarea. The borehole is drilled in the southern, quartz monzodiorite-rich, part of the Laxemar subarea. It is telescopic; implying that the upper 0–76 meters are percussion drilled (no drill core) and has a larger diameter than the core drilled part which starts at 76 meters of borehole length, which corresponds to 60.5 m in vertical depth from the surface at the drilling site. The core drilled part ends at 1,000 m (about 754 m vertical depth). The inclination is about –55° from the surface and the orientation is to the south (bearing 200°). The diameter of the borehole is 76 mm and the core diameter is about 50 mm.

The drill core is dominated by quartz monzodiorite (> 95%). Occasionally, fine-grained granite, fine-grained diorite to gabbro and pegmatite are found. The wall rock is generally fresh (Figure 4-1) but oxidation of the rock adjacent to fractures (Figure 4-2) is found in minor sections (most intense in: 325–330, 380–390, 400–410, 600–635, 670–680, 740–745 and 980–1,000 m).

The only major deformation zone is found at 980–1,000 m but about 10 smaller sections with crushed rock are also found.

***Figure 4-1.** The drill core is dominated by sections with low amounts of fractures and relatively fresh quartz monzodiorite wall rock, here exemplified by section KLX15A: 480.44–491.46 m.*

***Figure 4-2.** Red-stained wall rock adjacent to a reactivated fracture (filled with e.g. chlorite [green] and calcite [white]).*

5 Equipment

5.1 Description of equipment

The following equipment was used in this report.

- Scanning electron microscope (Zeiss DSM 940) with EDS (Oxford Instruments Link).
- Scanning electron microscope (Hitachi S–3400N) with EDS (Oxford Instruments).
- Microscopes (Leica DMRXP and Leica DMLP).
- Stereo microscope (Leica MZ12).
- Microscope camera (JVC TK–1280E).
- Digital camera (Canon IS S3).
- Rock saw.
- Knife.
- Magnifying lens.
- Scanner (Epson 3200) and Polaroid filters.
- Computer software, e.g. Corel Draw 11, Microsoft Office, WellCad, Link ISIS, INCA.

All of the equipment mentioned above is the property of the Earth Sciences Centre, Göteborg University, SKB or the authors.

See chapter 6 for more details.

6 Execution

6.1 Sample collection

Samples suitable for fracture mineral investigations were collected from the drill core at the drill core storage at Simpevarp. Sampling was focused on:

- Representative fracture fillings throughout the drill core.
- Samples with minerals of different generations (e.g. cross-cutting fractures).
- Both open and sealed fractures.

Wide sealed fractures with several minerals were preferred instead of narrow fractures with a few minerals of the same generation (which is more common). This is done in order to optimize the microscopic investigations and to yield more information from the limited number of samples.

The length of the samples ranges from 5 to 17 cm, but are normally 7–10 cm. All analysed samples are listed in Table 6-1.

Table 6-1. Investigated samples.

Sample (adjusted SecUp-SecLow)	Thin section	Fracture surface sample	Hand lens/stereo microscope investigation
KLX15A: 130.290–130.370			X
KLX15A: 251.130–251.200	X		
KLX15A: 254.150–254.200	X		
KLX15A: 262.956–263.046		X	
KLX15A: 263.701–263.761		X	
KLX15A: 276.661–276.831		X	
KLX15A: 381.929–382.030	X		
KLX15A: 571.010–571.090			X
KLX15A: 605.600–605.730	X		
KLX15A: 622.970–623.030	X		
KLX15A: 631.245–631.340			X
KLX15A: 918.171–918.250			X
KLX15A: 939.121–939.295			X
KLX15A: 1,000.345–1,000.425		X	

6.2 Sample preparation and analyses

6.2.1 Thin sections and fracture surface samples

The samples were photographed and sawed. Of these 5 thin sections were prepared at the Earth Sciences Centre, Göteborg University. They were scanned with an Epson 3200 scanner, using Polaroid filters in order to optimize scanning electron microscope investigations (SEM-EDS). The prepared samples were initially examined with petrographic microscope. The thin sections were then investigated with SEM-EDS and mineral specific micro analyses were carried out in order to identify the fracture minerals and to obtain information on the chemistry of the minerals.

Four samples from the fracture surfaces of open fractures were scanned with an Epson 3200 scanner. The samples were initially investigated with stereo microscope and then with SEM-EDS, with which mineral specific analyses were carried out. These analyses were only carried out in order to identify minerals and are not quantitative (see below).

SEM-EDS microanalyses of minerals in thin sections were carried out on an Oxford Instruments energy dispersive system (EDS) mounted on a Zeiss DSM 940 scanning electron microscope (SEM) at the Earth Sciences Centre, Göteborg University, Sweden. Polished thin-sections were coated with carbon for electron conductivity. The instruments were calibrated at least twice every hour using a cobalt standard linked to simple oxide and mineral standards, to confirm that the instrument drift was acceptable. Fe^{II} and Fe^{III} are not distinguished (given as FeO) and the H_2O content is not calculated. The acceleration voltage was 25 kV, the working distance about 24 mm and the specimen current was about 0.7nA. ZAF corrections were performed by an on-line LINK ISIS computer system. Detection limit is 0.1 oxide % (0.3% for Na_2O).

Fracture surface samples were investigated using an Oxford Instruments energy dispersive system (EDS) mounted on a Hitachi S–3,400N scanning electron microscope (SEM). The acceleration voltage was 20 kV, the working distance about 10 mm and the specimen current was about 1nA (using low vacuum mode). X-ray spectrometric corrections were made by an on-line computer system. Representative SEM-EDS analyses were not obtained from the surface samples due to the rough morphology of these samples. Instead, the mineralogy of these samples was identified by their spectra and elemental ratios.

7 Results and discussion

In this section, results from thin section analyses and surface sample analyses are presented and discussed. Relative ages of different fracture filling generations are shown in a schematic sequence of fracture fillings (Table 7-1). Earlier studies in the area e.g. /Tullborg 1988, 1997, Drake and Tullborg 2004, 2005, 2006a, 2007/ show that the fracture mineralogical features and occurrences are similar throughout the Simpevarp-Laxemar-Äspö area, although some minor differences exist, mostly regarding fracture frequencies and differences in amount of different minerals.

Sample descriptions and SEM-EDS analyses are found in the Appendix.

7.1 Amount of fracture minerals

The number of occurrences of each fracture mineral in KLX15A was extracted from the Boremap mapping file stored in the SKB database (SICADA). The fracture minerals present in each fracture were mapped but the abundance of each mineral in the fracture was not measured. Figure 7-1 shows how many percent of the open fractures (1,837 fractures [incl. 9 partly open] = 33% of the total number of fractures) and sealed fractures (3,681 fractures = 67% of the total number of fractures), respectively, that are filled (or coated for open fractures) with each mineral.

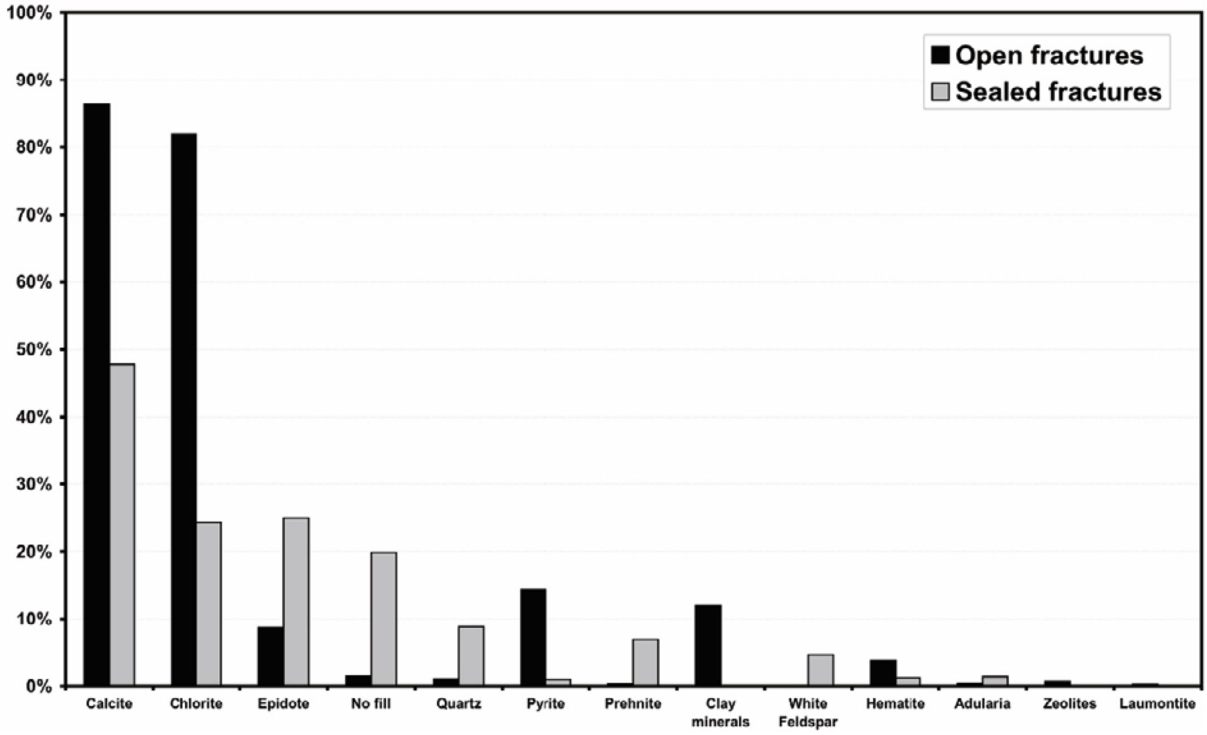

Figure 7-1. *Percentage of mineral occurrences in open and sealed fractures from KLX15A.*

Calcite and chlorite dominate in open fractures, in accordance with what is seen in other drill cores from the Laxemar subarea (KLX03, 04, 05, 06, 07A+B and KLX08), /Drake et al. 2006/. Compared to the data from /Drake et al. 2006/ calcite, chlorite and epidote are more common in open fractures in KLX15A and e.g. hematite, clay minerals and adularia are less common in KLX15A.

For the sealed fractures, calcite, chlorite, epidote, fractures with altered wall rock but with no visible filling, and quartz are most common, also in accordance with /Drake et al. 2006/, although the amount of quartz was generally higher and the epidote content was generally lower in the other Laxemar boreholes /Drake et al. 2006/. The amounts of prehnite is higher in sealed fractures in KLX15A compared to sealed fractures in the boreholes compiled in /Drake et al. 2006/, while the amount of hematite, clay minerals, adularia, and pyrite is lower.

Notable is that no fluorite, muscovite (or sericite), amphibole, gypsum, goethite (except for one occurrence), and chalcopyrite have been mapped in KLX15A. These minerals were found in 0.3–3% of the fractures in the compilation of /Drake et al. 2006/.

7.2 Fracture filling sequence

The fracture filling sequence presented below (Table 7-1) is slightly modified from /Drake and Tullborg 2007/ and is representative for the results from the present study. The sequence comprises a relative chronological sequence of the characteristic minerals of each fracture filling generation from the Simpevarp, Laxemar and Äspö areas, with results from drill cores KSH01A+B and KSH03A+B /Drake and Tullborg 2004, 2006a/, KLX02, KAS04, KA1755A /Drake and Tullborg 2005/, KKR01, KKR02, KKR03 /Drake and Tullborg 2006b/, KLX03, KLX04, KLX06, KLX07A, KLX08, KLX10 /Drake and Tullborg 2007/ and the present study. Only a few of the minerals in each generation are commonly observed in a single sample. The relative abundance of the minerals from each generation varies widely between different samples. Calcite and chlorite are present in most of the generations. These minerals have precipitated at several events under different conditions, ranging from hydrothermal to low temperature. SEM-EDS analyses of chlorite reveal differences in chemistry between chlorite of different generations /e.g. Drake and Tullborg 2004, 2006a/.

The characteristics of each fracture filling generation sampled in KLX15A are described below.

Table 7-1. Schematic fracture filling-sequence from Simpevarp/Laxemar/Äspö. The most abundant minerals in each generation are in bold letters. Minerals in brackets are only found occasionally

1.	**Mylonite; quartz, epidote,** muscovite, chlorite, albite, (titanite, apatite, calcite, K-feldspar)
2 a.	**Cataclasite; epidote, quartz, chlorite,** (K-feldspar, albite)
2 b.	**Cataclasite; K-feldspar, chlorite, quartz, hematite,** albite, (illite)
3 a.	**Quartz, epidote, chlorite, calcite,** pyrite, fluorite, muscovite, (K-feldspar, hornblende)
3 b.	**Prehnite,** (fluorite)
3 c.	**Calcite, laumontite, adularia, chlorite, quartz, illite, hematite,** (albite, fluorite)
4.	**Calcite, adularia, laumontite, chlorite, quartz, illite*, hematite,** (albite, apatite)
5.	**Calcite, adularia, chlorite, hematite, fluorite, quartz, pyrite, barite, gypsum, corrensite**,** apophyllite, harmotome, REE-carbonate, galena, illite, chalcopyrite, sphalerite, U-silicate, Cu(Zn,Ni,Sn)-rich minerals, apatite, laumontite (Ti-oxide, albite)
6.	**Calcite,** pyrite, clay minerals, Fe-oxyhydroxide (near surface)

*=also as illite/chlorite mixed-layer clay.

**=and other types of mixed-layer clay (smectite/illite etc).

Remarks:

Generation 2a; Green colour. Includes wall rock fragments.

Generation 2b; Reddish brown colour (low hematite content though). Includes wall rock fragments.

Generation 3a-c; Quartz, calcite, epidote, prehnite, laumontite and spherulitic chlorite are all often euhedral. Sealed fractures. Cross-cutting as well as pseudomorphs of earlier epidote by prehnite and of prehnite by laumontite is common.

Generation 4; Higher $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ (calcite) than in Generation 3. Lower $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ and higher $\delta^{13}C$ (calcite) than in Generation 5. Often fine-grained fillings (sometimes as reddish brown cataclasite). Sealed fractures.

Generation 5. Open and sealed fractures. Cubic pyrite and fluorite. Scalenohedral calcite.

Generation 6. Open fractures. Cubic pyrite. Scalenohedral, equant, nailhead or needle calcite.

7.2.1 Generation 1 and 2

Several occurrences of mylonite and cataclasite (Figure 7-2) are found in KLX15A (usually < 5 cm wide). Mylonites are normally rich in quartz, epidote, and have lower amounts muscovite, chlorite, albite, and some titanite, apatite, calcite and K-feldspar. Two different varieties of cataclasite exist (green and dark reddish brown) and these are often found in reactivated mylonite zones. The green coloured variety is composed of epidote, quartz and chlorite, albite, K-feldspar and minor amounts of calcite. The dark reddish brown is composed of K-feldspar, chlorite, quartz, hematite, albite, illite and minor amounts of calcite. The green coloured cataclasite is older than the red-colour variety. The chlorite is of "Fe-Mg" type and the epidote (< 13.3 wt.% FeO) is not as Fe-rich as later formed epidote (~15 wt.% FeO, see SEM-EDS analyses in Appendix). The K-feldspar is red-stained due to presence of sub-microscopic hematite crystals (as shown by FeO contents of up to 1.7 wt.%). All of these observations of Generation 1 and 2 are in accordance with earlier observations in the area /e.g. Drake and Tullborg 2006a, 2007/.

Figure 7-2. Photograph of the drill core showing mylonite (white arrows), green coloured cataclasite (yellow arrow) and brown coloured cataclasite (red arrow).The photograph is from a section at about 253.5 m (not sampled here).

7.2.2 Generation 3

This fracture filling generation is quite common in the Laxemar subarea and often consists of thick quartz fillings, Fe-Mg-chlorite (Figure 7-3), calcite, epidote, pyrite, fluorite, muscovite and occasionally K-feldspar. Calcite commonly has a low MnO content (below 0.1 wt.%). Later stages of this generation are dominated by prehnite (with small amounts of calcite and fluorite) and younger laumontite (Figure 7-4, with quartz, calcite, adularia and illite). Commonly, red-stained wall rock caused by hydrothermal alteration, is found adjacent to fractures of this generation. Calcite, chlorite ("Fe-Mg", Figure 7-5), epidote, prehnite, laumontite and K-feldspar (adularia), are all chemically similar to Generation 3 minerals in earlier studies in the area /Drake and Tullborg 2004, 2005, 2006a, 2007/.

This generation is very common in KLX15A, although pyrite and muscovite of this generation are less frequently observed in this borehole compared to earlier studies in the area.

Figure 7-3. Chlorite (green) and quartz (greyish white) of Generation 3.The wall rock is red-stained due to hydrothermal alteration. Photograph is from a section at about 379–380 m (not sampled here).

Figure 7-4. Fracture sealed with laumontite of Generation 3. Parts of the wall rock have red-stained plagioclase and/or plagioclase replaced by laumontite. Photograph is from a section at about 139.65 m (not sampled here).

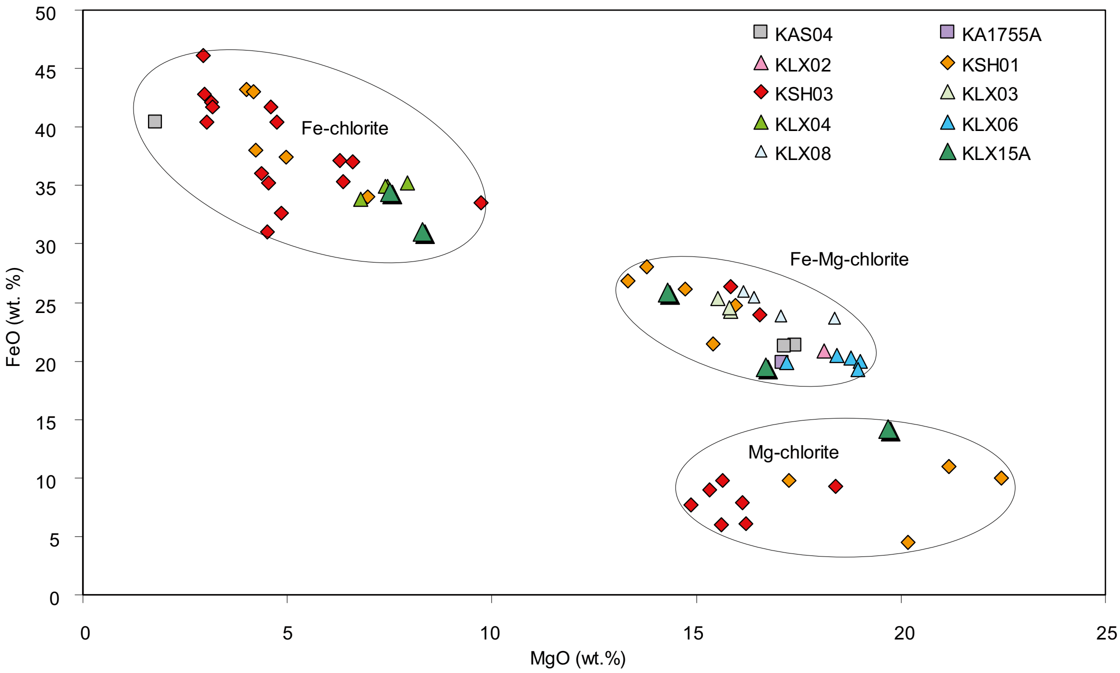

Figure 7-5. *FeO vs. MgO in chlorite of different types from KLX15A as well as from earlier studies /Drake and Tullborg 2004, 2005, 2006a, 2007/.*

7.2.3 Generation 4

Fracture filling Generation 4 (Table 7-1) is the most difficult to distinguish as shown in other studies in the area. Stable isotopes and Sr isotopes of calcite indicate that the fillings are formed at several events /Drake and Tullborg 2007/. The fillings are mainly rich in calcite, adularia, laumontite, illite and hematite. Slightly older dark reddish brown fillings (sometimes cataclastic) rich in adularia, Mg-chlorite (also as mixed layer-clay with illite) and hematite also belong to this generation. The calcite normally shows moderately to high amount of twinning-lamellae. Generation 4 fractures have been difficult to distinguish since isotopic data are lacking.

7.2.4 Generation 5

Generation 5 is dominated by calcite (Figure 7-6) often found together with one or more of the minerals fluorite, adularia, Fe-chlorite, pyrite, hematite, corrensite, barite, REE-carbonate, illite (often in mixed-layer clay), gypsum, harmotome (Ba-zeolite), apophyllite, chalcopyrite, U-silicate, galena, sphalerite, laumontite, Ti-oxide, albite, Cu(Zn,Ni,Sn,Fe)-rich minerals and apatite.

The calcite has a low amount of twin-lamellae and is commonly found as c-axis elongated crystals with scalenohedral morphology in open fractures. Generation 5 minerals have been found throughout the area (Simpevarp, Laxemar, Äspö and Götemar) /Drake and Tullborg 2004, 2005, 2006ab, 2007/. Dating of adularia (Simpevarp) and fluorite (Götemar) from this generation yielded ages of ~445–400 Ma /Alm et al. 2005, Drake et al. 2007/.

The chemistry of Fe-rich chlorite and Mg-rich chlorite of Generation 5 (Figure 7-5) resembles the chemistry of Fe-rich chlorite and Mg-rich chlorite found in other parts of the area including the Götemar granite (only Fe-rich chlorite) /Drake and Tullborg 2006ab, 2007/. However, the Fe content of Mg-rich chlorite is somewhat higher than what has earlier been reported for Mg-rich chlorite from the area. The chemistry of illite of Generation 5 is similar to what has been reported earlier in the area /e.g. Drake and Tullborg 2007/. MnO-contents in calcite of Generation 5 are highly variable and sometimes very high (up to 3.1 wt.% in sample 605.600–605.730 m), in accordance with earlier studies in the area /Drake and Tullborg 2004, 2005, 2006ab, 2007/.

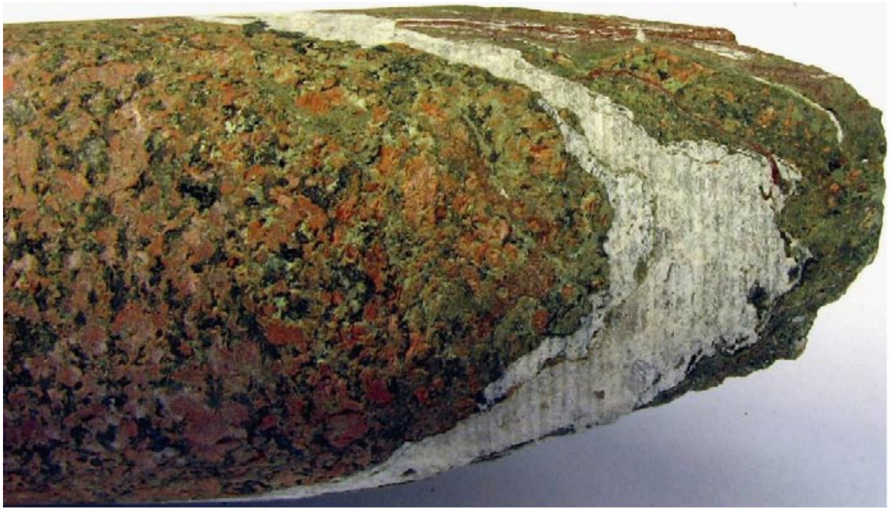

Figure 7-6. *Fracture sealed with calcite of Generation 5 (bright). This fracture is cutting through earlier formed cataclasites. Sample 605.600–605.730 m.*

7.2.5 Generation 6

Calcite considered to be formed later than Generation 5 is occasionally found on fracture surfaces (Figures 7-7, 7-8 and 7-9). These calcite crystals have different morphologies (e.g. scalenohedral, needle shaped, nailhead shaped or equant), in accordance with earlier studies. These crystal morphologies might reflect formation from fluids with different salinities (e.g. saline or brackish: scalenohedral, equant and needle, or meteoric/fresh water: nailhead), as suggested by /Folk 1974, Milodowski et al. 1997, 1998ab, 2005/.

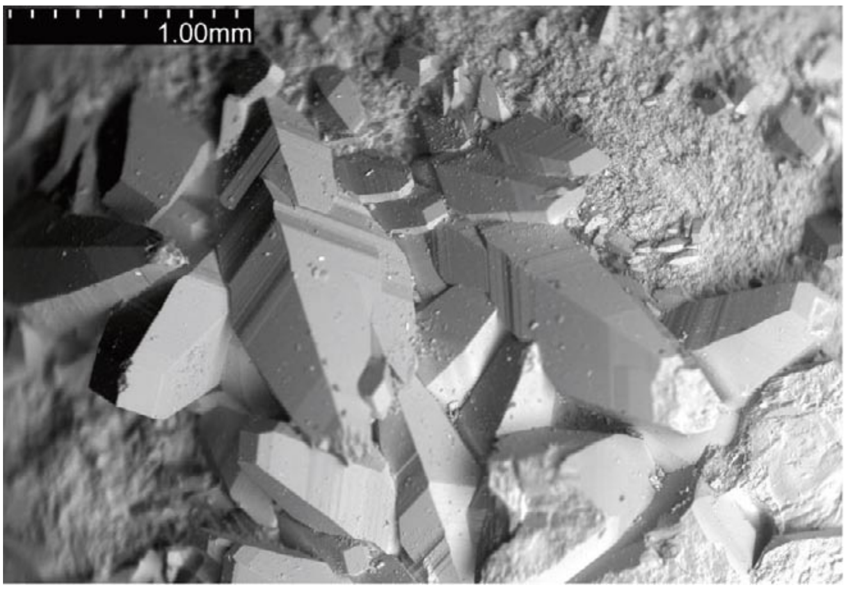

Figure 7-7. *Back-scattered SEM-image of scalenohedral calcite (a few crystals are equant) from sample KLX15A: 276.661–276.831 m.*

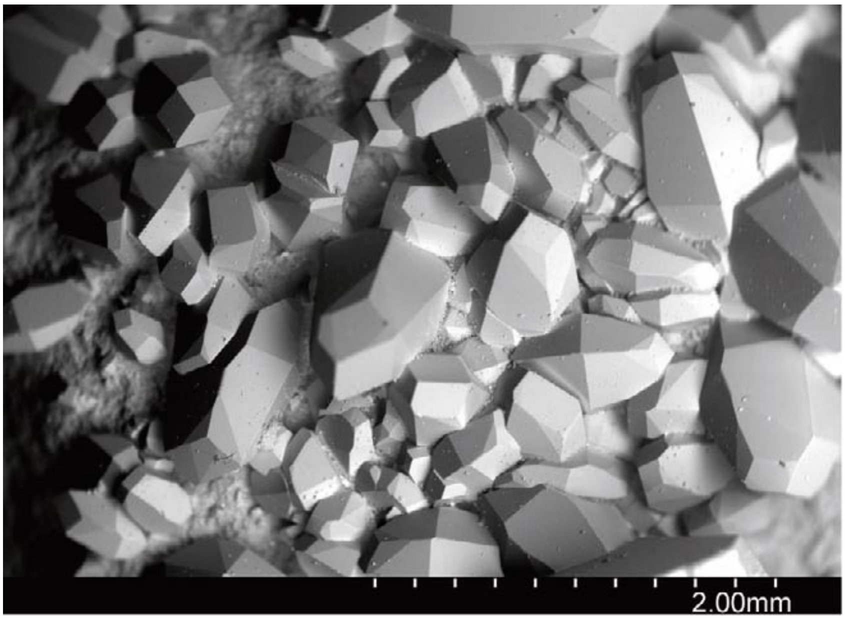

Figure 7-8. *Back-scattered SEM-image of equant calcite (a few crystals are scalenohedral) from sample KLX15A: 1,000.345–1,000.425 m.*

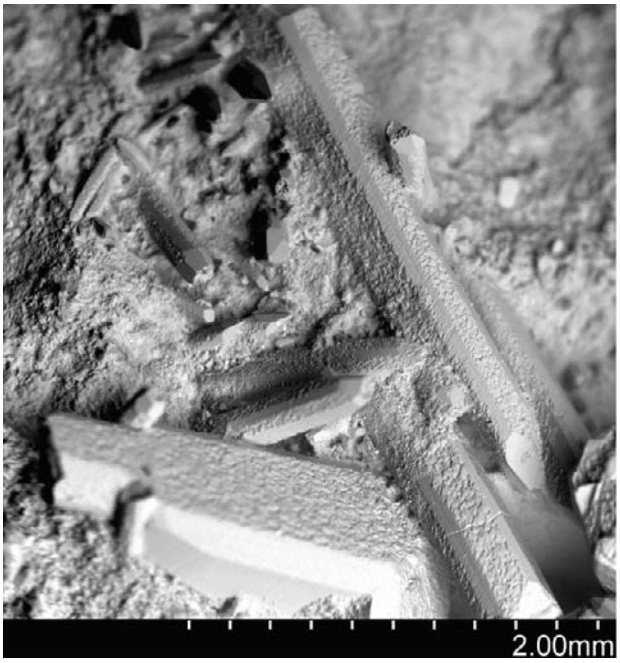

Figure 7-9. *Back-scattered SEM-image of needle shaped calcite in sample KLX15A: 262.956–263.046 m.*

8 Summary

The characteristics of the fracture fillings in KLX15A are similar to what has earlier been reported from other drill cores from the Laxemar subarea /Drake and Tullborg 2007/. Fracture fillings from six generations (Table 7-1) have been observed although Generation 4 is difficult to distinguish without any isotopic data. Fracture fillings of Generation 3 are most common. Calcite of the youngest generation (Generation 6) contain scalenohedral, equant, nailhead and needle calcite, which might reflect formation from fluids with different salinities (e.g. saline or brackish: scalenohedral, equant and needle, or meteoric/fresh water: nailhead), as suggested by /Folk 1974, Milodowski et al.1997, 1998ab, 2005/.

9 References

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Appendix 1

Sample descriptions

KLX15A: 130.290–130.370 m

Sample type: Hand lens and stereo microscope investigation.
Rock type: Mafic rock, fine-grained.
Fracture: Open calcite coated fracture (244°/78°) cutting through foliated, fine-grained mafic rock, with abundant quartz filled fractures.
Minerals: Calcite, quartz, chlorite and clay minerals.

Order:

1. Quartz.
2. Calcite.
3. Chlorite, clay minerals and nailhead calcite on the fracture surface.

Photograph of sample KLX15A: 130.290–130.370 m.

KLX15A: 251.130–251.200 m

Sample type: Thin section.
Rock type: Quartz monzonite to monzodiorite, equigranular to weakly porphyritic.
Fracture: Two sealed fractures (epidote-filled and calcite-filled, respectively) and one open fracture. Heavily saussuritized plagioclase and abundant epidote in the wall rock.
Minerals: Epidote, calcite, quartz, chlorite, adularia, apatite, (REE-carbonate, and chalcopyrite).

Order:

1. Epidote, quartz and Fe-Mg-chlorite.
2. Calcite, adularia, apatite, quartz, (REE-carbonate and chalcopyrite).

Photograph of sample KLX15A: 251.130–251.200 m.

KLX15A: 254.150–254.200 m

Sample type: Thin section.
Rock type: Quartz monzonite to monzodiorite, equigranular to weakly porphyritic.
Fracture: Several undulating sealed fractures and one open fracture (233º/51º).
Minerals: Calcite, chlorite, clay minerals, adularia, hematite, illite, albite, REE-carbonate (and Ti-oxide).

Order:

1. Cataclasite composed of adularia, hematite, calcite, chlorite, illite and wall rock fragments.
2. Cataclasite, same as "1" but more coarse-grained and with lower amount of hematite.
3. Calcite, adularia, albite, REE-carbonate (and Ti-oxide).
4. Chlorite and clay minerals in open fractures.

Photograph of sample KLX15A: 254.150–254.200 m.

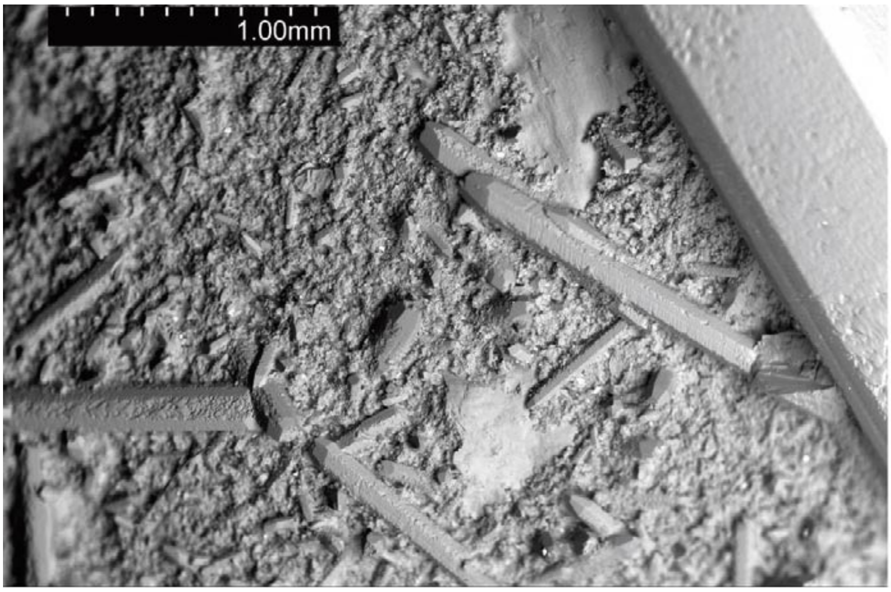
KLX15A: 262.956–263.046 m

Sample type: Fracture surface.
Rock type: Quartz monzonite to monzodiorite, equigranular to weakly porphyritic.
Fracture: Open fracture coated by an old calcite-chlorite-quartz filling (Generation 3) and younger chlorite (striated) and calcite (needle shaped) as well as chlorite/clay minerals (116º/88º).
Minerals: Calcite, chlorite, quartz and clay minerals (and hematite).

Order:

1. Calcite, chlorite and quartz.
2. Chlorite.
3. Calcite (needle, partly dissolved) and chlorite/clay minerals (and hematite).

Photograph of sample KLX15A: 262.956–263.046 m.



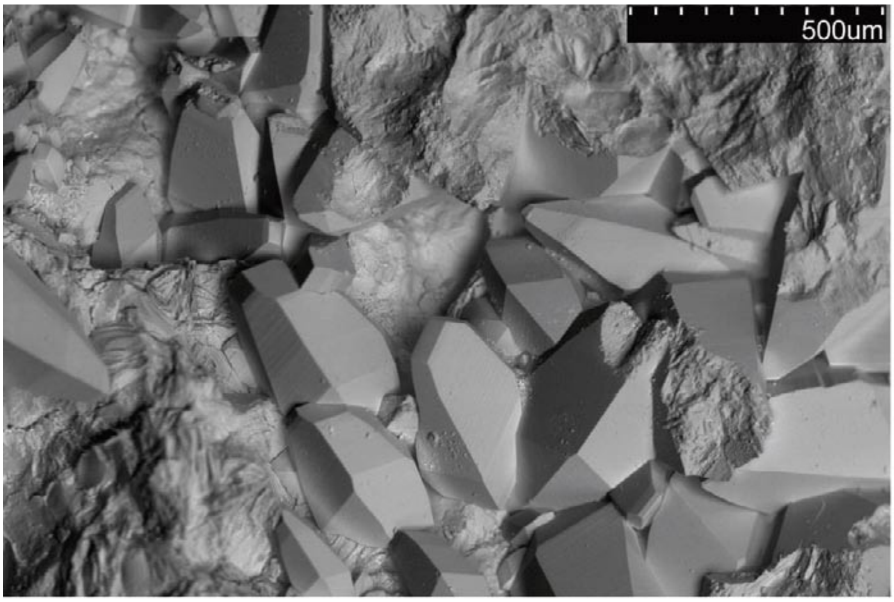
Back-scattered SEM-image of needle shaped calcite in sample KLX15A: 262.956–263.046 m.

KLX15A: 263.701–263.761 m

Sample type: Fracture surface.
Rock type: Granite, fine- to medium-grained.
Fracture: Open fracture coated by an old calcite-chlorite-laumontite filling (Generation 3) and younger chlorite, calcite (scalenohedral), adularia, apophyllite, barite, harmotome, quartz, and clay minerals.
Minerals: Calcite, chlorite, laumontite, quartz, hematite, clay minerals, pyrite, chalcopyrite, REE-carbonate and galena.

Order:

1. Calcite, chlorite and laumontite.
2. Calcite (scalenohedral/equant), quartz and chlorite, clay minerals, hematite, pyrite, chalcopyrite, REE-carbonate, galena (small amounts).



Back-scattered SEM-image of calcite from sample KLX15A: 263.701–263.761 m.

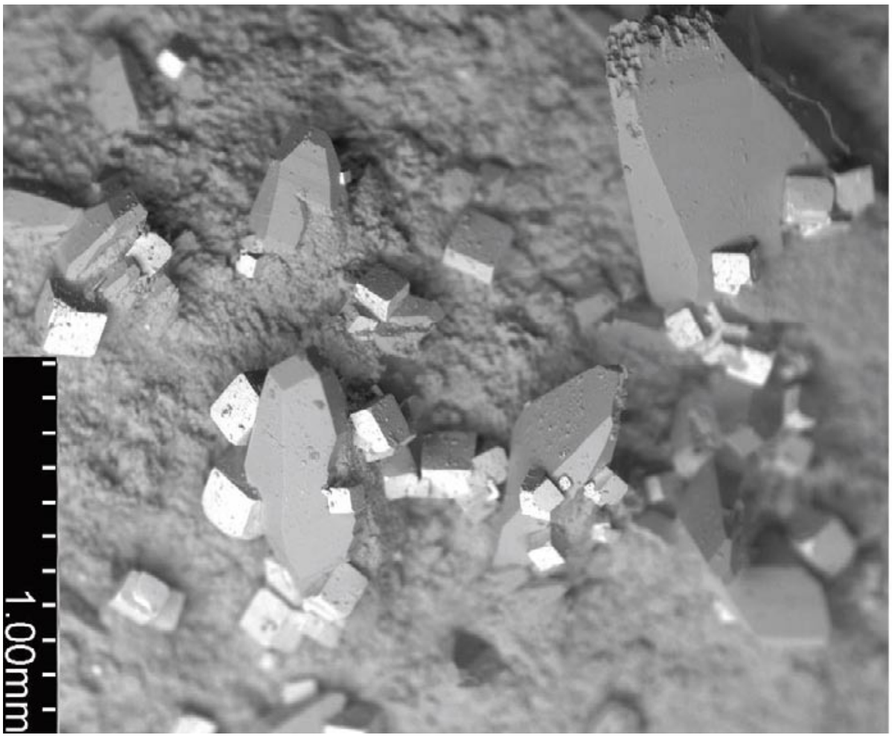
KLX15A: 276.661–276.831 m

Sample type: Fracture surface.
Rock type: Quartz monzonite to monzodiorite, equigranular to weakly porphyritic.
Fracture: Open fracture coated by an old calcite-epidote filling (Generation 3) and younger chlorite-clay minerals and calcite (scalenohedral/(equant)/(needle)) and pyrite (176º/86º).
Minerals: Calcite, epidote, chlorite, clay minerals, pyrite, barite and hematite.

Order:

1. Calcite and epidote.
2. Chlorite and clay minerals.
3. Calcite (scalenohedral/(equant)/(needle)), pyrite, barite and hematite.

Photograph of sample KLX15A: 276.661–276.831 m.



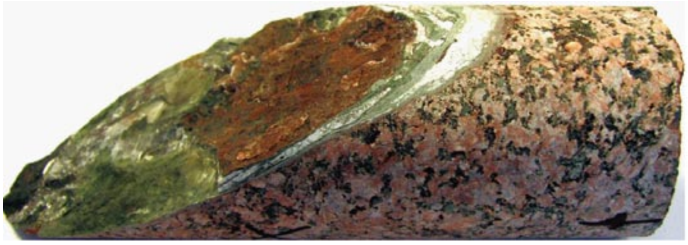
Back-scattered SEM-image of calcite and pyrite from sample KLX15A: 276.661–276.831 m.

KLX15A: 381.929–382.030 m

Sample type: Thin section.
Rock type: Quartz monzonite to monzodiorite, equigranular to weakly porphyritic.
Fracture: Open fracture coated with several generations of fracture fillings (161º/35º).
Minerals: Calcite, prehnite, hematite, adularia, chlorite, clay minerals, epidote, albite and titanite.

Order:

1. Cataclasite (epidote, albite, hematite, Fe-Mg-chlorite, prehnite, titanite, adularia).
2. Calcite and Fe-Mg-chlorite.
3. Prehnite, calcite, Fe-Mg-chlorite, and hematite.
4. Calcite, chlorite, clay minerals and hematite on the fracture surface.



Photograph of sample KLX15A: 381.929–382.030 m.

KLX15A: 571.010–571.090 m

Sample type: Hand lens and stereomicroscope investigation.
Rock type: Quartz monzonite to monzodiorite, equigranular to weakly porphyritic.
Fracture: Open fracture coated with several generations of fracture fillings (70º/27º).
Minerals: Calcite, quartz, chlorite, epidote, pyrite, hematite, laumontite, adularia and clay minerals.

Order:

1. Epidote-rich cataclasite.
2. Hematite-rich cataclasite.
3. Calcite, quartz and pyrite.
4. Calcite, laumontite and adularia.
5. Chlorite and clay minerals on the fracture surface.

Photograph of sample KLX15A: 571.010–571.090 m.

KLX15A: 605.600–605.730 m

Sample type: Thin section.
Rock type: Quartz monzonite to monzodiorite, equigranular to weakly porphyritic.
Fracture: Open fracture coated with several generations of fracture fillings (77º/71º).
Minerals: Calcite, quartz, chlorite, epidote, hematite, clay minerals, illite, adularia, titanite, (chalcopyrite, REE-carbonate and galena).

Order:

1. Epidote-rich cataclasite (epidote, adularia, calcite, illite, titanite and chlorite).
2. Hematite-rich cataclasite (adularia, illite, hematite [spherulitic], epidote, chlorite and small amounts of galena).
3. Calcite, Fe-chlorite, Mg-chlorite, hematite, adularia, illite, (chalcopyrite and REE-carbonate).
4. Chlorite and clay minerals on the fracture surface.

Photograph of sample KLX15A: 605.600–605.730 m.

KLX15A: 622.970–623.030 m

Sample type: Thin section.
Rock type: Quartz monzonite to monzodiorite, equigranular to weakly porphyritic.
Fracture: Open fracture coated with several generations of fracture fillings.
Minerals: Prehnite, calcite, adularia, laumontite, chlorite and illite.

Order:

1. Prehnite and chlorite.
2. Calcite, adularia, laumontite and illite.

Photograph of sample KLX15A: 622.970–623.030 m.

KLX15A: 631.245–631.340 m

Sample type: Hand lens and stereo microscope investigation.
Rock type: Granite, medium- to coarse-grained.
Fracture: Cataclasite and several open fractures coated with laumontite and small amounts of calcite (76º/87º and 114°/87°).
Minerals: Calcite, prehnite, chlorite, laumontite and hematite.

Order:

1. Hematite-rich cataclasite.
2. Prehnite and chlorite.
3. Laumontite and calcite.

Photograph of sample KLX15A: 631.245–631.340 m.

KLX15A: 918.171–918.250 m

Sample type: Hand lens and stereo microscope investigation.
Rock type: Mafic rock, fine-grained.
Fracture: Sealed (76º/87º) and open fracture (114°/87°).
Mineral: Calcite, quartz and adularia.

Order:

1. Calcite, quartz and adularia (sealed).
2. Calcite (open fracture).

Photograph of sample KLX15A: 918.171–918.250 m.

KLX15A: 939.121–939.295 m

Sample type: Hand lens and stereo microscope investigation.
Rock type: Quartz monzonite to monzodiorite, equigranular to weakly porphyritic.
Fracture: Sealed fracture and open fracture (161º/75º).
Mineral: Prehnite and calcite.

Order:

1. Prehnite with red-stained wall rock.
2. Calcite.
3. Calcite (nailhead).

Photograph of sample KLX15A: 939.121–939.295 m.

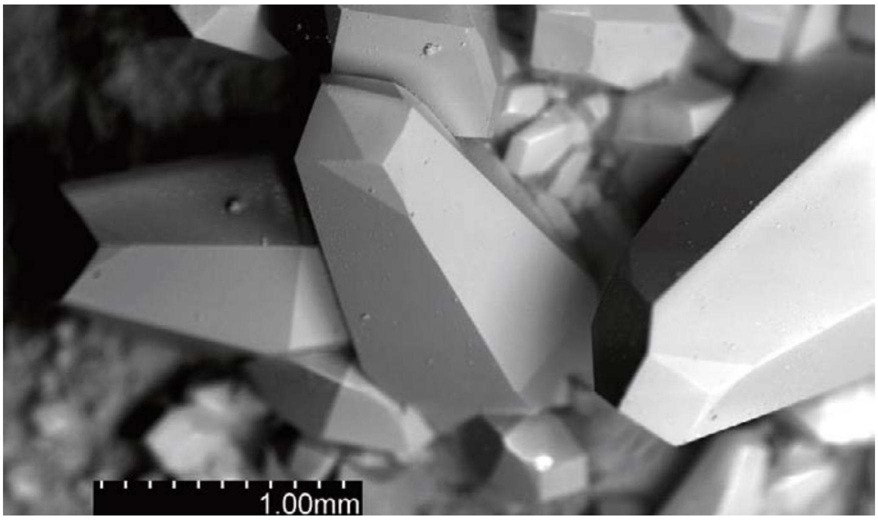
KLX15A: 1,000.345–1,000.425 m

Sample type: Fracture surface.
Fracture: Open fracture.
Mineral: Calcite, chlorite, clay minerals (e.g. illite), epidote, quartz, pyrite, chalcopyrite, galena, barite and hematite.

Order:

1. Epidote and quartz.
2. Calcite and hematite.
3. Calcite (scalenohedral and equant) and small amount of pyrite, chalcopyrite, barite and galena on top of chlorite and clay minerals (e.g. illite).

Photograph of sample KLX15A: 1,000.345–1,000.425 m.



Back-scattered SEM-image of scalenohedral calcite from sample KLX15A: 1,000.345–1,000.425 m.

Appendix 2

SEM-EDS-analyses

Adularia	Al_2O_3	SiO_2	K2O	CaO	FeO	BaO	Total
251.130-251.200-1	17.7	63.4	15.8	0.3	1.0	0.2	98.4
251.130-251.200-2	17.7	63.2	16.2	0.3	n.d.	n.d.	97.4
254.150-254.200	16.9	60.6	14.8	0.5	1.7	0.4	95.0
605.600-605.730-1	17.7	65.4	16.2	n.d.	n.d.	n.d.	99.3
605.600-605.730-2	18.0	64.6	16.2	n.d.	n.d.	n.d.	98.8

Calcite	Al_2O_3	CaO	MnO	Total
251.130-251.200-1	0.3	50.9	1.5	52.6
251.130-251.200-2	0.2	50.9	0.6	51.8
251.130-251.200-3	n.d.	48.2	2.2	50.8
254.150-254.200-1	n.d.	48.8	0.6	49.4
254.150-254.200-2	n.d.	49.3	0.4	49.7
381.929-382.030-1	n.d.	50.1	n.d.	50.1
381.929-382.030-2	n.d.	51.1	n.d.	51.1
605.600-605.730-1	n.d.	47.1	3.1	50.3
605.600-605.730-2	n.d.	49.2	1.7	50.9
605.600-605.730-3	n.d.	49.9	1.0	51.0
622.970-623.030	n.d.	51.5	n.d.	51.5

Fe-Mg-chlorite	MgO	Al_2O_3	SiO_2	CaO	MnO	FeO	Total	Comments
381.929-382.030-1	16.7	14.6	30.4	1.0	0.5	19.5	82.6	In cataclasite
381.929-382.030-2	14.3	21.2	26.0	n.d.	0.5	25.8	87.8	With prehnite

Mg-chlorite	MgO	Al_2O_3	SiO_2	CaO	MnO	FeO	Total
605.600-605.730	19.7	13.8	31.8	0.9	1.1	14.2	81.5

Fe-chlorite	MgO	Al_2O_3	SiO_2	CaO	MnO	FeO	Total
605.600-605.730-1	8.3	12.1	27.7	3.3	1.4	31.0	83.7
605.600-605.730-2	7.5	11.8	26.4	2.2	1.6	34.4	83.8

Epidote	Al_2O_3	SiO_2	CaO	TiO_2	MnO	FeO	Total	Comments
251.130-251.200 -1	21.9	37.5	22.6	n.d.	0.2	12.9	95.1	In mylonite/cataclasite
251.130-251.200 -2	22.5	37.3	22.6	n.d.	0.2	13.3	95.8	In mylonite/cataclasite
605.600-605.730	20.1	36.5	21.7	0.5	0.4	15.0	94.2	

Illite	MgO	Al_2O_3	SiO_2	K_2O	CaO	MnO	FeO	Total
605.600-605.730	4.1	20.6	52.1	7.2	0.6	0.2	5.1	89.9

Laumontite	Al_2O_3	SiO_2	CaO	Total
622.970-623.030 -1	22.1	54.0	11.4	87.6
622.970-623.030 -2	22.0	54.3	11.2	87.5

Prehnite	Al_2O_3	SiO_2	CaO	FeO	Total
381.929-382.030 -1	23.1	42.0	25.9	1.8	92.8
381.929-382.030 -2	21.6	42.9	25.6	2.7	92.8
622.970-623.030 -1	20.1	42.6	25.5	5.1	93.3
622.970-623.030 -2	23.0	43.5	27.0	2.5	96.0

REE-carbonate*	MgO	Al_2O_3	SiO_2	CaO	FeO	Y_2O_3	La_2O_3	Ce_2O_3	Pr_2O_3	Nd_2O_3	Sm_2O_3	Total
251.130-251.200	0.5	0.5	3.4	5.2	5.4	4.2	7.7	19.4	1.8	7.7	1.1	56.8

"n.d." = below the detection limit.

*Possibly slightly contaminated with calcite.