

Oskarshamn site investigation

Mineralogy in water conducting zones

**Results from drill cores KLX13A and KLX17A
with additional fracture mineralogical data
from drill cores KLX14A, KLX19A, KLX20A and
KLX26A**

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January 2008

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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

Data in SKB's database can be changed for different reasons. Minor changes in SKB's database will not necessarily result in a revised report. Data revisions may also be presented as supplements, available at www.skb.se.

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Abstract

This report is a part of the SKB site investigation in Oskarshamn and reports results from detailed studies of fracture coatings/fillings from water conducting sections (sections sampled for complete ground water characterization) in bore holes KLX13A and KLX17A in the Laxemar subarea. Methods used are mineral identification (XRD, SEM-EDS), geochemistry (ICP-AES/QMS and ICP-MS), and stable isotopes ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$). Additional samples (trace element analyses, isotope analyses of $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ or for mineral identification to support the Boremap mapping) from bore holes KLX13A, KLX14A, KLX17A, KLX19A, KLX20A and KLX26A (not from sections sampled for complete ground water characterization) are also included in the appendix.

Sammanfattning

Denna rapport ingår i SKB:s platsundersökningar i Oskarshamnsområdet. I rapporten presenteras resultat från detaljerade undersökningar av sprickfyllningar/beläggningar i vattenförande zoner (sektioner provtagna för komplett grundvattenkaraktärisering) i borrhål KLX13A och KLX17A. Metoder som använts är mineralidentifikation (SEM-EDS, XRD), kemi (ICP-AES/QMS och ICP-MS), och stabila isotoper ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$, och $^{87}\text{Sr}/^{86}\text{Sr}$). Ytterligare prover (spårämnesanalyser, isotopanalyser av $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, och $^{87}\text{Sr}/^{86}\text{Sr}$ eller mineralidentifikation som stöd för Boremap-karteringen) från borrhål KLX13A, KLX14A, KLX17A, KLX19A, KLX20A och KLX26A (inte i sektioner provtagna för komplett grundvattenkaraktärisering) är inkluderade i appendix.

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1 Introduction

This document reports results from detailed studies of fracture coatings/fillings from water conducting sections (sections sampled for complete ground water characterization) in bore holes KLX13A and KLX17A in the Laxemar subarea.

Additional samples (for trace element analyses, isotope analyses of $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, och $^{87}\text{Sr}/^{86}\text{Sr}$ or for mineral identification to support the Boremap mapping) from bore holes KLX13A, KLX14A, KLX17A, KLX19A, KLX20A and KLX26A (sampled from sections not used for complete ground water characterization) are also included in the appendix. Both the activity plan and the method description are SKB's internal controlling documents, Table 1-1.

Included in the detailed studies of the water conducting sections are mineral identification (XRD, SEM-EDS), chemistry (SEM-EDS, ICP-AES/QMS, ICP-MS) and stable isotopes ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$, och $^{87}\text{Sr}/^{86}\text{Sr}$ in calcite).

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 tillägg 1 och 2.

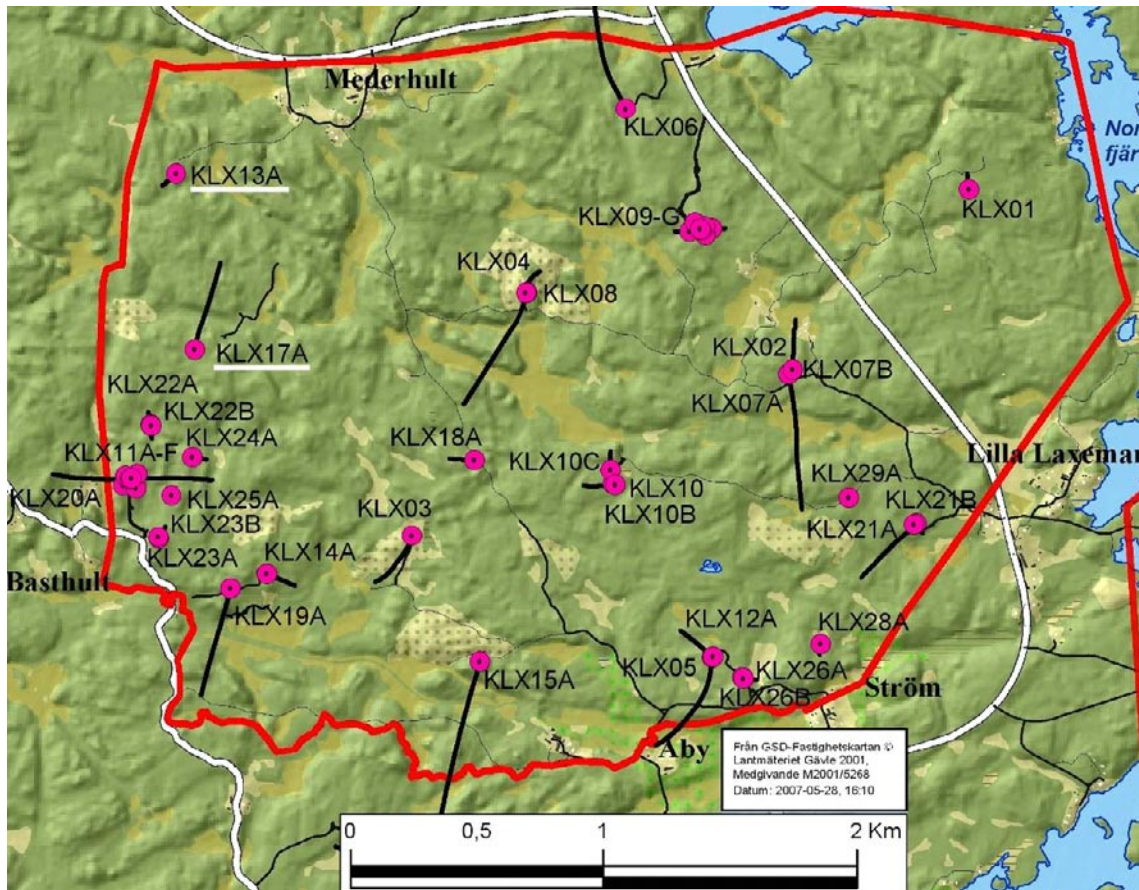


Figure 1-1. Map of the Laxemar subarea with the investigated bore holes KLX13A and KLX17A underlined by white lines.

2 Objective and scope

The objective and scope is to investigate the mineralogy (SEM-EDS, XRD and trace element chemistry), chemistry (ICP-AES/QMS) and isotope signatures ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$, och $^{87}\text{Sr}/^{86}\text{Sr}$) of sections sampled for complete groundwater characterisation in bore holes KLX13A and KLX17A, Laxemar subarea. The task is:

- Give input to hydrogeochemical modelling and give a background to paleohydrogeological interpretations.
- Identify minerals; the drill core mapping is based on macroscopic determination of fracture minerals. SEM-analysis or XRD is needed to give a more detailed and precise description of the mineralogy in water conducting sections.

Additional samples from bore hole KLX13A, KLX14A, KLX17A, KLX19A, KLX20A and KLX26A (not in sections sampled for complete ground water characterization) are also included in the Appendix. These samples were taken for isotope and trace element studies or for mineral identification to support the Boremap mapping.

3 Equipment

3.1 Description of equipment

The following equipment is used in the investigations:

- Scanning electron microscope (Hitachi S-3400N) with EDS (IncaDryCool).
- Stereo microscope (Leica MZ12).
- Digital camera (Canon S3 IS).
- Rock saw.
- Rock Labs swing mill.
- Knife.
- Magnifying lens – 10×.
- Scanner (Epson 3200).
- Computer software, e.g. Corel Draw 11, Microsoft Word, Microsoft Excel, Link ISIS.
- Mass-spectrometer.
- ICP-MS.

All equipment listed above is property of Earth Sciences Centre, University of Gothenburg, or the authors. For equipment used for whole rock chemistry analyses, X-ray diffraction and isotope analyses of calcite, see Chapter 4 below.

4 Execution

4.1 Sample collection and preparations

Samples were collected from the drill cores KLX13A and KLX17A. Sampling was focused on sections sampled for complete ground water characterization. Unfortunately, some of these sections did not include suitable samples. Therefore, samples were also collected in the less water conducting zones, scattered throughout the drill core (however, mostly focused to water conducting zones of low transmissivity). Flow logs were used as a support to the sampling. BIPS and boremap mapping data for each borehole was used to localise orientations of fractures, crush zones and sealed network. Additional samples from bore holes KLX13A, KLX14A, KLX17A, KLX19A, KLX20A and KLX26A (not in sections sampled for complete ground water characterization) are also included.

The fracture surface of most of the samples was removed (by sawing if needed), glued to a piece of glass to obtain a horizontal surface and scanned in order to support the SEM investigations. SEM-EDS was used to identify major minerals (as well as some minor and accessory), and to characterize the fracture surface morphology.

After this procedure, the minerals on the fracture surfaces of the samples were scraped off using a knife. The scrape off material was then sieved and the material with a grain size smaller than 0.125 mm was collected for ICP-AES/ICP-QMS chemical analyses and X-ray diffraction (if enough material was obtained).

Samples including a significant amount of calcite, were investigated with a hand lens, stereo microscope and SEM in order to identify the crystal morphology. The calcite crystals were then scraped off with a knife. This material was checked for purity in stereo microscope and then analysed for stable isotopes ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$, $^{87}\text{Sr}/^{86}\text{Sr}$) and trace elements.

Investigation methods for each sample from water conducting zones are listed in Table 4-1. Investigation methods for additional samples are listed in Table 4-2.

Table 4-1. Samples and methods.

Section* (m)	Sample SecUp (m)	Sample SecLow (m)	Chemical analysis	XRD	$\delta^{13}\text{C}$, $\delta^{18}\text{O}$ (Calcite)	$^{87}\text{Sr}/^{86}\text{Sr}$ (Calcite)	ICP-MS (Calcite)	SEM
KLX13A			5	4	4	0	0	8
	373.220	373.270						
	404.450	404.460			X			X
	450.800	450.850			X			X
495–506.65	494.323	494.423	X	X				X
495–506.65	494.770	494.871	X	X				X
495–506.65	506.750	506.999			X			X
	538.380	538.480	X		X			X
	557.964	558.114	X	X				X
	570.000	570.329	X	X				X
KLX17A			4	4	4	1	1	6
	110.274	110.544	X	X				X
180–219	200.100	200.351	X	X				X
	315.479	315.759			X	X	X	X
419–434	423.250	423.450	X	X	X			X
416–437	426.100	426.360	X	X	X			X
416–437	431.460	431.660			X			X

* = Sections sampled for complete ground water characterization

Table 4-2. Additional samples and investigation methods.

Borehole	Sample SecUp (m)	Sample SecLow (m)	$\delta^{13}\text{C}$, $\delta^{18}\text{O}$ (Calcite)	$^{87}\text{Sr}/^{86}\text{Sr}$ (Calcite)	ICP-MS (Calcite)	SEM
KLX13A	337.153	337.479				X
KLX13A	497.242	497.392	X			
KLX14A	80.245	80.262	X	X	X	X
KLX14A	80.940	81.040	XX		X	X
KLX14A	81.300	81.360	X		X	X
KLX17A	449.800	449.880				X
KLX17A	590.652	590.766				X
KLX19A	412.430	412.531	X		X	X
KLX20A	216.180	216.230	X			X
KLX20A	224.180	224.210	X			X
KLX26A	17.780	17.930	X	X		X

4.2 SEM-EDS analyses

The SEM investigations and EDS micro analyses were carried out using an IncaDryCool EDS mounted on a Hitachi S-3400N scanning electron microscope at the Earth Sciences Centre, University of Gothenburg, Sweden. The acceleration voltage was 20 kV, the working distance 10 mm and the specimen current was about 1nA. The investigations were carried out using low-vacuum mode (15–20 Pa). The instrument was calibrated at least twice every hour by using a cobalt standard linked to simple oxide and mineral standards, to confirm that the drift was acceptable. X-ray spectrometric corrections were made by an on-line computer system. Proper mineral analyses were not possible to carry out due to the uneven surface of the samples, (a polished surface is needed). The mineralogy (except for clay minerals) was identified based on element ratios and spectra.

4.3 ICP-AES, ICP-QMS

ICP-AES/ICP-QMS analyses were carried out by Analytica AB. The following is valid for Co, Cu, Ni and Zn: Digestion was done by microwave heating in closed teflon vessels with HNO₃/H₂O 1:1. The following is valid for the other elements: 0.125 g sample is fused with 0.375 g LiBO₂ and dissolved in dilute HNO₃. LOI (Loss on ignition) is not carried out due to small sample volumes. Concentrations of the elements are determined by ICP-AES and ICP-QMS. Analyses are carried out according to EPA methods (modified) 200.7 (ICP-AES) and 200.8 (ICP-QMS).

4.4 X-ray diffraction

The analyses were carried out by SGU, Uppsala according to the following procedure. The fine-fraction (< 35 µm) of each sample was dispersed in distilled water, filtered and oriented according to /Drever 1973/. In samples of small volumes the suspension was repeatedly put on glass and dried. Three measurements were carried out on each of the fine fraction samples for clay mineral identification; 1) dried samples 2) saturated with ethyleneglycol for two hours and finally 3) after heating to 400°C in two hours. Coarser material was wet sieved and dried. The > 35µm fraction was ground by hand in an agate mortar. The sample powder was randomly orientated in the sample holder (and very small sample volumes on a piece of glass). The radiation (CuK_α) in the diffractometer was generated at 40 kV and 40 mA, and the X-rays were focused with a graphite monochromator. Scans were run from 2°–65° (2-theta) or from 2°–35° (samples with preferred crystal orientation) with step size 0.02° (2-theta) and counting time 1 s step⁻¹. The analyses were performed with a fixed 1° divergence and a 2 mm receiving slit. The XRD raw files were taken up in the Bruker/Siemens DIFFRACPLUS software (version 2.2), and evaluated in the programme EVA. The minerals were identified by means of the /PDF 1994/ computer database. Additional data for clay minerals were taken from /Brindley and Brown 1984, Starkey et al. 1984, Jasmund and Lagaly 1993/.

4.5 δ¹³C and δ¹⁸O

Analyses of stable carbon (¹³C/¹²C, expressed as δ¹³C) and oxygen (¹⁸O/¹⁶O, expressed as δ¹⁸O) were carried out at the Earth Sciences Centre, University of Gothenburg, Sweden (samples from drill cores KLX13A, KLX20A and KLX26A) and at the Institute for Energy Technology (IFE), Norway (samples from drill cores KLX17A, KLX14A and KLX19A).

The stable carbon and oxygen isotope analyses from Earth Sciences Centre, University of Gothenburg, were made accordingly: 150–250 µg samples were roasted in vacuum for 30 minutes at 400°C to remove possible organic material and moisture. Thereafter, the samples were

analysed using a VG Prism Series II mass spectrometer with a VG Isocarb preparation system on line. In the preparation system each sample was reacted with 100% phosphoric acid at 90°C for 10 minutes, whereupon the released CO₂ gas was analysed in the mass spectrometer. Results are reported as δ¹³C and δ¹⁸O per mil relative to the Vienna Pee Dee Belemnite (VPDB) standard (accuracy ± 0.05‰ for δ¹³C and 0.1‰ for δ¹⁸O, 2 sigma). The analyses are calibrated to the PDB scale via NBS-18 and NBS-19.

The stable carbon and oxygen isotope analyses (VPDB, accuracy ± 0.1‰ for δ¹³C and 0.2‰ for δ¹⁸O, 2 sigma) carried out at the Institute for Energy Technology (IFE), Norway, were made accordingly. About 100 µg sample was transferred to a 10 ml vacutainer, put in a temperature controlled Al block and flushed with He for 5 minutes. 0.1 ml 100% H₃PO₄ is added and the reaction is controlled at 30.0°C for 2 hours. The produced CO₂ gas is then flushed out with He flow on to a Poraplot Q GC column and analysed directly on a Finnigan MAT DeltaXP, Isotope Ratio Mass Spectrometer. The analyses are calibrated to the PDB scale via NBS-18.

Two samples were analysed twice.

4.6 ⁸⁷Sr/⁸⁶Sr

Sr-isotope analyses of three samples from drill cores KLX14A, KLX17A and KLX26A were carried out at the Institute for Energy Technology, Norway, according to the following procedure. About 30 to 40 mg of the carbonate samples were transferred to 2 ml centrifuge tubes, added 200 µl 0.2 M HCl, and shaken. The samples were let to react for 10 minutes while shaken in order to release the CO₂ gas. If not completely dissolved 20 µl 2 M HCl was added once or twice until most of the calcite was decomposed. The samples were centrifuged for about 4 minutes and the liquids transferred to new clean centrifuge tubes by use of a pipette. New pipette tips were used for each sample. The centrifuge tubes were put on a hotplate and evaporated to dryness. To avoid disturbances in measuring the isotopic composition, strontium had to be separated from other elements present in the sample. After evaporation to dryness the samples were dissolved in 200 µl ultrapure 3M HNO₃, centrifuged and loaded onto ion-exchange columns packed with a Sr-Spec crown-ether resin from Eichrom, which retained Sr and allowed most other elements to pass. After rinsing out the remaining unwanted elements from the columns, strontium was collected with ultrapure water (Millipore). The collected Sr- fractions were then evaporated to dryness and loaded on pre-gassed Re filaments on a turret holding 12 samples and 1 NIST/NBS 987 Sr standard. The isotopic composition of Sr was determined by thermal ionization mass spectrometry (TIMS) on a Finnigan MAT 261 with a precision of about 20 ppm and a Sr blank of 50–100 pg. The ⁸⁷Sr/⁸⁶Sr ratio of the carbonate analysis were monitored by analysing one NIST/NBS SRM 987 Sr standard, for each turret of 12 samples, and the standard has a recommended ⁸⁷Sr/⁸⁶Sr value of 0.710248. The presented results were not corrected to the NBS 987 recommended value but given together with the specific measured NBS 987 value for the relevant turret.

4.7 ICP-MS analyses of calcite

ICP-MS analyses on calcite leachates (5 samples from drill cores KLX14A, KLX17A and KLX19A) were carried out at Earth Sciences Centre, University of Gothenburg, according to the following procedure. 12 mg calcite sample (weight registered ± 0.01 mg) was placed in a 50 ml tube, where 47 ml 5% HNO₃ was added containing 15 ppb of indium and rhenium respectively, to be used as internal standards. The sample was leached for 1 hour with stirring every 15 minutes. Thereafter, 20 ml of the solution was used for analyses carried out on an Agilent 7500a ICP-MS (additional analyses on a Hewlett-Packard 4500 ICP-MS). Certified multi element standards from Merck (no. VI) and Agilent (no. I) were used. A leachate from one of the samples was analysed twice.

5 Results and discussion

5.1 Mineralogy

Most of the samples contained fractures that have been reactivated. This is shown by old fracture sets (sometimes cataclasites, usually with epidote, chlorite, quartz, calcite, prehnite, K-feldspar, hematite, illite etc) which have been re-activated and are filled or coated with younger minerals. Sample descriptions are found in Appendix 1 and Appendix 2.

The mineralogy on the fracture surfaces of the open fractures are of special interest for this report. The mineralogy identified with SEM-EDS and XRD differs somewhat because XRD samples are scraped off from the surface (underlying material might be included, and a deeper “section” of the fracture coating is analysed), while only the uppermost layer on the fracture surfaces are investigated with SEM-EDS and this layer is often clay minerals, chlorite or calcite which may cover underlying fracture fillings, if present.

Most of the sampled fracture surfaces were coated by a mixture of clay minerals (often mixed layer clay/chlorite and illite), chlorite, hematite, pyrite, calcite and wall rock fragments such as K-feldspar, quartz, plagioclase and sometimes biotite. Chlorite, clay minerals (illite and mixed layer-clay/chlorite; sometimes swelling), calcite and wall rock fragments (quartz, plagioclase/albite and K-feldspar) are found in large amounts using both SEM-EDS and XRD. However, plagioclase, K-feldspar and quartz are more commonly observed by XRD than by SEM-EDS investigations. Hematite is observed on most fracture surfaces (both macroscopically due to coloration and as fine-grained crystals using SEM-EDS) but was only identified in less than half of the XRD analyses, which shows that the hematite content is generally small. SEM-EDS investigations show presence of small amounts of pyrite, barite, and more rarely REE-carbonate, galena, apatite, goethite, sphalerite, titanite, chalcopyrite, epidote and zeolites (analcime and harmotome). These occurrences were generally too small to be observed in the XRD-analyses (some of these samples were not analysed using XRD).

The fracture surface morphology varies widely between different samples but also within a single sample. Most common is a fairly smooth surface with minor parts of the surface being more rugged due to crystal aggregates. The crystals in the smooth parts are sometimes striated (especially chlorite and clay minerals but also calcite). Some fracture surfaces, commonly rich in chlorite and clay minerals, are very smooth and occasionally slickensided. The freely grown crystals on the surfaces are sometimes euhedral. Calcite crystals are scalenohedral (c-axis elongated), equant (short c-axis/round), and nailheaded (c-axis flattened) or have no distinct morphology. Pyrite crystals are mostly cubic and fresh, only one sample contained somewhat altered pyrite crystals.

There are no significant differences in mineralogy between the KLX13A-samples and the samples from KLX17A. Further, no major variation in mineralogy with increasing depths has been observed in the samples studied.

5.2 Chemistry

Results from the chemical analyses are found in Appendix 9 and Appendix 10. Most samples are from Ävrö granite rich parts of the rock. Values for Ävrö granite from /Drake et al. 2006/ are used for comparison.

5.2.1 Major elements, minor elements and Loss on Ignition

The SiO₂ content is lower compared to Ävrö granite (57.6–69.7 wt. %) in all fracture filling samples (34.5–53.7 wt. %, generally somewhat lower concentrations in the KLX17A samples than in KLX13A). This might be due to the generally lower amount of SiO₂-rich silicates (e.g. quartz and feldspars), and generally higher amount of chlorite, clay minerals, and calcite in the fracture fillings. Al₂O₃ is found in about the same concentration in the fracture fillings as in the wall rock. The only exceptions are “KLX17A: 200.100–200.351 m” (hematite-rich) and “KLX17A: 423.250–423.450 m” (calcite-rich), with 2–3 wt. % lower Al₂O₃ concentrations than in the wall rock. These samples contain less Al₂O₃-rich minerals than the other samples.

The CaO content (1.38–4.97 wt. %, except for one very calcite-rich sample which has 10 wt. % CaO) in the fracture filling is very similar to CaO-concentrations of the Ävrö granite (1.34–5.39 wt. %) and is mainly dependent on the calcite content (as shown by XRD analyses).

The Fe₂O₃ (8.67–32.9 wt. %) and MgO (3.12–12.9 wt. %) concentrations are higher in all fracture filling samples compared to the Ävrö granite (2.94–6.44 wt. % Fe₂O₃ and 0.92–2.79 wt. % MgO), see Figure 5-1. The higher concentrations of these elements in the fracture fillings compared to the wall rock are mainly due to the higher contents of chlorite, clay mineral (e.g. Mg-rich illite) and partly also due to hematite (at least in the very Fe₂O₃- and hematite-rich sample KLX17A:200.100–200.351 m) compared to the wall rock. For basically the same reasons (higher amounts of chlorite, clay minerals and hematite), MnO concentrations are generally higher in the fracture fillings (0.12–0.33 wt. %) than in the Ävrö granite (0.05–0.13 wt. %).

The K₂O concentrations are between 1.5 to 6.5 wt. % with an average of 3.81 wt. % which is close to the Ävrö granite average (3.87 wt. %) although the range in K₂O is smaller in the Ävrö granite (2.6–4.6 wt. %). The K₂O concentration in the fracture fillings vary with the amount of K-feldspar, illite, K-rich clay minerals and possibly also mica.

Like SiO₂, the Na₂O content is lower in all fracture filling samples than in the Ävrö granite. This is due to the generally lower amount of feldspars (plagioclase and albite) in the fracture fillings compared to the wall rock.

P₂O₅ and TiO₂ are generally found in similar amounts in the fracture fillings and in the Ävrö granite, although TiO₂ is sometimes enriched in the fracture filling, both as fine-grained Ti-oxide and in mixed-layer clay (as shown by SEM-EDS observations).

Loss on Ignition (LOI) was only measured for the KLX13A samples (the KLX17A samples were too small). LOI is very high in the KLX13A samples 3.1–7.0 wt. % (average 5.24 wt. %) which is much higher than in Ävrö granite which has LOI in the range of 0.1–1.1 wt. % (average 0.68 wt. %). Similar or higher LOI value as in KLX13A can also be expected for the KLX17A samples because their total measured values are similar or lower than in KLX13A. The high LOI values are mostly related to high amounts of water-bearing minerals such as chlorite and clay minerals in the fracture fillings.

There are no significant differences in major and minor element chemistry between the KLX13A-samples and the samples from KLX17A and no major variation in chemistry with increasing depths was observed.

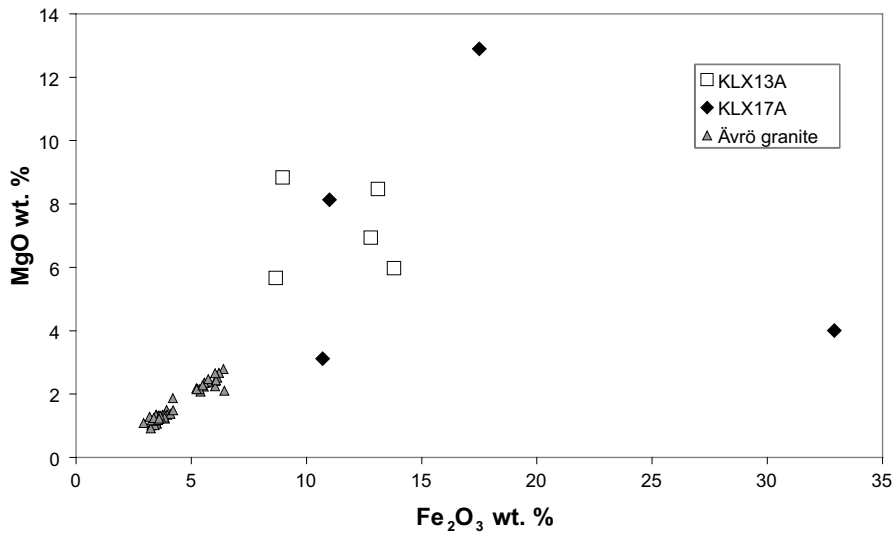


Figure 5-1. MgO plotted versus Fe₂O₃ for fracture fillings from KLX13A and KLX17A as well as for Ävrö granite /Drake et al. 2006/.

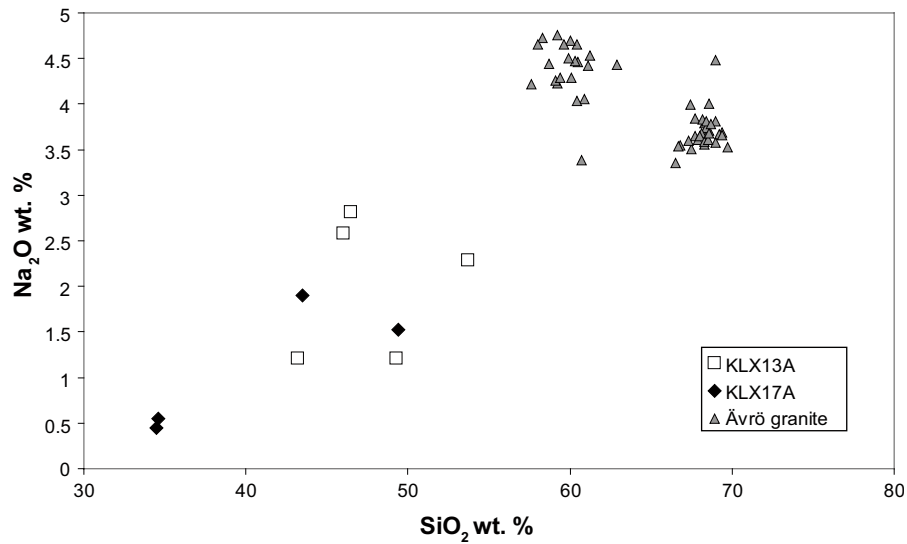


Figure 5-2. Na₂O plotted versus SiO₂ for fracture fillings from KLX13A and KLX17A as well as for Ävrö granite /Drake et al. 2006/.

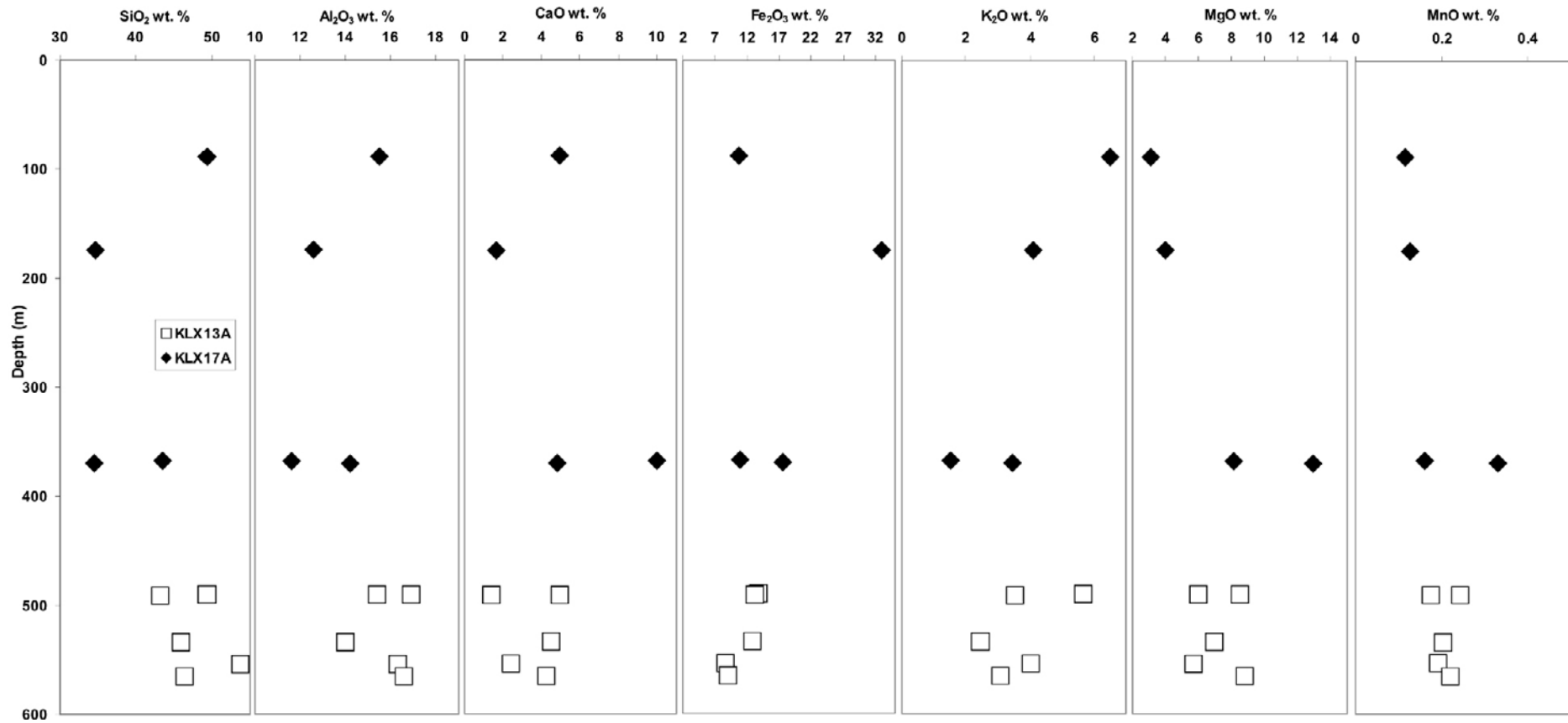


Figure 5-3. SiO₂, Al₂O₃, CaO, Fe₂O₃, K₂O, MgO and MnO versus depth.

5.2.2 Trace elements

The Ba content is generally lower in the fracture fillings than in the wall rock (which has high Ba contents in the K-feldspar). The fracture fillings with Ba contents in the same order as the wall rock are the samples with the highest contents of K-feldspar (according to XRD analyses) and some of these samples include small crystals of barite as well (only identified using SEM-EDS).

Elements such as Cu, Ga, Hf, Mo, Nb, Sn, Sr, Ta, Th, U, Y, W and Zr are generally found in similar concentrations in the fracture fillings as in the wall rock. However, sample KLX13A-494.323–494.423 m is very low in Sr (212 ppm), which is related to the very low amount of Ca-Al-silicates and possibly also calcite (also shown in the CaO content) in this sample. Further, sample KLX17A:200.100–200.351 m has a much higher Cu content (related to the presence of chalcopyrite) than the wall rock and a couple of samples have significantly higher W contents (generally related to occurrences of a fine-grained W-rich mineral, probably wolframite) than the wall rock. W-rich minerals have not been identified in the current study but have been identified earlier in open fractures in this area /Drake and Tullborg 2007/. Three samples have slightly higher U contents (8.7–16 ppm, generally the values are 3.9–7 ppm) than in the wall rock (1.3–7.9 ppm). These values may be due to the presence of fine-grained U-rich phases (identified earlier in open fractures in this area /Drake and Tullborg 2007/).

The elements Cr, Cs, Ni, Rb and Sc have similar concentrations as the wall rock in about 50% of the samples and slightly higher to significantly higher concentrations in the other samples. The enrichment of these elements are related to high chlorite and clay mineral contents (mainly Cs, Rb, Sc, possibly also Cr and Ni), high feldspar contents (Rb and possibly Cs) and high hematite contents (Cr, Ni and Sc), respectively, which is in accordance with XRD and SEM-EDS results. It should be noted the Cs is only found in very high concentrations in the KLX17A samples.

Be, Co, V and Zn generally have higher concentrations in the fracture fillings compared to the wall rock. The higher value of Be, which is related to Al /Bailey 1971/, is somewhat dubious because Al is not enriched in the fracture fillings. Be might possibly be enriched relatively to Al during breakdown of feldspars and biotite and subsequent formation of chlorite and clay minerals. The high Co and V concentrations are related to the high Fe₂O₃ concentrations and thus related to the high chlorite, clay mineral, and the occasionally high hematite content. The high concentration of Zn is probably related to the small amounts of native Zn (observed using SEM-EDS), or due to contamination during sampling.

There are no significant differences in trace element chemistry between the KLX13A-samples and the samples from KLX17A but the KLX17A samples generally have more homogeneous chemistry than the KLX13A samples (Figure 5-4).

The REE-values for fracture fillings from KLX13A and KLX17A (Figures 5-5 and 5-6) are all very similar to one another. They are also very similar to REE-values from Ävrö granite within the Laxemar subarea (similar chondrite-normalized patterns, generally with a slightly negative Eu-anomaly) /Drake et al. 2006/, which shows that no major fractionation of REEs has occurred. However, the REE concentrations are somewhat higher in most of the fracture filling samples compared to Ävrö granite, indicating that REE and especially LREE have been mobilised and incorporated in the fracture minerals. The small enrichment of LREE may be due to complexation of REE with organic matter (favourably LREE) as suggested by /Tullborg et al. 1999/ in studies of fracture calcite from the nearby Äspö Hard Rock Laboratory, where the La/Yb-ratio in calcite decreases with increased depth. No such trend is obvious in the samples from KLX13A and KLX17A (Figure 5-7).

There are no major fractionations of the redox sensitive elements Ce and Eu. The small negative Eu anomalies are most probably inherited from the wall rock. Ce “anomalies” are consistent and small (Ce*/Ce: 0.96–1.12, Figure 5-8).

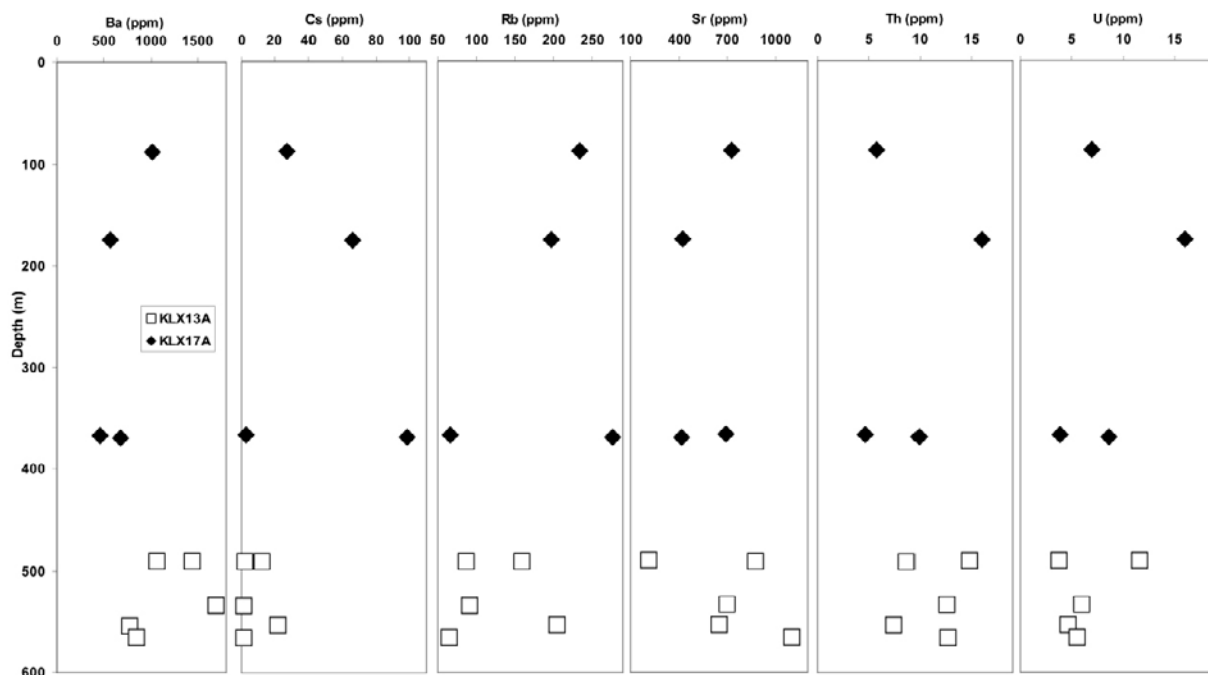


Figure 5-4. Ba, Cs, Rb, Sr, Th and U versus depth.

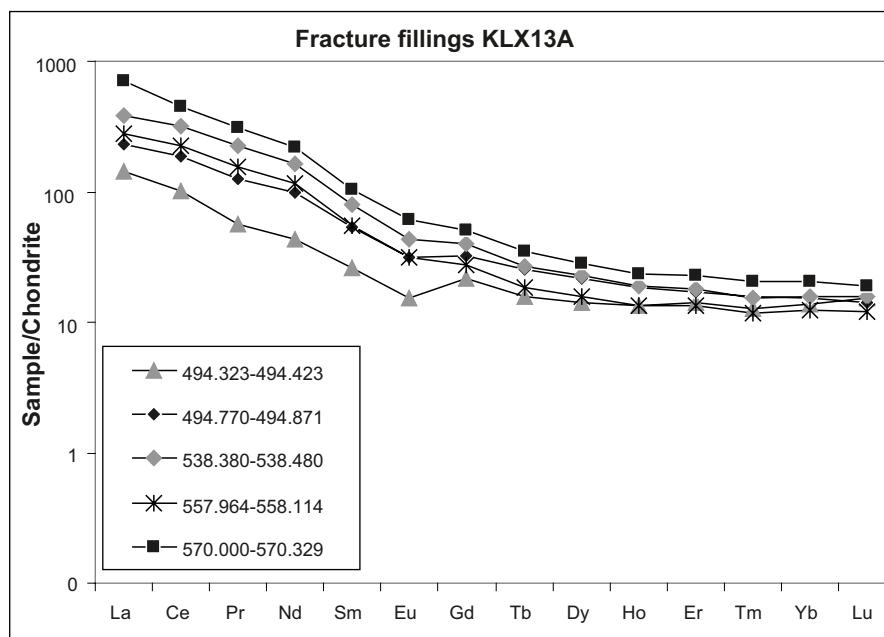


Figure 5-5. Chondrite-normalized REE-values from KLX13A samples. Chondrite values from /Evansen et al. 1978/.

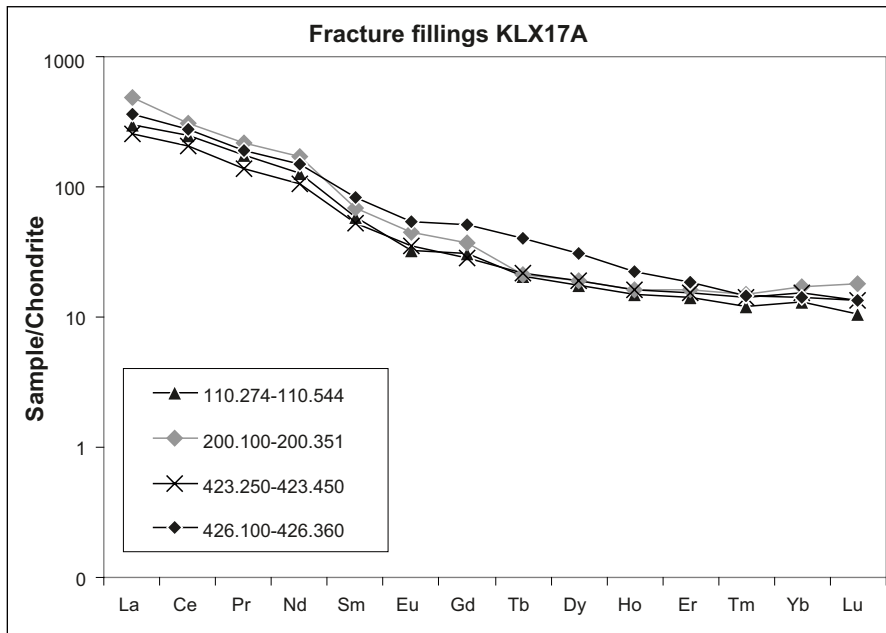


Figure 5-6. Chondrite-normalized REE-values from KLX17A samples. Chondrite values from /Evansen et al. 1978/.

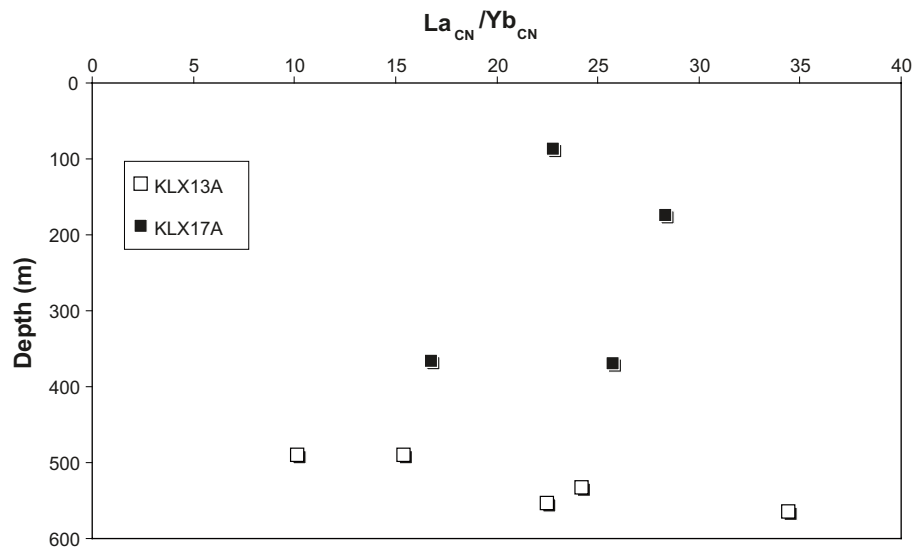


Figure 5-7. Chondrite-normalized La/Yb for KLX13A and KLX17A versus depth. Chondrite values from /Evansen et al. 1978/. CN=Chondrite normalized.

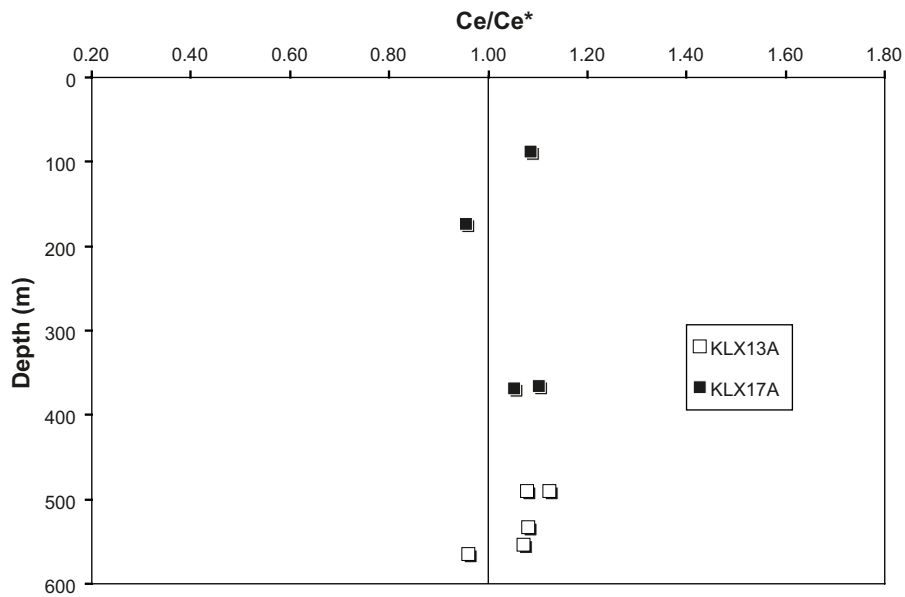


Figure 5-8. Chondrite-normalized Ce/Ce^* for KLX13A and KLX17A versus depth. Chondrite values from /Evansen et al. 1978/. $Ce^*=(La_{CN}*Pr_{CN})/2$.

5.3 $\delta^{13}C$ and $\delta^{18}O$

In order to provide palaeohydrogeological information from water conducting zones 4 calcite samples from KLX13A and 4 calcite samples from KLX17A have been analysed for $\delta^{13}C$ ($^{13}C/^{12}C$, VPDB) and $\delta^{18}O$ ($^{18}O/^{16}O$, VPDB). Results from these analyses are shown in Appendix 11.

The calcites are sampled from open fractures. In some of these fractures it has been possible to sample euhedral calcite crystals grown in open space. Notations have been made on crystal morphology when possible since correspondence between calcite morphology (long and short c-axis) and groundwater salinity has been found in other studies e.g. in Sellafeld /Milodowski et al. 1998/ and in the PADAMOT study /Milodowski et al. 2005/. The observations from these studies support that carbonates precipitated from fresh water usually form short c-axis crystals (nailhead shaped) whereas calcite precipitated from saline waters preferably form long c-axis crystals (scalenohedral shapes). Equant crystals are common in transition zones of brackish water.

In the samples from KLX13A and KLX17A it has been possible to analyse scalenohedral and equant crystals for $\delta^{13}C$ and $\delta^{18}O$. Two samples from KLX17A with calcite crystals without any specific morphology were also analysed. The KLX13A samples are from about 401 to 534 m (vertical depth) and the KLX17A samples are from about 276 to 374 m (vertical depth). The $\delta^{13}C$ versus $\delta^{18}O$ values for the KLX13A and KLX17A calcites are plotted in Figure 5-9 together with previously analysed calcites from Laxemar, Simpevarp and Götemar, values from /Drake and Tullborg 2004, 2006ab, 2007, 2008/.

The KLX13A and KLX17A calcites show extreme variations in $\delta^{13}C$ (-99.7 to -7.3‰) while the variation in $\delta^{18}O$ is relatively small (-10.9 to -5.5‰). Based on fractionation factors by /O'Neil et al. 1969/, the $\delta^{18}O$ values indicate that these calcites possibly precipitated from meteoric or brackish Baltic Sea water at ambient temperatures in the range of $7-15^{\circ}C$. The large spread in the $\delta^{13}C$ values support interaction with biogenic carbon. Extreme $\delta^{13}C$ values ($< -30\text{‰}$ down to -99.7‰) indicate biogenic activity in the groundwater aquifers causing disequilibria in situ. It should be noted that the fractionation between HCO_3^- and $CaCO_3$ is only a few per mille and the $\delta^{13}C$ value in the calcite therefore largely reflects the composition in the bicarbonate at the time of calcite formation. Scalenohedral crystals show much larger variation in $\delta^{13}C$ (-99.7 to -14.2‰) and slightly larger variation in $\delta^{18}O$ (-9.1 to -5.5‰) than equant crystals ($\delta^{13}C$: -24.5

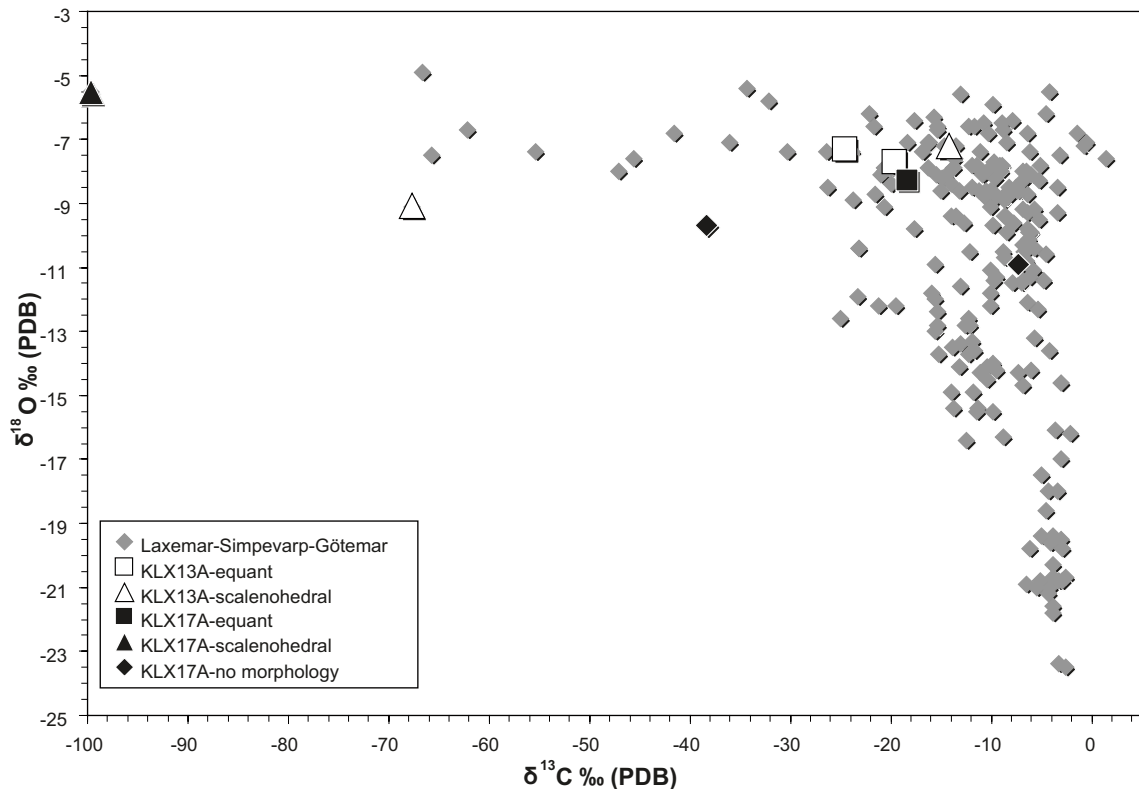


Figure 5-9. $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ plot of calcite with different crystal shapes from KLX13A and KLX17A along with earlier analysed calcite from Laxemar, Simpevarp and Götemar.

to 18.4‰; $\delta^{18}\text{O}$: -8.3 to -7.3‰). Hydrothermal values ($\delta^{18}\text{O}$: -25 to -15, and $\delta^{13}\text{C}$: -7 to -3‰), without signs of biogenic carbon or typical “warm brine” signatures ($\delta^{18}\text{O}$: ~-17 to -11, and $\delta^{13}\text{C}$: -16 to -10‰) are lacking. These types have earlier been distinguished in this area /Bath et al. 2000, Drake and Tullborg 2004, 2006ab, 2007, Tullborg 2004/ and are thought to be formed before 1,400 Ma and at ~ 443–400 Ma, respectively /Drake et al. 2007/. This, along with earlier results indicates that the analysed calcite crystals KLX13A and KLX17A are younger than 400 Ma.

$\delta^{18}\text{O}$ -values close to zero have been found in calcites from the Äspö drill cores (interpreted as possible precipitates from marine waters of Ocean type), but are not found in the analysed samples from the KLX13A and KLX17A.

Figures 5-10 and 5-11 show $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ plotted versus depth for KLX13A and KLX17A calcite samples along with previously analysed calcites from Laxemar, Simpevarp and Götemar, values from /Drake and Tullborg 2004, 2006ab, 2007, 2008/.

Figure 5-10 shows that calcite that might be precipitated meteoric water (samples with no morphology and possibly also equant calcite, scalenohedral is thought to be formed from saline waters, though) at ambient temperatures is found in both KLX13A and KLX17A; down to depths of 533 m in KLX13A and 367 m in KLX17A. Figure 5-10 also shows that calcite that might be precipitated from Baltic Sea water (scalenohedral crystals) at ambient temperatures is found in KLX17A only and that this water may have reached at least down to depths of 374 m in this borehole.

Figure 5-11 shows that KLX13A- and KLX17A-calcites with carbon of biogenic origin are found down to at least 534 m and 374 m, respectively and that microbial influence (in situ disequilibrium) is traceable down to 447 m (KLX13A) and 374 m (KLX17A) which is in accordance with earlier studies in the Laxemar subarea, which have shown $\delta^{13}\text{C}$ values of below -50‰ down to 660 m depth (e.g. /Drake and Tullborg 2007/).

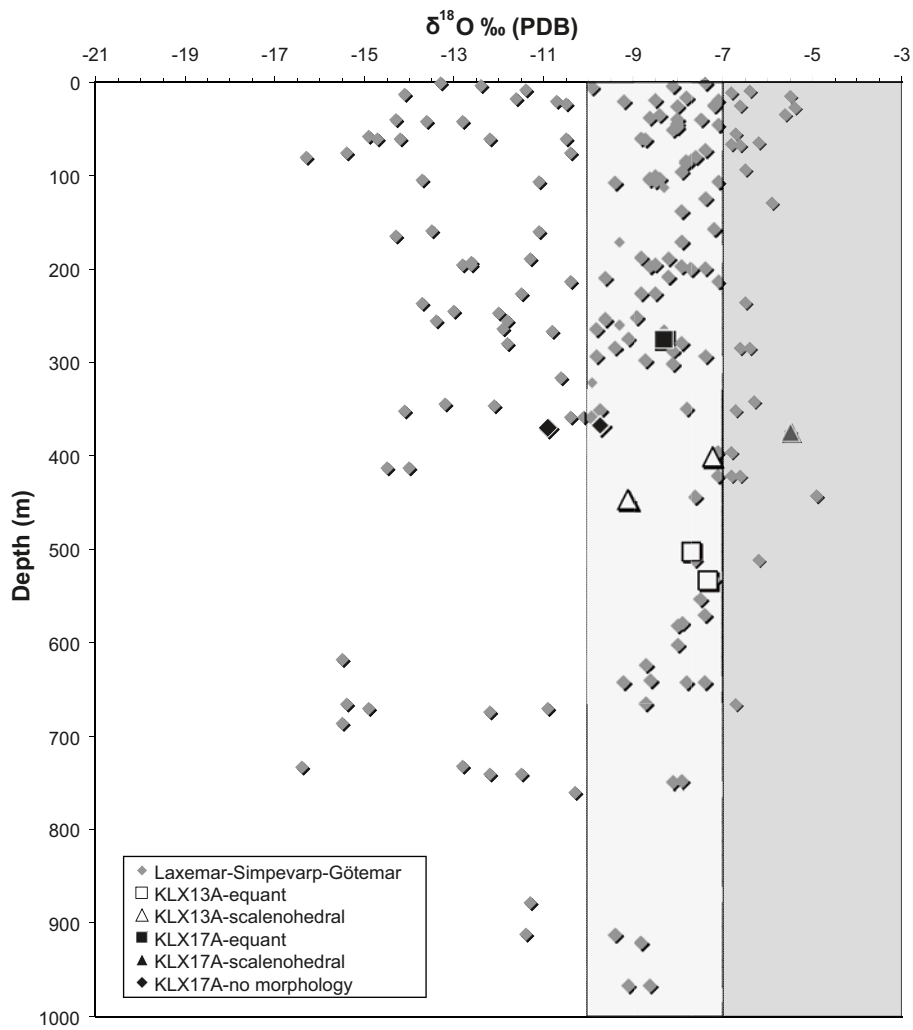


Figure 5-10. Plot of $\delta^{18}\text{O}$ versus depth for samples from KLX13A and KLX17A along with calcite from Laxemar, Simpevarp and Götemar. Included in the plot are fields representing calcite precipitated from Baltic Sea water (dark grey) and meteoric water (to the left of Baltic Sea water) at ambient temperatures.

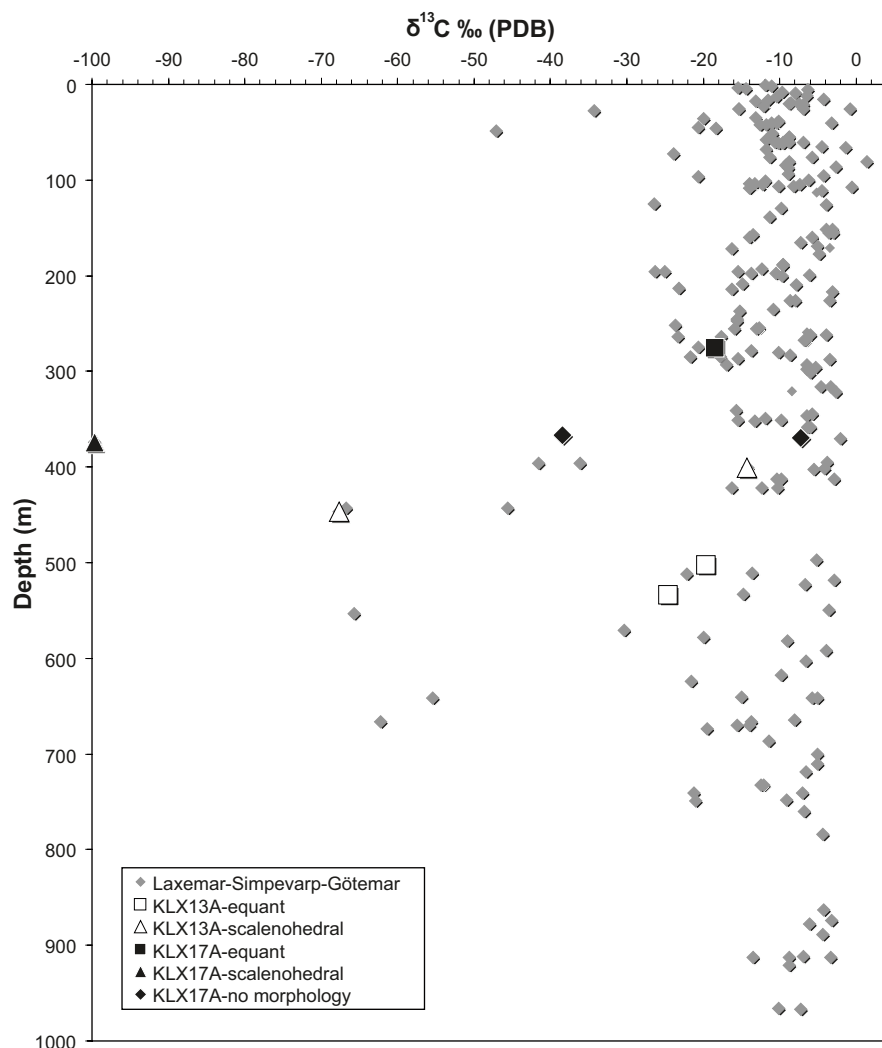


Figure 5-11. Plot of $\delta^{13}\text{C}$ versus depth with samples from KLX13A and KLX17A along with calcite from Laxemar, Simpevarp and Götemar.

5.4 $^{87}\text{Sr}/^{86}\text{Sr}$

Sample KLX17A: 315.479–315.759 m is the only calcite sampled for $^{87}\text{Sr}/^{86}\text{Sr}$ and has a ratio of 0.714615 (± 0.000012). This ratio is somewhat lower than earlier analysed young, potentially recent, calcite ($^{87}\text{Sr}/^{86}\text{Sr}$: 0.715–0.717) from the Laxemar subarea /Wallin and Peterman 1999, Drake and Tullborg 2004, 2006ab, 2007, 2008/ which is in the range of the present groundwater $^{87}\text{Sr}/^{86}\text{Sr}$ composition. The slightly lower value in the sample from KLX17A might however reflect the mafic wall rock composition. Most of the Laxemar subarea is composed of Ävrö granite, which has a higher Rb content than the mafic rock, thus giving higher input of radiogenic Sr to the fracture fluids in Ävrö granitic rock than in mafic sections. Such wall rock influence on the fracture-filling calcite has earlier been shown by /Drake and Tullborg 2007/.

5.5 Trace element analysis of calcite

The trace element content in calcite was analysed for sample KLX17A:315.479–315.759 m (equant crystals), and was analysed twice on the same bulk leachate. The results are found along with analyses of additional samples from KLX14A and KLX19A in Appendix 12. The calcite from sample KLX17A:315.479–315.759 m shows low trace element content, e.g. of REEs, Sr, Mn, Ba, Th and U.

6 Summary

There are no significant differences in fracture filling mineralogy with increasing depth or between the samples from KLX13A and KLX17A. Most of the sampled fractures were coated by a mixture (proportions vary between the samples) of clay minerals (often mixed layer clay/chlorite; sometimes swelling, and illite), chlorite, calcite, hematite, pyrite, and wall rock fragments such as K-feldspar, quartz, plagioclase and sometimes biotite. Hematite is observed on most fracture surfaces but the content is generally small. There are also trace amounts of barite and more rarely REE-carbonate, galena, apatite, goethite, sphalerite, titanite, chalcopyrite, epidote and zeolites (analcime and harmotome) in some samples.

The fracture surface morphology varies between different samples and within the samples. Most common is a fairly smooth surface with minor parts of the surface being rugged due to crystal aggregates. Some fracture surfaces, commonly chlorite/clay mineral-rich, are very smooth and occasionally slickensided. Euhedral calcite and pyrite crystals are common on several of the investigated fracture surfaces, indicating a) the minerals were formed in open fractures with apertures enough to allow euhedral crystals of up to ~100 μm (locally of millimetre size) to form and b) if movements along the fracture planes have taken place they have been very limited.

Most samples are from Ävrö granite rich sections. There are no significant differences in major, minor and trace element chemistry between the KLX13A-samples and the samples from KLX17A and no major chemical variation with depth has been observed in the samples studied.

The concentrations of SiO_2 and Na_2O are lower in all fracture filling samples compared to Ävrö granite. This is generally due to a lower amount of quartz and feldspars in the fracture fillings than in the wall rock. Al_2O_3 , K_2O , CaO , P_2O_5 , TiO_2 , Cu, Ga, Hf, Mo, Nb, Sn, Sr, Ta, Th, U, Y, W and Zr are similar in the fracture fillings as in the wall rock. The K_2O concentration in the fracture fillings depends on the amount of K-feldspar, illite, K-rich clay minerals and possibly mica. The CaO and Sr concentration mainly depends on the calcite, plagioclase and possibly also clay mineral content of the fracture filling.

The concentrations of Fe_2O_3 , MgO, MnO, Co and V (and partly Cr, Ni and Sc) are generally higher in the fracture filling samples compared to the Ävrö granite. The higher concentrations of these elements in the fracture fillings compared to the wall rock are mainly due to the higher contents of chlorite, clay mineral (e.g. Mg-rich illite) and partly also hematite (at least in the very Fe_2O_3 - [33 wt. %] and hematite-rich sample KLX17A:200.100–200.351 m).

Loss on Ignition (LOI) was only measured for the KLX13A samples. LOI is much higher in the KLX13A samples than in the wall rock, due to the amount of water-bearing minerals such as chlorite and clay minerals in the fracture fillings. An equally high or higher LOI value as in KLX13A can also be expected for the KLX17A (based on the total values).

The Ba content is generally lower in the fracture fillings than in the wall rock (which has high Ba contents in K-feldspar). The fracture fillings with similar Ba contents as in the wall rock have high contents of K-feldspar and occasionally include small crystals of barite as well.

Cs and Rb are found in slightly higher to significantly higher concentrations than in the wall rock in about 50 percent of the samples. The enrichment of these elements is related to breakdown of biotite in the wall rock and the high chlorite and clay mineral (and probably also K-feldspar) contents in the fracture fillings.

The REE-values for fracture fillings from KLX13A and KLX17A are all very similar to each other and have similar chondrite-normalized patterns, as the Ävrö granite, which shows that no major fractionation of REEs have occurred. However, the REE concentrations are generally

somewhat higher and La/Yb-ratios are sometimes higher in the fracture filling samples compared to Ävrö granite, which might suggest organic influence. There are no major fractionations of the redox sensitive elements Ce and Eu.

Calcite samples from KLX13A and KLX17A show extreme variations in $\delta^{13}\text{C}$ (-99.7 to -7.3‰) while the variation in $\delta^{18}\text{O}$ is smaller (-10.9 to -5.5‰). The $\delta^{18}\text{O}$ values indicate that the calcites possibly were precipitated from meteoric or brackish Baltic Sea water at ambient temperatures in the range of $7\text{--}15^\circ\text{C}$. The large spread in the $\delta^{13}\text{C}$ values support interaction with biogenic carbon and the extreme $\delta^{13}\text{C}$ values ($< -30\text{‰}$, traceable down to 447 m in KLX13A and organic influence down to 534 m and down to 374 m in KLX17A) indicate biogenic activity in the groundwater aquifers causing disequilibria in situ. Scalenohedral crystals show much larger variation in $\delta^{13}\text{C}$ and slightly larger variation in $\delta^{18}\text{O}$ than equant crystals. Typical hydrothermal, “warm brine” or oceanic signature are not found although identified in this area by /Wallin and Peterman 1999, Bath et al. 2000, Drake and Tullborg 2004, 2006ab, 2007, Tullborg 2004/.

Calcite that might be precipitated from meteoric water (crystals without any specific morphology and possibly equant crystals) at ambient temperatures is found in both KLX13A and KLX17A down to depths of 533 m in KLX13A and 367 m in KLX17A. Scalenohedral calcite that might be precipitated from Baltic Sea water at ambient temperatures is found in KLX17A only down to depths of 374 m.

The only calcite sampled for $^{87}\text{Sr}/^{86}\text{Sr}$ has a slightly lower value than earlier analysed young, potentially recent, calcite from the Laxemar subarea /Drake and Tullborg 2004, 2006ab, 2007, 2008/. However, this lower value might reflect the atypical (mafic) wall rock composition of this sample. This sample also shows low trace element compositions.

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Sample descriptions KLX13A

KLX13A: 404.450–404.460 m

Sample type: Surface sample.

Rock type: Ävrö granite.

Fracture: Open fractures (342°/85°, 319°/62°, 86°/6°, 315°/11°).

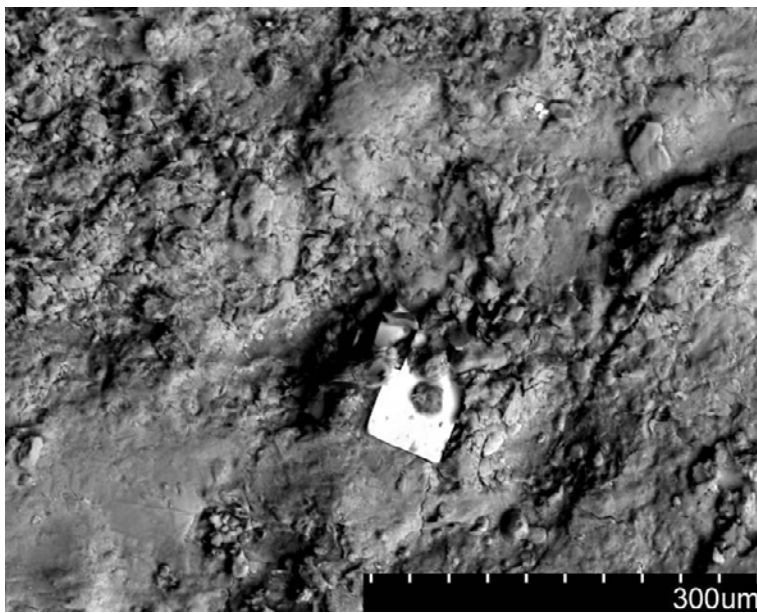
Deformation zone: None.

Crush zone: No.

Sealed network: No.

Minerals (identified using SEM-EDS): Chlorite (also as mixed-layer clay, Ca- or K-rich), quartz, illite, pyrite (cubic), albite, calcite (scalenohedral) and hematite.

Surface: Partly rough and partly smooth.



*Euhedral pyrite (bright) and chlorite/mixed layer-clay. Back-scattered SEM-image.
Sample KLX13A: 404.450–404.460 m.*

KLX13A: 450.800–450.850 m

Sample type: Surface sample.

Rock type: Ävrö granite.

Fracture: Highly fractured section. Orientations of the bordering fractures are $130^{\circ}/4^{\circ}$ and $35^{\circ}/30^{\circ}$. Orientations of fractures within the fractured section are $82^{\circ}/50^{\circ}$, $77^{\circ}/77^{\circ}$ and $266^{\circ}/85^{\circ}$.

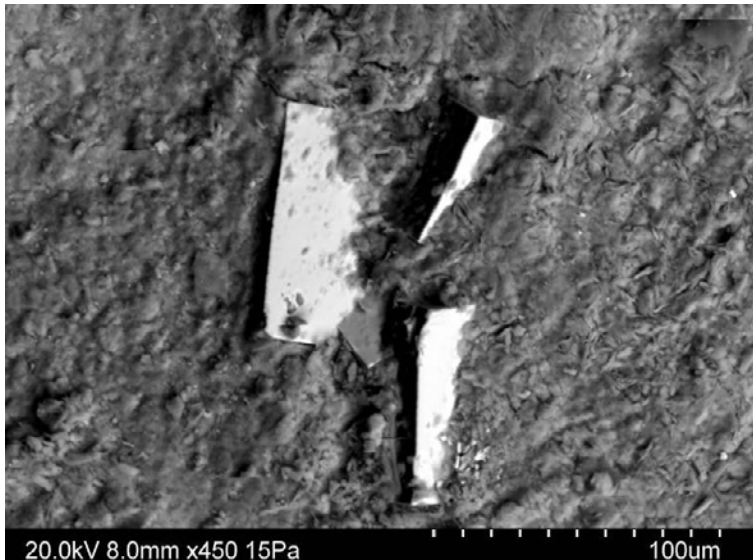
Deformation zone: None.

Crush zone: Yes.

Sealed network: No.

Minerals (identified using SEM-EDS): Chlorite (also as mixed-layer clay, Ca- or K-rich, sometimes Mn-rich), K-feldspar, calcite (with barite and pyrite on the crystal surface), illite, pyrite (cubic), hematite, plagioclase and apatite.

Surface: Partly quite rough and partly smooth.



*Euhedral pyrite (bright) and chlorite/mixed layer-clay. Back-scattered SEM-image.
Sample KLX13A: 450.800–450.850 m.*

KLX13A: 494.323–494.423 m

Sample type: Surface sample.

Rock type: Ävrö granite.

Fracture: Cataclasite with wall rock fragments of variable sizes and numerous parallel open fractures (with high amount of loose, crush material). Orientations of the fractures are: 75°/67°, 73°/68°, 73°/67°, 81°/65°, 81°/50°, 64°/51° and 103°/59°.

Deformation zone: ZSMEW120A.

Crush zone: Yes.

Sealed network: Yes.

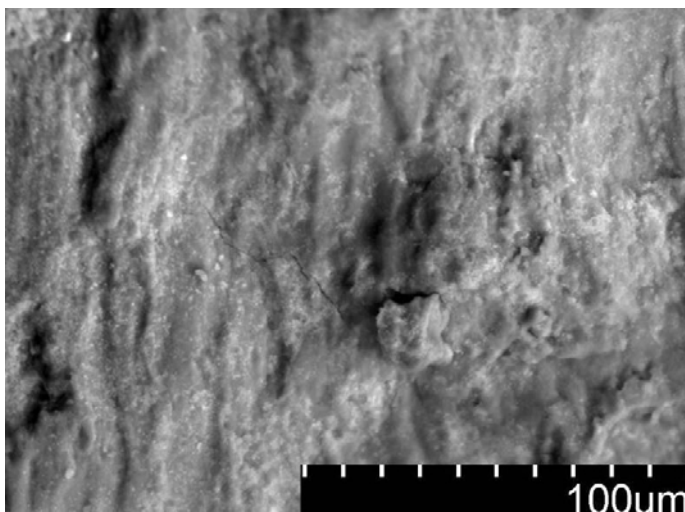
Minerals (identified using SEM-EDS): Chlorite (also as mixed-layer clay, K-rich and often Ti-rich), quartz, illite, hematite, wall rock fragments and barite.

Minerals (identified using XRD): Plagioclase, K-feldspar, quartz, chlorite, hematite and illite (fine-grained).

Surface: Mostly smooth, sometimes slickensided.



Photograph of the drill core KLX13A: 494.323–494.423 m.



Rather smooth fracture surface mainly consisting of chlorite/mixed layer-clay and hematite (bright spots). Back-scattered SEM-image. Sample KLX13A: 494.323–494.423 m.

KLX13A: 494.770–494.871 m

Sample type: Surface sample.

Rock type: Ävrö granite.

Fracture: Cataclasites and numerous open fractures with a high amount of loose, fine-grained, crush material. Orientations of the fractures are similar to those in the sample above. Orientations of open fractures: 103°/59°, 52°/65°, 318°/7°. Orientation of sealed network: mainly 318°/7°.

Deformation zone: ZSMEW120A.

Crush zone: Yes.

Sealed network: Yes.

Minerals (identified using SEM-EDS): Chlorite (also as mixed-layer clay, Ca- and K-rich), illite, wall rock fragments and hematite.

Minerals (identified using XRD): Chlorite, plagioclase, K-feldspar, quartz, calcite, swelling clay (smectite and minor amounts of illite) and hematite.

Surface: Rough.



Photograph of sample KLX13A: 494.770–494.871 m. High amount of fine-grained material is contained in the plastic bag. The rock is highly fractured and consists of cataclasites of different grades.

KLX13A: 506.750–506.999 m

Sample type: Surface sample.

Rock type: Ävrö granite.

Fracture: Open fracture (157°/78°).

Deformation zone: ZSMEW120A.

Crush zone: No.

Sealed network: Yes.

Minerals (identified using SEM-EDS): Calcite (nailhead and sometimes equant), chlorite (also as mixed-layer clay; Ca⁻ and K-rich), illite, K-feldspar, albite, quartz, pyrite (cubic fresh), wall rock fragments, titanite and barite.

Surface: Rather smooth.



Photograph of the fracture surface of sample KLX13A: 506.750–506.999 m, consisting of calcite (bright) on top of e.g. chlorite.

KLX13A: 538.380–538.480 m

Sample type: Surface sample.

Rock type: Ävrö granite.

Fracture: Open fractures ($11^{\circ}/33^{\circ}$, $184^{\circ}/88^{\circ}$, $146^{\circ}/82^{\circ}$, $318^{\circ}/7^{\circ}$) and cataclasite (sealed network $318^{\circ}/7^{\circ}$) with altered wall rock.

Deformation zone: ZSMEW120A.

Crush zone: Yes.

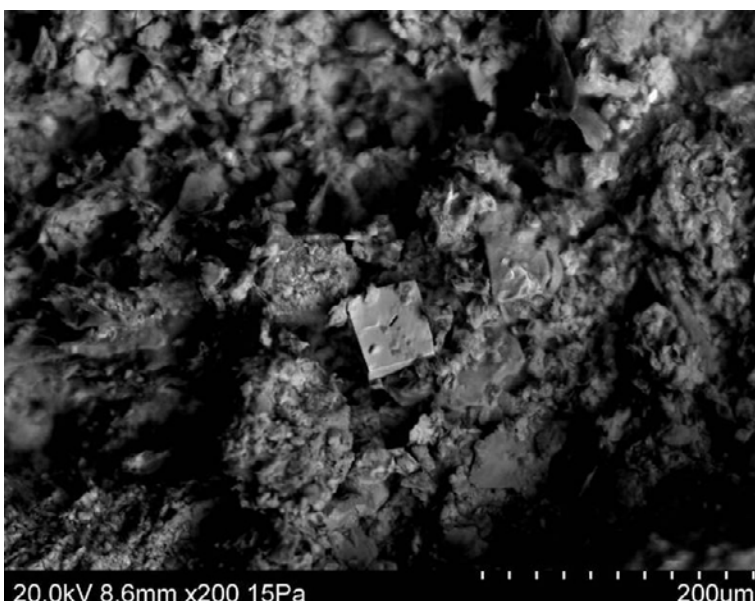
Sealed network: Yes.

Minerals (identified using SEM-EDS): Chlorite (also as mixed-layer clay, Ca- and K-rich often Ti-rich), illite, calcite, K-feldspar, albite, quartz, pyrite (cubic fresh), hematite, wall rock fragments, apatite and barite.

Surface: Moderately rough.



Photograph of the drill core KLX13A: 538.380–538.480 m.



*Rather rough fracture surface mainly consisting of chlorite/mixed layer-clay and pyrite (cubic).
Back-scattered SEM-image. Sample KLX13A: 538.380–538.480 m.*

KLX13A: 557.964–558.114 m

Sample type: Surface sample.

Rock type: Ävrö granite.

Fracture: Numerous open fractures and high amount of fine-grained, loose, crush material. The wall rock is heavily altered (e.g. red-stained and mineral specific dissolution) and penetrated by cataclasites. Orientation of the upper rim of the fractured section: $99^{\circ}/35^{\circ}$. Orientation of the lower rim of the fractured section: $124^{\circ}/30^{\circ}$. Sealed network: $319^{\circ}/7^{\circ}$.

Deformation zone: ZSMEW120A.

Crush zone: No.

Sealed network: Yes.

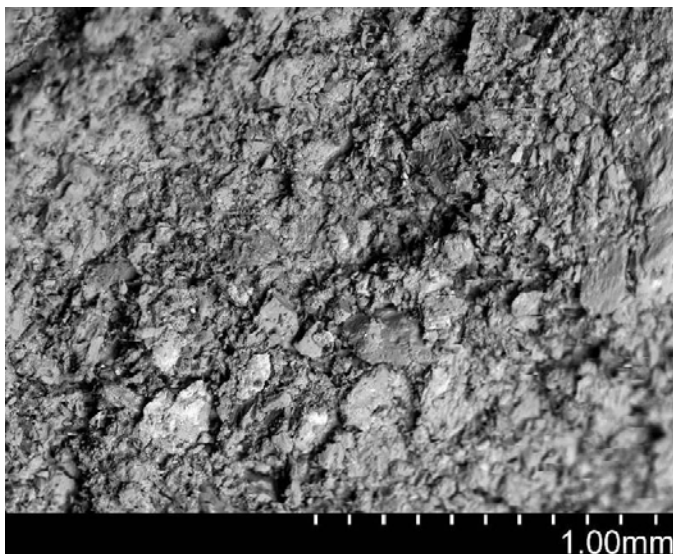
Minerals (identified using SEM-EDS): Illite, chlorite (also as mixed-layer clay; Ca- and K-rich), wall rock fragments and hematite.

Minerals (identified using XRD): Chlorite, plagioclase, K-feldspar, quartz, illite and swelling clay (illite/smectite and/or smectite/illite).

Surface: Rough.



Photograph of the drill core KLX13A: 557.964–558.114 m characterised by highly fractured rock (cataclasite dominated) with high amount of fine-grained (crush) material.



Rather rough fracture surface mainly consisting of chlorite/mixed layer-clay and illite along with wall rock fragments. Back-scattered SEM-image. Sample KLX13A: 557.964–558.114 m.

KLX13A: 570.000–570.329 m

Sample type: Surface sample.

Rock type: Ävrö Granite.

Fracture: Pronounced open fracture (209°/88°) running parallel with the borehole for more than a meter. Less pronounced (minor) open fractures have orientations 335°/52°, 312°/42°, 304°/46°, 348°/31°, 340°/52° and 284°/39°. Sealed network has an orientation of 319°/7°.

Deformation zone: ZSMEW120A.

Crush zone: No.

Sealed network: Yes.

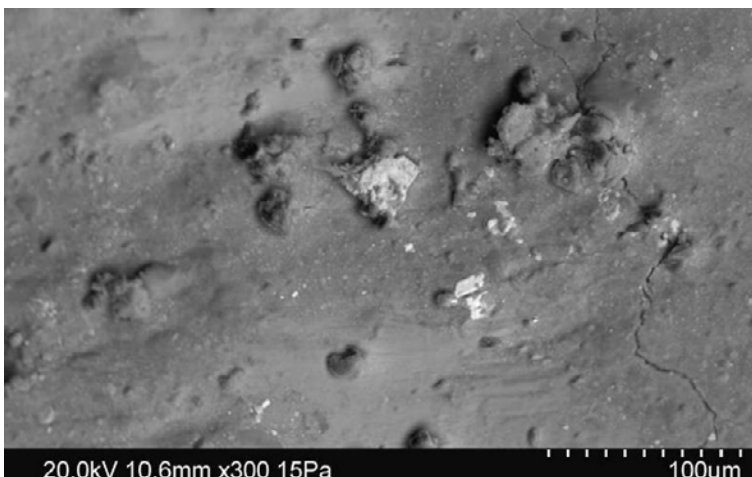
Minerals (identified using SEM-EDS): Chlorite (also as mixed-layer clay; Ca- and K-rich often Ti-rich), illite, pyrite (partly altered), hematite, wall rock fragments, galena, sphalerite and native Zn.

Minerals (identified using XRD): Chlorite, plagioclase, K-feldspar, quartz, calcite, and clay minerals (vermiculite, illite and corrensite).

Surface: Smooth, slickensided.



Photograph of the drill core KLX13A: 570.000–570.329 m, with smooth fracture surfaces dominated by clay minerals/chlorite along with hematite (red-stained parts) and wall rock fragments.



Smooth fracture surface mainly consisting of chlorite/mixed layer-clay and illite, covered by brighter sulphides (pyrite, galena, sphalerite) and some hematite. Back-scattered SEM-image. Sample KLX13A: 570.000–570.329 m.

Sample descriptions KLX17A

KLX17A: 110.274–110.544 m

Sample type: Surface sample.

Rock type: Ävrö granite.

Fracture: Several parallel open fractures (orientations e.g. $99^{\circ}/59^{\circ}$ and $77^{\circ}/41^{\circ}$), partly gouge, crushed sections ($87^{\circ}/29^{\circ}$, $187^{\circ}/29^{\circ}$, $229^{\circ}/14^{\circ}$ and $189^{\circ}/30^{\circ}$) and cataclasites ($103^{\circ}/29^{\circ}$, $170^{\circ}/25^{\circ}$ and $57^{\circ}/39^{\circ}$). The wall rock is altered (red-stained).

Deformation zone: ZSMEW900A.

Crush zone: Yes.

Sealed network: Yes.

Minerals (identified using SEM-EDS): Clay minerals (chlorite in mixed-layer clay), illite, quartz, K-feldspar, hematite, calcite (mostly scalenohedral), albite (and apatite).

Minerals (identified using XRD): Chlorite, plagioclase, K-feldspar, quartz, illite, and hematite.

Surface: Mostly rough (with some smooth parts).



Photograph of drill core KLX17A: 110.274–110.544 m, showing a very rough fracture surface with variable thickness of the coating.

KLX17A: 200.100–200.351 m

Sample type: Surface sample.

Rock type: Ävrö granite.

Fracture: Cataclasite (partly gauge) with open and sealed fractures (orientations: 108°/30°, 108°/30°, 68°/27° and 284°/9°). Red-stained wall rock.

Deformation zone: None.

Crush zone: No.

Sealed network: Yes.

Minerals (identified using SEM-EDS): Clay minerals, chlorite, hematite, epidote, chalcopyrite, and small amounts of Te- and Tc-rich minerals.

Minerals (identified using XRD): Chlorite, hematite, illite, illite/smectite, K-feldspar, quartz, and small amounts of apatite.

Surface: Mostly rough.



Photograph of the drill core KLX17A: 200.100–200.351 m, rich in cataclasite and loose material.

KLX17A: 315.479–315.759 m

Sample type: Surface sample.

Rock type: Mafic rock, fine-grained.

Fracture: Open fractures (reactivated prehnite-epidote dominated breccia). One of the open fracture surfaces is rough with euhedral mm-sized crystals of calcite ($228^{\circ}/12^{\circ}$). Other fracture surfaces are smooth and sometimes striated and covered with Prehnite, epidote, chlorite and clay minerals, possibly along with wall rock fragments.

Deformation zone: None.

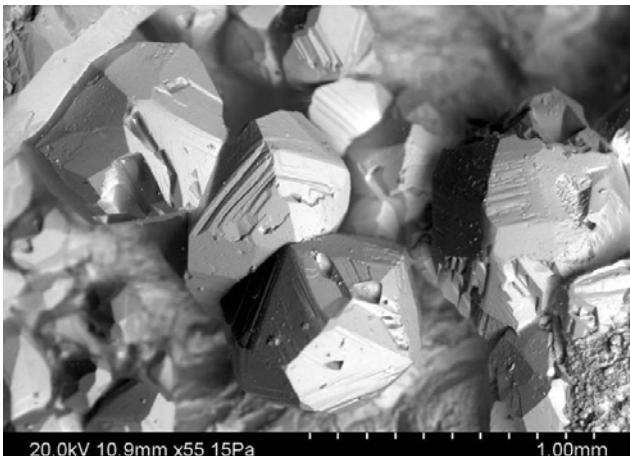
Crush zone: No.

Sealed network: No.

Minerals (identified using SEM-EDS): Calcite (equant), and small amounts of pyrite, clay minerals and REE-carbonate.



Photograph of the one of the fracture surfaces of sample KLX17A: 315.479–315.759 m. The surface is mainly coated by equant calcite crystals.



Back-scattered SEM-image of equant calcite crystals. Sample KLX17A: 315.479–315.759 m (same fracture surface as above).

KLX17A: 423.250–423.450 m

Sample type: Surface sample.

Rock type: Ävrö granite.

Fracture: Open fractures, with crush material (65°/35°, 63°/44°, 65°/35° and 359°/23°). Fracture surfaces are covered with chlorite, clay minerals, pyrite (possibly also goethite) and fine-grained wall rock fragments.

Deformation zone: None.

Crush zone: Yes.

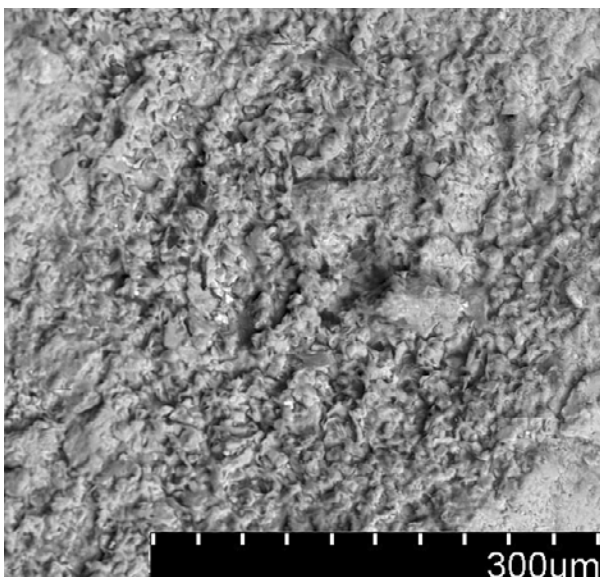
Sealed network: No.

Minerals (identified using SEM-EDS): Chlorite, mixed-layer clay, pyrite, calcite (and goethite).

Minerals (identified using XRD): Calcite, chlorite, clay minerals (swelling; vermiculite, smectite, smectite/chlorite), quartz, K-feldspar and plagioclase.



Photograph of the highly fractured drill core sample KLX17A: 423.250–423.450 m.



*Back-scattered SEM-image chlorite/mixed-layer clay coating a fracture surface.
KLX17A: 423.250–423.450 m.*

KLX17A: 426.100–426.360 m

Sample type: Surface sample.

Rock type: Mafic rock, fine-grained.

Fracture: Four sub-parallel open fractures (38°/31°, 42°/28°, 41°/33°, 88°/23°) with smooth surfaces (partly striated).

Deformation zone: None.

Crush zone: No.

Sealed network: Yes.

Minerals (identified using SEM-EDS): Chlorite, clay minerals, a thin partial calcite cover, and wall rock fragments.

Minerals (identified using XRD): Chlorite, calcite, plagioclase, K-feldspar, clay minerals (swelling; smectite/illite), illite, quartz, and biotite.



Photograph of the drill core sample KLX17A: 426.100–426.360 m.



Photograph of one of the fracture surfaces of sample KLX17A: 426.100–426.360 m, showing a smooth, slickensided chlorite/clay mineral-dominated fracture coating.

KLX17A: 431.460–431.660 m

Sample type: Surface sample.

Rock type: Mafic rock, fine-grained.

Fracture: Three sub-parallel open fractures ($350^{\circ}/20^{\circ}$, $6^{\circ}/13^{\circ}$, $359^{\circ}/13^{\circ}$, $16^{\circ}/14^{\circ}$) with rough fracture surfaces. Mm-sized crystals of analcime are visible on the surfaces. The fractures are oriented sub-parallel to the foliation of the rock.

Deformation zone: None.

Crush zone: No.

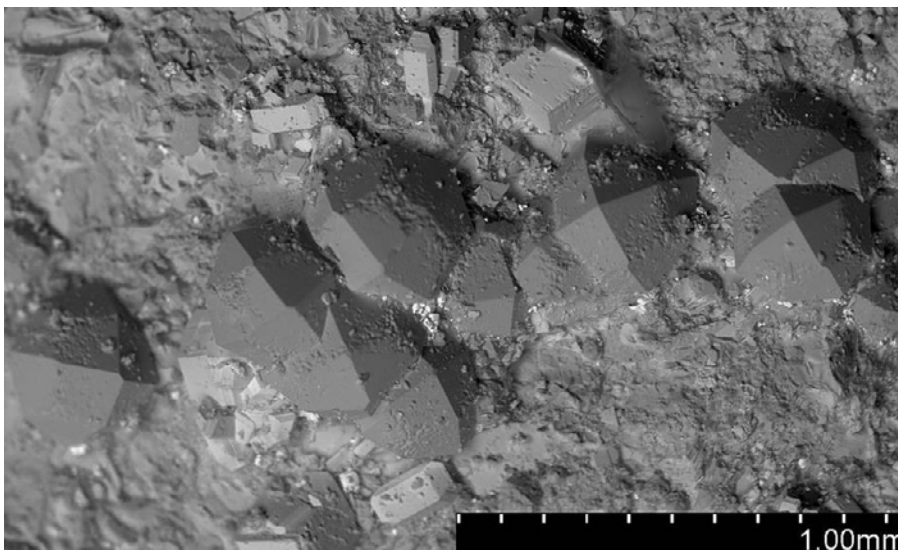
Sealed network: No.

Minerals on the fracture surface (identified using SEM-EDS): Analcime (both as Euhedral cubes and as elongated needle shaped crystals), harmotome (euhedral), calcite (mostly scalenohedral), pyrite, mixed-layer clay, barite and hematite.

Surface: Mostly rough.



Photograph of the drill core sample KLX17A: 431.460–431.660 m.



*Back-scattered SEM-image of euhedral analcime (dark) and harmotome (bright).
Sample KLX17A: 431.460–431.660 m.*

Sample description KLX13A (additional sample)

KLX13A: 337.153–337.479 m

Sample type: Thin section.

Rock type: Ävrö granite.

Fracture: Sealed fracture (87°/72°).

Deformation zone: None.

Crush zone: No.

Sealed network: No.

Minerals (identified using SEM-EDS): Quartz, plagioclase, calcite, titanite, pyrite and biotite.

Sample descriptions KLX17A (additional samples)

KLX17A: 449.800–449.880 m

Sample type: Surface sample.

Rock type: Ävrö granite.

Fracture: Single open fracture (38°/19°) in relatively un-fractured part of the drill core.
No visible wall rock alteration.

Deformation zone: None.

Crush zone: No.

Sealed network: No.

Minerals (identified using SEM-EDS): Apophyllite, mixed-layer clay/chlorite, chlorite, calcite, gypsum, pyrite, barite, hematite, biotite (and gold, < 10 µm, single occurrence).



*Photograph of the fracture surface of sample KLX17A: 449.800–449.880 m.
Gypsum is present along with apophyllite as a thin whitish-grey coating.*

KLX17A: 590.652–590.766 m

Sample type: Surface sample.

Rock type: Ävrö granite.

Fracture: Single open fracture (286°/75°) in relatively un-fractured part of the drill core.
No visible wall rock alteration.

Deformation zone: None.

Crush zone: No.

Sealed network: No.

Minerals (identified using SEM-EDS): Apophyllite, gypsum, celestine, calcite and hematite.



*Photograph of the fracture surface of sample KLX17A: 590.652 –590.766 m.
Gypsum is present along with apophyllite as a thin bright grey coating.*

Sample descriptions KLX14A (additional samples)

KLX14A: 80.245–80.262 m

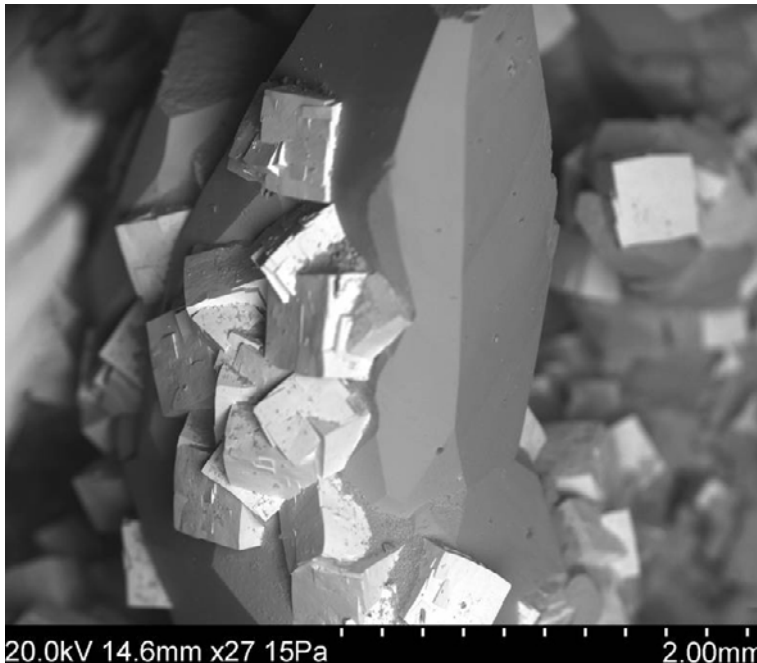
Sample type: Surface sample.

Rock type: Quartz monzodiorite.

Fracture: Open and partly open fractures coated by euhedral calcite crystals covered by pyrite crystals.

Deformation zone: NS059A.

Minerals (identified using SEM-EDS): Calcite (scalenohedral), pyrite (cubic), (mixed-layer clay, Ti-oxide, REE-carbonate).



Back-scattered SEM-image of scalenohedral calcite crystals and cubic pyrite crystals from sample KLX14A: 80.245–80.262 m.

KLX14A: 80.940–81.040 m

Sample type: Surface sample.

Rock type: Granite, fine- to medium-grained.

Fracture: Sealed, open and partly open fractures filled and coated by calcite (euhedral in cavities) and minor amounts of hematite.

Deformation zone: NS059A.

Minerals (identified using SEM-EDS): Calcite (scalenohedral in cavities) and small amounts of hematite.



Photograph of sample KLX14A: 80.940–81.040 m, showing fractures sealed by mainly calcite. Cavities are partly filled with scalenohedral calcite coated by small amounts of hematite.

KLX14A: 81.300–81.360 m

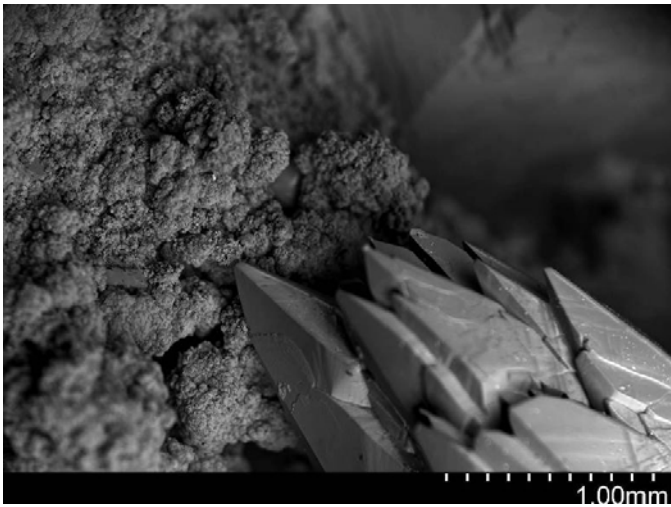
Sample type: Surface sample.

Rock type: Granite, fine- to medium-grained.

Fracture: Sealed, open and partly open fractures filled and coated by mainly calcite (euhedral in cavities).

Deformation zone: NS059A.

Minerals (identified using SEM-EDS): Calcite (scalenohedral, sometimes with overgrowth, no difference in Mn-content), hematite, REE-carbonate, corrensite (spherulitic aggregates), pyrite, chalcopyrite and galena.



Back-scattered SEM-image of scalenohedral calcite crystals (right hand side) and clay minerals (probably mainly corrensite, left) from sample KLX14A: 81.300–81.360 m.

Sample description KLX19A (additional sample)

KLX19A: 412.430–412.531 m

Sample type: Surface sample.

Rock type: Quartz monzodiorite.

Fracture orientation: Upper rim: 115°/89°; lower rim: 117°/87°.

Deformation zone: Not modelled.

Minerals (identified using SEM-EDS): Calcite (scalenohedral, up to 1 cm), chlorite and hematite.



Photograph of sample KLX19A: 412.430–412.531, showing a fracture partly sealed by calcite (white, mostly scalenohedral, sometimes coated by hematite) and chlorite (green).

Sample descriptions KLX20A (additional samples)

KLX20A: 216.180–216.230 m

Sample type: Surface sample.

Rock type: Dolerite.

Fracture: Sealed and open fractures.

Deformation zone: ZSMNS001C.

Minerals in sealed fractures (identified using SEM-EDS):

- Greyish white fracture: Harmotome (partly euhedral) and calcite.
- Green-grey fracture: Fe-Mg-rich chlorite with detected amounts of Ca, Na and Mn but low in Al.



Photograph of the drill core sample KLX20A: 216.180–216.230 m.

KLX20A: 224.180–224.210 m

Sample type: Surface sample.

Rock type: Dolerite.

Fracture: Sealed and open fractures (slickensided, 85°/36° and 83°/38°).

Deformation zone: ZSMNS001C.

Minerals in sealed fracture (identified using SEM-EDS): Calcite, and Mg-rich chlorite (including some Ca).

Minerals in open fracture (identified using SEM-EDS): Ca-Na-Mn-rich chlorite/mixed-layer clay, hematite (on the surface of chlorite/mixed-layer clay).



Photograph of the drill core sample KLX20A: 224.180–224.210 m.

Sample description KLX26A (additional sample)

KLX26A: 17.780–17.930 m

Sample type: Surface sample.

Rock type: Diorite to gabbro.

Fracture: Planar open fracture (332°/68°).

Deformation zone: Not modelled.

Minerals (identified using SEM-EDS): Calcite (needle shaped, nailhead shaped and sometimes scalenohedral), Mixed-layer clay/chlorite, chalcopyrite and Cu-rich mineral.



Photograph of the drill core sample KLX26A: 17.780–17.930 m.

Chemical analyses of fracture fillings – KLX13A

ELEMENT	SecUp	494.323	494.770	538.380	557.964	570.000
	SecLow	494.423	494.871	538.480	558.114	570.329
SiO ₂	%	49.3	43.2	46	53.7	46.5
Al ₂ O ₃	%	15.4	16.9	14	16.3	16.6
CaO	%	1.38	4.97	4.51	2.44	4.29
Fe ₂ O ₃	%	13.8	13.1	12.8	8.67	8.97
K ₂ O	%	5.65	3.53	2.45	4	3.06
MgO	%	5.97	8.47	6.93	5.66	8.83
MnO	%	0.175	0.244	0.203	0.191	0.219
Na ₂ O	%	1.21	1.21	2.58	2.29	2.81
P ₂ O ₅	%	0.449	0.327	0.495	0.41	0.551
TiO ₂	%	1.34	1.27	1.29	0.976	1.47
Total	%	99.5	99.1	98.3	100	96.4
LOI	%	4.8	5.9	7	5.4	3.1
Ba	ppm	1,440	1,060	1,690	770	845
Be	ppm	12.5	7.07	5.14	12	8.77
Co	ppm	26.2	30.4	14.8	14.3	12.8
Cr	ppm	207	178	49.8	42.9	56.2
Cs	ppm	12.2	1.94	1.69	21.6	1.4
Cu	ppm	< 6	< 6	24.3	< 6	< 6
Ga	ppm	25.7	33.4	26.6	29.9	33.8
Hf	ppm	9.17	6.12	9.55	8.28	12.5
Mo	ppm	< 2	< 2	< 2	< 2	< 2
Nb	ppm	21	16	24.5	15.4	28.1
Ni	ppm	80.4	87.2	< 10	33.7	25.5
Rb	ppm	159	87.4	91	204	64
Sc	ppm	22	34.2	15.2	12.8	18.6
Sn	ppm	3.83	3.8	3.34	3.49	3.26
Sr	ppm	212	876	698	648	1,100
Ta	ppm	1.62	1.17	1.96	1.05	1.75
Th	ppm	14.8	8.71	12.5	7.41	12.7
U	ppm	11.6	3.71	5.98	4.61	5.5
V	ppm	177	182	162	126	244
W	ppm	32.8	10.2	4.17	4.03	3.45
Y	ppm	20.9	26.5	28.1	21.1	36.6
Zn	ppm	274	352	2,340	330	314
Zr	ppm	339	210	359	316	487
La	ppm	34.7	57.1	92.7	68.7	175
Ce	ppm	64.1	118	201	143	289
Pr	ppm	5.42	12.1	21.6	15	30
Nd	ppm	20.5	46.8	77.7	54.7	105
Sm	ppm	3.97	8.34	12.2	8.44	16
Eu	ppm	0.898	1.81	2.54	1.84	3.52
Gd	ppm	4.38	6.54	8.12	5.68	10.4
Tb	ppm	0.588	0.945	1	0.696	1.32

	SecUp	494.323	494.770	538.380	557.964	570.000
ELEMENT	SecLow	494.423	494.871	538.480	558.114	570.329
Dy	ppm	3.58	5.55	5.77	4.01	7.24
Ho	ppm	0.766	1.04	1.07	0.755	1.32
Er	ppm	2.35	2.79	2.96	2.21	3.76
Tm	ppm	0.324	0.403	0.397	0.304	0.528
Yb	ppm	2.3	2.5	2.58	2.06	3.43
Lu	ppm	0.387	0.363	0.396	0.309	0.485

Chemical analyses of fracture fillings – KLX17A

ELEMENT	SecUp	110.274	200.100	423.250	426.100
	SecLow	110.544	200.351	423.450	426.360
SiO ₂	%	49.4	34.6	43.5	34.5
Al ₂ O ₃	%	15.5	12.6	11.6	14.2
CaO	%	4.94	1.68	10	4.82
Fe ₂ O ₃	%	10.7	32.9	11	17.5
K ₂ O	%	6.52	4.09	1.54	3.43
MgO	%	3.12	4.01	8.13	12.9
MnO	%	0.115	0.127	0.16	0.33
Na ₂ O	%	1.52	0.547	1.9	0.45
P ₂ O ₅	%	0.445	0.285	0.429	0.23
TiO ₂	%	0.935	0.681	1.08	1.25
Total	%	93.2	91.5	89.3	89.6
LOI	%	n.a.	n.a.	n.a.	n.a.
Ba	ppm	1,020	565	459	673
Be	ppm	7.59	6.65	6.01	11.5
Co	ppm	< 6	487	11.2	24.5
Cr	ppm	< 10	392	203	1,580
Cs	ppm	27	65.8	2.76	98.4
Cu	ppm	25	532	< 6	< 6
Ga	ppm	26.1	35.8	19.8	26
Hf	ppm	7.09	8.01	9.96	5.76
Mo	ppm	< 6	< 6	< 6	< 6
Nb	ppm	15.9	9.36	14.4	10.9
Ni	ppm	58.8	63.9	18.9	17.2
Rb	ppm	234	197	66.8	277
Sc	ppm	< 1	19.3	16	40.4
Sn	ppm	< 20	< 20	< 20	< 20
Sr	ppm	725	425	692	420
Ta	ppm	0.893	0.667	0.892	0.5
Th	ppm	5.79	16	4.65	9.84
U	ppm	7	16	3.86	8.67
V	ppm	236	515	147	291
W	ppm	5.5	55.6	17.5	5.4
Y	ppm	35.7	27.7	27.4	34.5
Zn	ppm	717	1,320	345	333
Zr	ppm	283	341	423	230
La	ppm	72.9	118	62.9	88.5
Ce	ppm	158	198	133	176
Pr	ppm	16.8	21	13.4	18.3
Nd	ppm	60.9	81	50.1	70
Sm	ppm	9.09	10.7	8.02	12.7
Eu	ppm	1.88	2.61	2.04	3.15
Gd	ppm	6.23	7.56	5.88	10.4
Tb	ppm	0.779	0.803	0.815	1.49

ELEMENT	SecUp	110.274	200.100	423.250	426.100
	SecLow	110.544	200.351	423.450	426.360
Dy	ppm	4.48	4.77	4.82	7.83
Ho	ppm	0.849	0.927	0.925	1.25
Er	ppm	2.38	2.69	2.57	3.05
Tm	ppm	0.308	0.379	0.365	0.37
Yb	ppm	2.16	2.81	2.53	2.32
Lu	ppm	0.269	0.458	0.342	0.341

$\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ in calcite

Borehole	SecUp	SecLow	$\delta^{13}\text{C}$ ‰ _{PDB}	$\delta^{18}\text{O}$ ‰ _{PDB}	$^{87}\text{Sr}/^{86}\text{Sr}$	±	Morphology
KLX13A	404.450	404.460	-14.236	-7.218			Scalenohedral
KLX13A	450.800	450.850	-67.652	-9.092			Scalenohedral
KLX13A*	497.242	497.392	-5.219	-9.5			Sealed
KLX13A	506.750	506.999	-19.593	-7.694			Equant
KLX13A	538.380	538.480	-24.541	-7.313			Equant
KLX14A*	80.245	80.262	-10.6	-8.8	0.712942	0.000015	Scalenohedral
KLX14A*	80.940	81.040	-9.5	-14.2			Scalenohedral
KLX14A*	80.940	81.040	-6.9	-14.7			Sealed
KLX14A*	81.300	81.360	-10.1	-12.2			Scalenohedral
KLX17A	315.479	315.759	-18.4 (-18.4)	-8.3 (-8.5)	0.714614	0.000012	Equant
KLX17A	423.250	423.450	-38.4	-9.7			
KLX17A	426.100	426.360	-7.3	-10.9			
KLX17A	431.460	431.660	-99.7 (-100.0)	-5.5 (-5.2)			Scalenohedral
KLX19A*	412.430	412.531	-6.4	-12.1			Scalenohedral
KLX20A*	216.180	216.230	-7.271	-14.315			
KLX20A*	224.180	224.210	-3.415	-9.286			Sealed
KLX26A*	17.780	17.930	-4.183	-5.461	0.716298	0.000017	Needle

*=Additional samples. Value in brackets is a second analysis of the same bulk sample.

ICP-MS analyses – calcite

Borehole	KLX14A*	KLX14A*	KLX14A*	KLX17A	KLX17A(B)	KLX19A*
SecUp	80.245	80.940	81.300	315.479	315.479	412.430
SecLow	80.262	81.040	81.360	315.759	315.759	412.531
Na	14.50	29.69	42.65	24.61	24.92	40.11
Mg	77.01	97.51	80.52	87.26	89.30	29.03
Al	7.76	19.54	7.41	31.24	38.56	6.45
K	10.36	27.93	17.82	22.89	81.70	19.38
Sc	3.12	5.02	10.63	0.09	0.08	12.68
Ca	402,000	397,600	398,400	396,400	406,700	405,400
Mn	5,657	7,337	10,220	430	539	3,065
Fe	1,482	1,523	1,792	1,226	1,254	1,427
Rb	0.00	0.02	0.07	0.04	0.28	0.01
Sr	82.67	55.02	71.88	51.05	55.74	64.36
Y	60.47	49.17	112.80	0.12	0.11	55.74
Ba	6.41	4.11	4.74	2.98	3.52	4.60
La	56.39	32.55	222.80	21.84	25.90	52.76
Ce	113.50	64.82	484.00	17.33	21.42	86.78
Pr	13.10	7.43	56.55	1.09	1.36	9.42
Nd	52.23	30.25	217.90	2.93	3.52	35.50
Sm	10.49	6.93	38.31	0.12	0.13	8.44
Eu	2.41	1.67	7.60	0.02	0.01	1.89
Gd	11.01	8.05	31.49	0.14	0.15	9.54
Tb	1.71	1.42	4.46	0.01	0.00	1.74
Dy	10.46	9.09	25.04	0.02	0.02	10.94
Ho	2.21	1.93	4.96	0.01	0.00	2.22
Er	6.58	6.07	14.81	0.02	0.01	6.80
Tm	0.97	0.99	2.34	0.01	0.00	1.10
Yb	6.46	7.49	17.00	0.02	0.01	8.28
Lu	0.98	1.26	2.82	0.01	0.00	1.33
Th	0.22	0.13	0.03	0.01	0.00	0.09
U	0.01	0.03	0.08	0.05	0.03	< 0.01

"B"= Re-analysed sample of the same leachate.

*=Additional samples. All values in ppm.