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Forsmark site investigation

Quantitative mapping of fracture minerals in Forsmark

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Abstract

The campaign included quantitative fracture mineral mapping of water flowing fractures identified by the Posiva flow log (PFL) in the Forsmark core drilled boreholes KFM01C, KFM01D, KFM02A, KFM02B, KFM03A, KFM03B, KFM04A, KFM05A, KFM06A, KFM06B, KFM07A, KFM07C, KFM08A, KFM08B, KFM08C, KFM08D, KFM10A and KFM11A.

The purpose of the activity was to obtain quantitative data of fracture minerals from a large number of fractures within borehole sections characterised by anomalous water flow rates. This was done by mapping parameters from which fracture mineral volumes can be determined. Parameters recorded during the mapping were thickness of fracture filling minerals as well as coverage estimations based on comparison charts. The recording of these parameters underwent calibration during the campaign.

Such quantitative data of different fracture-filling minerals are important in-data for modelling hydrogeochemical evolutionary processes as well as for radionuclide transport modelling.

During the campaign a total of 2,035 fractures and 17 crush zones underwent quantitative mapping of fracture minerals. Out of the total number of fractures, 1,660 contained fracture filling minerals.

Sammanfattning

Aktiviteten inkluderade kvantitativ sprickmineralkartering av sprickor som har identifierats vara vattenförande med hjälp av Posiva flow logg (PFL) i de kärnborrade Forsmarksborrhålen KFM01C, KFM01D, KFM02A, KFM02B, KFM03A, KFM03B, KFM04A, KFM05A, KFM06A, KFM06B, KFM07A, KFM07C, KFM08A, KFM08B, KFM08C, KFM08D, KFM10A samt KFM11A.

Syftet med aktiviteten var att erhålla kvantitativa data över olika sprickmineral från en stor mängd sprickor inom borrhålssektioner karakteriserade av flödesanomalier, så kallade PFL-anomalier. Detta utfördes genom mätning av mineralbeläggningstjocklek samt uppskattning av mineralens beläggningsgrad, vilken baserades på jämförelser med referensdiagram. Kvantitativa sprickmineraldata av detta slag utgör väsentliga indata vid modellering av grundvattenkemiska utvecklingsprocesser och även vid modellering av radionuklidtransport.

Förkalibrering av karteringsparametrarna genomfördes under uppdraget.

Totalt 2 035 sprickor och 17 krosszoner genomgick kvantitativ sprickmineralkartering under aktiviteten. Av det totala antalet sprickor innehöll 1 660 sprickmineral.

Contents

1 Introduction

This document reports the data gained by the *Quantitative mapping of fractures in Forsmark*, which is one of the activities performed within the site investigation at *Forsmark*. The work was carried out in accordance with activity plan AP PF 400-07-056. In Table 1-1 controlling documents for performing this activity are listed. Both activity plan and method descriptions are SKB's internal controlling documents.

This activity concerns quantitative drill core mapping of fracture minerals. Fracture filling minerals are assumed to be available for reaction with flowing groundwater. For the purpose of the study, hydraulically conductive fracture zones were specifically targeted, as these are of great interest for modelling of groundwater-chemical evolutionary processes within and around the repository. Furthermore, radionuclides that are potentially released from the repository will encounter fracture minerals, and therefore the nature and quantity of the latter are of great interest also for modelling of radionuclide transport.

The activity, which was performed during January–February 2008, included quantitative mapping of fracture minerals in boreholes KFM01C, KFM01D, KFM02A, KFM02B, KFM03A, KFM03B, KFM04A, KFM05A, KFM06A, KFM06B, KFM07A, KFM07C, KFM08A, KFM08B, KFM08C, KFM08D, KFM10A and KFM11A, see Figure 1-1. All boreholes have previously undergone standard Boremap mapping.

Original data from the reported activity are stored in the primary database Sicada, where they are traceable by the Activity Plan number (AP PF 400-07-056). Only data in SKB's databases are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in the databases may be revised, if needed. Such revisions will not necessarily result in a revision of the P-report, although the normal procedure is that major data revisions entail a revision of the P-report. Minor data revisions are normally presented as supplements, available at www.skb.se.

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

Activity plan	**Number**	**Version**
Kvantitativ kartering av sprickmineral Forsmark	AP PF 400-07-056	1.0
Method descriptions	**Number**	**Version**
Instruktion: Regler för bergarters benämningar vid platsundersökning i Forsmark	SKB MD 132.005	1.0
Method Description for Boremap mapping	SKB MD 143.006	2.0
Nomenklatur vid Boremapkartering	SKB MD 143.008	1.0
Metodbeskrivning för kvantitativ kartering av sprickmineral	SKB MD 143.009	1.0
Mätsystembeskrivning för Boremap	SKB MD 146.005	1.0
Instruktion för längdkalibrering vid undersökningar i kärnborrhål	SKB MD 620.010	2.0

Figure 1-1. *Location of the boreholes included in this activity.*

2 Objective and scope

The campaign included quantitative fracture mineral mapping of water flowing fractures identified by the Posiva flow log (PFL) in the cored boreholes KFM01C, KFM01D, KFM02A, KFM02B, KFM03A, KFM03B, KFM04A, KFM05A, KFM06A, KFM06B, KFM07A, KFM07C, KFM08A, KFM08B, KFM08C, KFM08D, KFM10A and KFM11A, see Figure 1-1.

The purpose of the work was to obtain quantitative data of fracture minerals from a high number of fractures. This was achieved by performing a second mapping, focused on quantifying fracture minerals, of drill cores that had previously been mapped according to conventional Boremap mapping. During the quantitative mapping, the mineral coverage percentage of the fracture surface and thickness of fracture minerals were measured in the drill core. This provided quantitative data of different fracture-filling minerals within the investigation site, which constitute important in-data when modelling the hydrogeochemical evolutionary history of the Forsmark groundwaters as well as when modelling transport of radionuclides in the fracture network.

Selection of boreholes and core sections to be investigated in the campaign was based on hydraulic measurements in the respective boreholes. Sections with flow anomalies were mapped as well as the adjacent rock. The surrounding rock to be mapped was limited to one metre above and below the flow anomaly interval. Each such section is called a PFL-anomaly.

The volume of different fracture filling minerals was determined based on measurements and calibrated estimations.

3 Equipment

3.1 Description of equipment/interpretation tools

During mapping the following equipment was used:

- Scale loupe with 10X magnification and equipped with a 0.1 mm interval scale bar.
- Comparison charts for visual estimation of cover percentages.
- Tungsten carbide scriber for testing mineral hardness.
- 10% hydrochloric acid.
- Digital camera (minimum resolution requirement 2,832x2,128 dpi).

The mapping was executed in localities specifically adapted for the purpose, equipped with mapping stages for core boxes as well as lighting corresponding to daylight.

All data obtained during the mapping were recorded in Boremap version 4003 (or later) software.

Image analysis was performed using MapInfo Professional version 9.0.

4 Execution

4.1 General

The quantitative mapping was performed using both drill core and BIPS information. Only open fractures with aperture >0 and crush zones were mapped within each PFL anomaly. The minerals of interest in the campaign were calcite, chlorite, clay minerals, hematite, iron oxide and pyrite. Other minerals were excluded from the mapping as they were regarded to be of minor importance.

Each open fracture was mapped with regard to fracture minerals present. Minerals belonging to the wall rock were excluded. When mapping an open fracture, each of the two fracture surfaces was treated separately. The order in which the minerals were mapped was determined by their relative position on the fracture surface. Mineral 1 is the mineral regarded to have the uppermost position on the fracture surface (disregarding up/down in the borehole), i.e. partially or completely covering the fracture surface including other fracture-filling minerals on the surface. Mineral 2 is the mineral interpreted to be the next in order according to these criteria. Up to four minerals were mapped in this manner for each fracture surface. For each mineral an estimation of the coverage was made. This was done through visual comparisons with mathematically accurate charts specifically developed for this purpose. The coverage is expressed as a percentage of the entire fracture surface. Two different coverage parameters were recorded; surface coverage and total coverage. Surface coverage is the visual percentage of the fracture surface that is covered by the particular mineral. Total coverage is an estimation of the total percentage of the fracture that is covered by the mineral. This is commonly greater than the surface coverage, as fracture mineral fills often overlap each other. Mineral thickness was measured for each mineral using a scale loupe. This process was repeated for each mineral present on the fracture surface.

Some minerals present on the fracture surfaces were, however, treated in a different manner from the process described above. This occurred when the mineral appeared as visually separate, well developed discrete crystals on the fracture surface. Mapping surface coverage percentage and thickness for such minerals was determined to be less than satisfactory. Instead these fracture minerals were mapped as "spot minerals". Parameters mapped and recorded for spot minerals were crystal size, frequency (crystals/cm^2) and mineral thickness. In the campaign, pyrite was the only mineral regularly mapped as a "spot mineral".

Each crush zone was treated as a set of fractures. One parameter that was mapped was the number of fractures constituting the crush zone. This was estimated from core and BIPS. By performing coverage estimations and thickness measurements of fracture minerals on all the fractures present (if possible) within the crush zones, averages of these parameters could be calculated. These averages were then used to represent all fractures within the crush zone.

Detailed descriptions of the method are presented in method description SKB MD 143.009, SKB internal document (Table 1-1).

4.2 Preparations

4.2.1 Basis for selecting drill core sections

The main part of the campaign was devoted to mapping drill core sections associated with in total 401 PFL-anomalies. Such a drill core section is in this document called a PFL-section and comprises the rock surrounding the anomaly by one metre at each side. All selected borehole sections to be mapped are shown in Appendix 1–4.

Out of the 401 PFL-sections that were suggested to be documented, 323 anomalies are found within the target volume for repository layout studies. 78 anomalies that should be documented for comparison are situated outside the target volume area. The numbers of PFL-sections to be mapped in different elevation ranges are shown in Table 4-1 below. Also the numbers for PFL-anomalies in different transmissivity ranges are presented.

Table 4-1. PFL-anomalies in different elevation and transmissivity ranges that were mapped within the activity.

Borehole	E > –100 masl*	–100 ≥ E ≥ –400 masl	–400 > E ≥ –600 masl	E < –600 masl	T < 10^{-8} m^2/s	10^{-8} ≤ T ≤ 10^{-6} m^2/s	T > 10^{6} m^2/s
KFM01A	–	–	–	–	–	–	–
KFM01D	7	26	1	–	13	19	2
KFM02A	–	–	49	1	23	26	1
KFM02B	5	14	22	–	2	25	14
KFM03A	–	12	10	11	11	19	3
KFM04A	10	11	1	1	7	10	6
KFM05A	12	13	–	2	10	13	4
KFM06A	–	21	1	5	16	10	1
KFM07A[1]	–	–	–	3	–	–	–
KFM07C	1	14	–	–	6	7	2
KFM08A	–	–	3	–	1	1	1
KFM08C	–	–	9	–	7	2	–
KFM08D[2]	11	17	5	2	15	17	2
KFM10A	32	24	–	–	14	27	15
KFM11A	21	21	3	–	16	24	5
Total	**99**	**173**	**104**	**25**	**141**	**200**	**56**

[1] No transmissivity obtained for the three selected anomalies.

[2] No transmissivity obtained for one selected anomaly

* masl = metres above sea level (RHB70)

In the motivation document for this activity, given in the activity plan (se Table 1-1), it is proposed to document core sections distant to an adjoining PFL-anomaly. In total 60 m of such drill core sections from the boreholes KFM01D, KFM03A, KFM06A, and KFM08D were mapped.

Furthermore, which is not suggested in the motivation document, an extra effort was made to map shallow drill core sections. In Forsmark there is no borehole where both the drill core exists and PFL-logging has been performed close to the ground surface. Therefore, even if there is no way of knowing whether the drill core section includes a PFL-anomaly or not, open fractures at shallow depth were documented in borehole KFM01C, KFM03B, KFM06B, and KFM08B, encompassing in total 104 m drill core length.

The campaign in Forsmark aimed at being comparable to a corresponding campaign at Laxemar in terms of total length of mapped drill core. In total 767 metres of drill core were mapped at Forsmark.

In the planning of this campaign, the motivation document has been used as a general guideline, rather than as a controlling document.

As mentioned, the selection of boreholes and drill core sections to be investigated in this campaign was largely based on hydrogeologic measurements with the Posiva Flow Log (PFL). This tool can detect flow anomalies with small resolutions, in the Forsmark boreholes down to 0.1 m section length by so called overlapping flow measurements. For such measurements the flow logging tool, which is supplied with two packers situated one metre apart, is successively transferred past the flow anomaly (and surrounding rock) by 0.1 m increments. In this document, a 2 m long drill core section comprising the rock surrounding a PFL-anomaly by one metre at each side is called a PFL-section. In cases where the spacing between two investigated PFL-anomalies is less than 2 m, the overlapping PFL-logging has not been performed twice, and therefore the total length of drill core is less than the product of the number of investigated PFL-sections and 2 m.

Concerning PFL-anomalies, many of them are in the reports presenting Posiva Flow logging results marked as uncertain. It is for example stated in /Pöllänen and Sokolnicki 2004/:

"Some fracture-specific results were rated to be "uncertain"… The criterion of "uncertain" was in most cases a minor flow rate (< 30 mL/h). In some cases fracture anomalies were unclear, since the distance between them was less than one metre."

However, for the present campaign fractures of low hydraulic conductivity are of great importance and should therefore not be excluded. Furthermore, closely spaced anomalies are handled by mapping the drill core including the closely spaced anomalies. Therefore, in this campaign no distinctions are made beforehand between PFL-anomalies marked as uncertain or not in the background documents. In the subsequent analysis, however, it is recommended to investigate whether this decision affects the obtained data.

4.2.2 Image analysis

Image analysis was carried out on surface coverage percentages and mineral thicknesses. The purpose of this was to increase the accuracy of the mapping method by using the image analysis results as a form of precalibration. A random selection of fractures was made from three boreholes. These fractures were first mapped in accordance with the quantitative mapping method. Image analysis of visible coverage percentages was then done by photographing fracture surfaces and subsequently performing analysis of these photographs in Mapinfo Professional 9.0 (Figure 4-1). Accurate coverage percentages were thus obtained for each mineral. These results could then be compared to those from the mapping (Appendix 3). This process improved the accuracy of the estimations of coverage percentages as the random selection of fractures yielded fracture surfaces of different character which helped familiarize the mappers with the varying occurrence habits of fracture filling minerals.

For the purpose of analysing mineral thicknesses, the fractures selected for image analysis were mapped in accordance with the quantitative mapping method. Subsequently these fractures were cut perpendicular to the fracture surface using a rock saw. The exposed cutting surface, on which a cross-section of any fracture mineral fills was visible, was then photographed. The photographs were analysed in Mapinfo Professional 9.0, whereby average thicknesses of each fracture mineral exposed along the cut surface were obtained. These data were then used to compare the analytical data with those recorded during mapping of the same fractures. However, the results turned out less than satisfactory due to complications during the preparations. During cutting of the fractures, the mineral fills were damaged and partially to extensively lost form the fracture surface due to vibrations from the cutting process. No satisfying alternative solution was found due to time constraints, and therefore analysis of mineral thicknesses was aborted before completion.

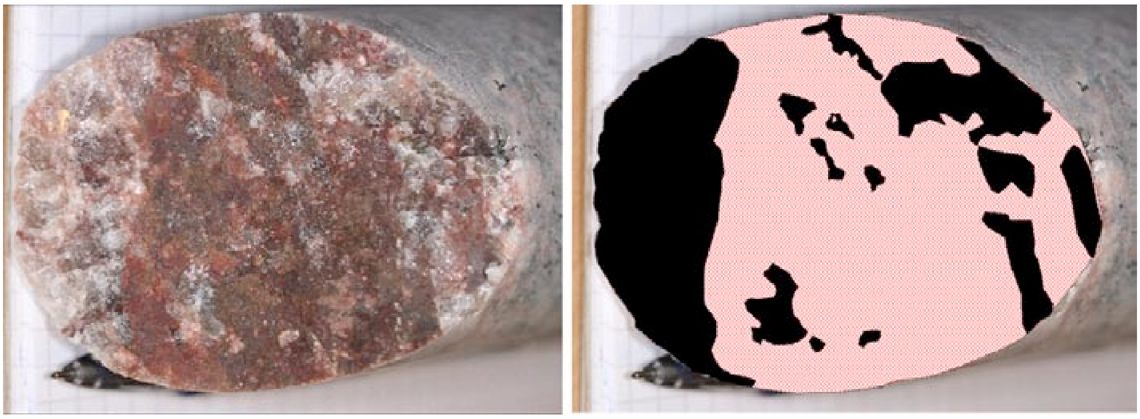


Figure 4-1. *Image analysis of fracture surface coverage (KFM01D Adjusted sec up 736.322 m). The visible hematite coverage on the fracture surface (left picture) was estimated at 70%. Image analysis (right picture) yielded an absolute visible hematite coverage (cross hatched) of 63%.*

4.2.3 Hematite pigmentation

Analysis of mineral mixes consisting of hematite + chlorite/calcite/clay minerals was carried out by Isochron GeoConsulting at the University of Gothenburg. The purpose of this was to obtain better knowledge of the content of hematite in such mineral mixes. A range of different fracture fills with varying appearances and containing hematite as well as other minerals was selected. Analysis of these revealed that very small amounts of hematite can cause strong coloration of other minerals. Results from the analysis showed that no pure hematite was encountered in the mineral fills (Appendix 5). Instead, hematite only occurred as a pigmentation of other minerals. Hematite content did not exceed 2% in any of the hematite pigmented mineral mixes analysed. For the purpose of the activity, it was thus decided not to map pure hematite but rather to document minerals that were pigmented by hematite. Hematite pigmented chlorite, calcite and clay minerals were therefore added to the mineral list as additions to the existing list comprising calcite, chlorite, clay minerals, iron oxide and pyrite.

4.3 Data handling/post processing

The mapping was performed on-line on the SKB network, thus ensuring highest possible data security. Before every break (>15 mins) a back-up of the mapping was saved on the local disk. An internal routine in the Boremap software performs quality checks before the data is exported to and archived in SKB's database Sicada. Personnel from SKB also perform spot test controls and regular quality revisions. All primary data were stored in Sicada and only these data are used for subsequent interpretation and modelling.

4.4 Nonconformities

The main nonconformity with respect to the activity plan concerned missing core sections during the mapping. This was generally a result of either core loss during drilling, crush zones with the majority of core pieces missing, or core sections missing due to previous sampling for laboratory analyses. Of these different causes, sections missing due to sampling was the most significant factor, as core samples often tend to be localised in anomalies such as crush zones that coincide with PFL-anomalies. Nonconformities arising from missing core pieces and sections are listed in Appendix 2.

Some core boxes containing sections listed for mapping in the activity plan were unavailable during the mapping. These sections are also listed in Appendix 2.

Image analysis of mineral thickness was excluded from this campaign.

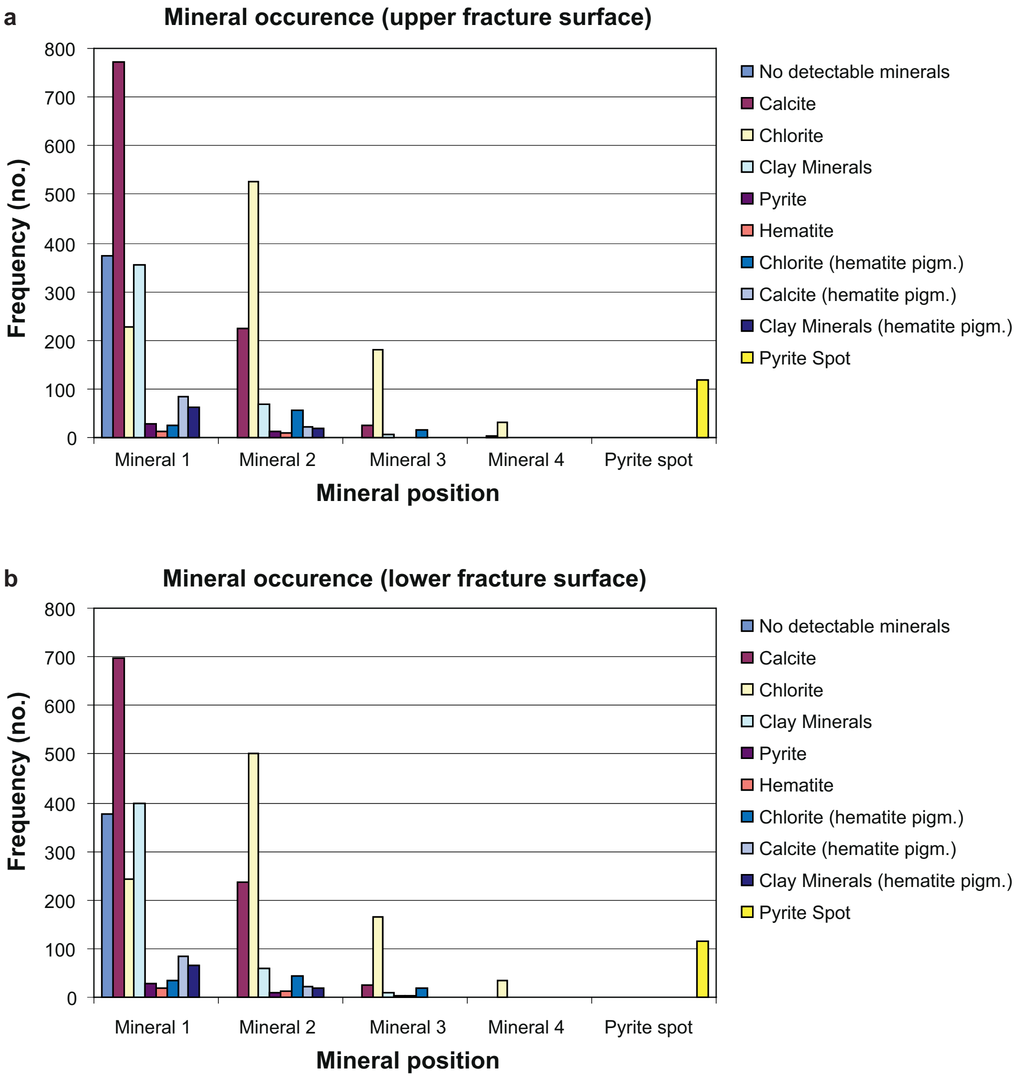
5 Results

A total of 2,035 fractures and 17 crush zones underwent quantitative mapping of fracture minerals during the campaign. Of the fractures, 1,660 contained fracture filling minerals.

The data obtained during the activity highlight differences between minerals regarding the parameters recorded during mapping. Basic plots of mineral occurrences in different mineral positions (Figure 5-1) show differences in occurrence habits between the mapped minerals. Most minerals display a decreasing trend being most common in position 1 and least common in position 4. Exceptions to this are chlorite, which is most common in mineral position 2.

Regarding mineral coverage percentages, minor patterns can be discerned. For most of the mapped minerals, Visible and Total coverage curves (Figure 5-2) are relatively similar. The obvious exception to this is chlorite, which has a distinctive peak in the number of total coverage percentages >90%.

A plot of the frequency of mineral volumes within different volume intervals (Figure 5-3) determines that all mapped minerals display overall decreasing trends in terms of frequency with increasing volume.



Figur 5-1. *Mineral distributions based on mineral position on the upper (a) and lower (b) fracture surface.*

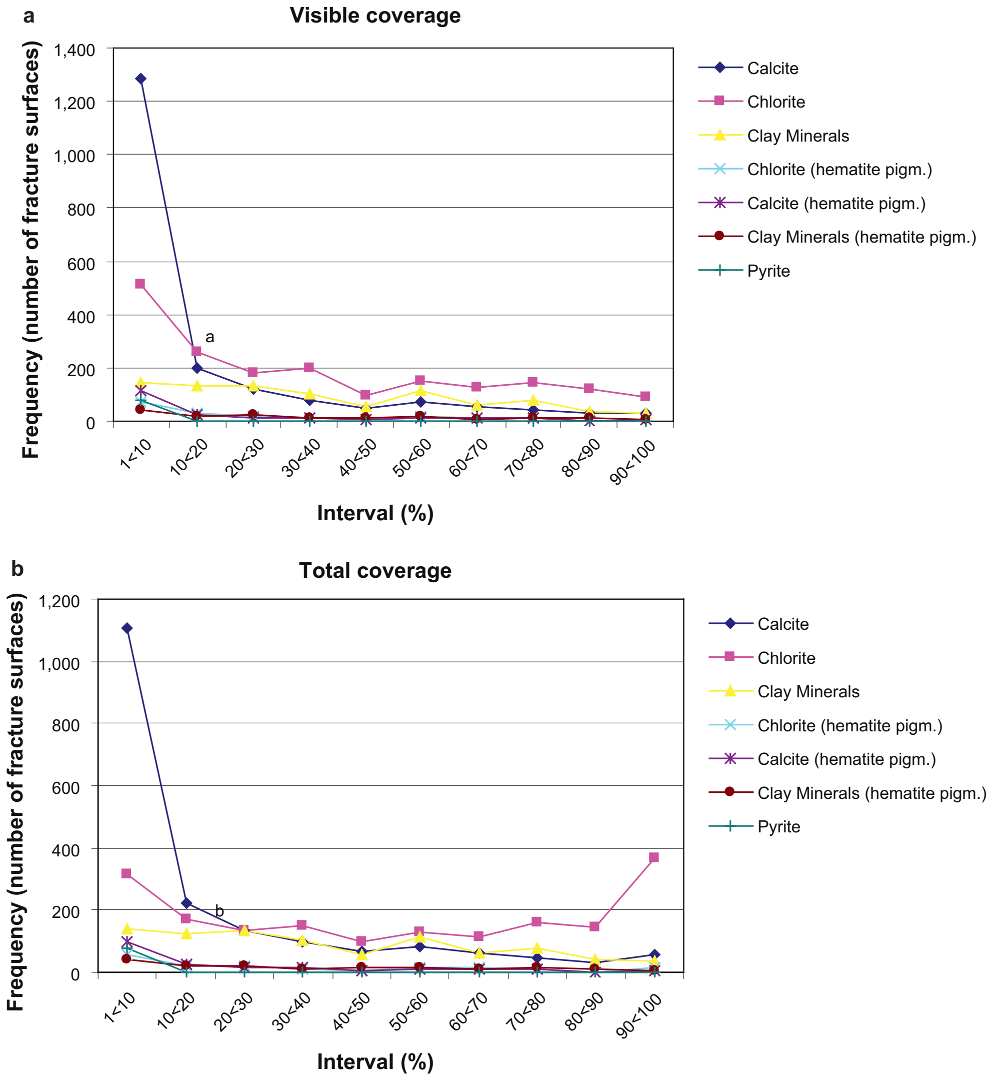


Figure 5-2. Plots of the mapped minerals and their distribution of visible (a) and total (b) coverage percentages. Coverage percentages are divided into intervals with frequency representing the total number of fractures with a coverage percentage within that interval.

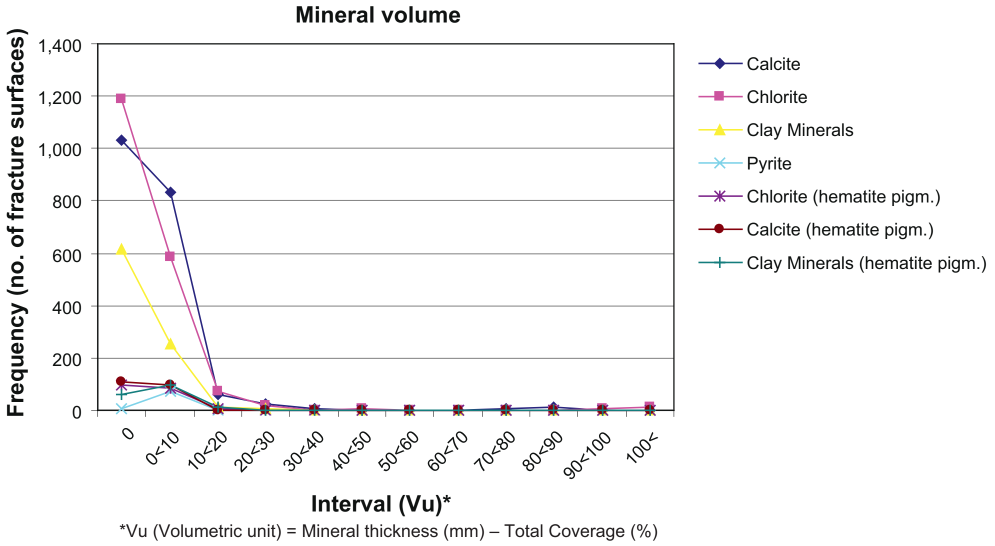


Figure 5-3. Distribution of minerals in terms of volume. The volume is split into intervals with the frequency representing the total number of fracture surfaces with a mineral volume within that interval.

6 References

Pöllänen J, Sokolnicki M, 2004. Difference flow logging in borehole KFM03A. Forsmark site investigation, SKB P-04-189, Svensk Kärnbränslehantering AB.

Appendix 1

Lists of drill core sections

All values in the appendices are borehole length. Adjusted borehole length of the drill cores should be used!

KFM01C – total drill core length 15 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM01C	23.5	28.5	No PFL-logging in section
KFM01C	49.5	54.5	No PFL-logging in section
KFM01C	75.5	80.5	No PFL-logging in section

KFM01D – total drill core length 67 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM01D	105	107	106
KFM01D	119.9	123.7	120.9
KFM01D			121.9
KFM01D			122.7
KFM01D	124	132.4	125
KFM01D			125.5
KFM01D			125.7
KFM01D			126.7
KFM01D			128
KFM01D			129.5
KFM01D			131.2
KFM01D			131.4
KFM01D	141.8	146.5	142.8
KFM01D			143.4
KFM01D			144.9
KFM01D			145.5
KFM01D	147	149	148
KFM01D	149.8	155.9	150.8
KFM01D			151.9
KFM01D			153.9
KFM01D			154.9
KFM01D	156.4	159.4	157.4
KFM01D			158.4
KFM01D	193.4	195.4	194.4
KFM01D	248	253	No PFL-anomaly
KFM01D	263.3	265.3	264.3
KFM01D	306.4	308.4	307.4
KFM01D	315.9	317.9	316.9
KFM01D	352.2	356.2	353.2
KFM01D			355.2
KFM01D	368.5	370.5	369.5
KFM01D	376.9	378.9	377.9
KFM01D	381	383	382
KFM01D	430.5	432.5	431.5
KFM01D	492.5	497.5	No PFL-anomaly
KFM01D	570.2	572.2	571.2
KFM01D	732	737	No PFL-anomaly

KFM02A – total drill core length 63.4 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM02A	410.2	412.8	411.2
KFM02A			411.8
KFM02A	415.5	420.9	416.5
KFM02A			417.3
KFM02A			418.4
KFM02A			419.9
KFM02A	422.7	429.9	423.7
KFM02A			425.1
KFM02A			425.9
KFM02A			426.8
KFM02A			427.2
KFM02A			428.9
KFM02A	433.4	435.4	434.4
KFM02A	436	439.5	437
KFM02A			437.3
KFM02A			438.5
KFM02A	440.2	442.2	441.2
KFM02A	447.1	449.8	448.1
KFM02A			448.8
KFM02A	453	455.9	454
KFM02A			454.4
KFM02A			454.9
KFM02A	458.7	460.7	459.7
KFM02A	461.5	464.2	462.5
KFM02A			463.2
KFM02A	464.3	466.3	465.3
KFM02A	467.6	469.6	468.6
KFM02A	476.8	482.2	477.8
KFM02A			479.2
KFM02A			480.4
KFM02A			481.2
KFM02A	483.6	487.4	484.6
KFM02A			485.6
KFM02A			486.1
KFM02A			486.4
KFM02A	492.4	494.4	493.4
KFM02A	494.5	502.4	495.5
KFM02A			496.5
KFM02A			497.3
KFM02A			498.1
KFM02A			498.3
KFM02A			500.3
KFM02A			500.9
KFM02A			501.4
KFM02A	505.5	507.5	506.5
KFM02A	511.3	514.6	512.3
KFM02A			512.6
KFM02A			513.1
KFM02A			513.6
KFM02A	893	895	894

KFM02B – total drill core length 58.7 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM02B	87.6	89.6	88.6
KFM02B	90.4	92.4	91.4
KFM02B	101.6	103.6	102.6
KFM02B	103.9	105.9	104.9
KFM02B	107.2	109.2	108.2
KFM02B	111.7	113.7	112.7
KFM02B	129.2	131.2	130.2
KFM02B	157.1	159.1	158.1
KFM02B	166.3	169	167.3
KFM02B			168
KFM02B	174.2	176.2	175.2
KFM02B	220.7	222.7	221.7
KFM02B	270	272	271
KFM02B	329.7	332	330.7
KFM02B			331
KFM02B	398.4	400.4	399.4
KFM02B	409.8	416.1	410.8
KFM02B			412.2
KFM02B			413.1
KFM02B			414.5
KFM02B			415.1
KFM02B	418.4	424.3	419.4
KFM02B			420.5
KFM02B			421.1
KFM02B			422.3
KFM02B			423.3
KFM02B	425.1	430.6	426.1
KFM02B			426.3
KFM02B			426.9
KFM02B			428.4
KFM02B			429.6
KFM02B	435.4	437.4	436.4
KFM02B	469.2	472.5	470.2
KFM02B			471
KFM02B			471.5
KFM02B	496.1	498.8	497.1
KFM02B			497.8
KFM02B	499	503	500
KFM02B			500.8
KFM02B			501
KFM02B			502

KFM03A – total drill core length 70.2 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM03A	112.2	114.2	113.2
KFM03A	119.6	121.6	120.6
KFM03A	122.1	124.1	123.1
KFM03A	125.5	127.5	126.5
KFM03A	129.2	131.7	130.2
KFM03A			130.7
KFM03A	149.8	151.8	150.8
KFM03A	156	161	No PFL-anomaly
KFM03A	313.4	315.4	314.4
KFM03A	304	309	No PFL-anomaly
KFM03A	353.4	355.4	354.4
KFM03A	357.5	360.6	358.5
KFM03A			359.1
KFM03A			359.6
KFM03A	409.7	412.5	410.7
KFM03A			411.5
KFM03A	448.4	452.3	449.4
KFM03A			451.3
KFM03A	453.6	455.6	454.6
KFM03A	461.4	463.4	462.4
KFM03A	499.5	501.5	500.5
KFM03A	514.9	518.7	515.9
KFM03A			517.7
KFM03A	532.7	534.7	533.7
KFM03A	560.5	565.5	No PFL-anomaly
KFM03A	641.2	644.9	642.2
KFM03A			643.9
KFM03A	802.8	804.8	803.8
KFM03A	812.7	814.7	813.7
KFM03A	943.2	945.2	944.2
KFM03A	945.5	947.5	946.5
KFM03A	985.2	987.5	986.2
KFM03A			986.5
KFM03A	991.9	995	992.9
KFM03A			993.8
KFM03A			994

KFM03B – total drill core length 15 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM03B	8.5	13.5	No PFL-logging in section
KFM03B	28.5	33.5	No PFL-logging in section
KFM03B	48.5	53.5	No PFL-logging in section

KFM04A – total drill core length 35.0 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM04A	108.6	114.9	109.6
KFM04A			110.3
KFM04A			111.4
KFM04A			112.4
KFM04A			112.8
KFM04A			113.9
KFM04A	115.1	118	116.1
KFM04A			117
KFM04A	119.2	121.2	120.2
KFM04A	124.3	126.3	125.3
KFM04A	194.3	196.3	195.3
KFM04A	201.1	203.8	202.1
KFM04A			202.8
KFM04A	206.1	209.2	207.1
KFM04A			208.2
KFM04A	296.1	298.1	297.1
KFM04A	356.8	360.8	357.8
KFM04A			358.2
KFM04A			359.8
KFM04A	418	420	419
KFM04A	420.9	422.9	421.9
KFM04A	520.5	522.5	521.5
KFM04A	953.8	955.8	954.8

KFM05A – total drill core length 38.9 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM05A	107.9	114.3	108.9
KFM05A			110.1
KFM05A			111.6
KFM05A			112.6
KFM05A			112.9
KFM05A			113.3
KFM05A	114.8	117.5	115.8
KFM05A			116.5
KFM05A	118.7	122.9	119.7
KFM05A			120.2
KFM05A			120.6
KFM05A			121.9
KFM05A	123.1	127.1	124.1
KFM05A			124.4
KFM05A			126.1
KFM05A	129.9	133.2	130.9
KFM05A			132.2
KFM05A	141.4	143.4	142.4
KFM05A	148	150	149
KFM05A	162.9	164.9	163.9
KFM05A	165.4	169.7	166.4
KFM05A			167.2
KFM05A			168.7
KFM05A	174.6	176.6	175.6
KFM05A	263.4	265.4	264.4
KFM05A	701.7	703.7	702.7
KFM05A	719	721	720.0

KFM06B – total drill core length 59 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM06B	6	65	No PFL-logging in section

KFM06A – total drill core length 57.1 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM06A	105.4	107.4	106.4
KFM06A	108.3	112.5	109.3
KFM06A			110.6
KFM06A			111.5
KFM06A	112.6	117.9	113.6
KFM06A			115.4
KFM06A			116.4
KFM06A			116.9
KFM06A	122.1	124.1	123.1
KFM06A	203.4	207.2	204.4
KFM06A			205.7
KFM06A			205.9
KFM06A			206.2
KFM06A	207.3	209.3	208.3
KFM06A	211.6	213.6	212.6
KFM06A	214.6	219.2	215.6
KFM06A			216.3
KFM06A			218.2
KFM06A	226	231	No PFL-anomaly
KFM06A	287	292	No PFL-anomaly
KFM06A	302.0	304.0	303.0
KFM06A	305.2	307.2	306.2
KFM06A	307.4	309.4	308.4
KFM06A	448.4	450.4	449.4
KFM06A	504	509	No PFL-anomaly
KFM06A	621.4	623.4	622.4
KFM06A	652.9	654.9	653.9
KFM06A	742.3	744.3	743.3
KFM06A	769.6	771.8	770.6
KFM06A			770.8

KFM07A – total drill core length 4.9 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM07A	915.3	918.2	916.3
KFM07A			917.2
KFM07A	969.0	971.0	970

KFM07C – total drill core length 26.4 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM07C	97.4	99.4	98.4
KFM07C	107.1	109.9	108.1
KFM07C			108.9
KFM07C	110.3	112.3	111.3
KFM07C	113.7	116.8	114.7
KFM07C			115.8
KFM07C	122.1	124.1	123.1
KFM07C	133.3	135.3	134.3
KFM07C	143.1	145.1	144.1
KFM07C	149.9	151.9	150.9
KFM07C	155.5	157.5	156.5
KFM07C	162.8	164.8	163.8
KFM07C	224.9	226.9	225.9
KFM07C	278.3	280.8	279.3
KFM07C			279.8

KFM08A – total drill core length 5.5 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM08A	479.5	483.0	480.5
KFM08A			482
KFM08A	686.0	688.0	687

KFM08B – total drill core length 15 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM08B	14.5	19.5	No PFL-logging in section
KFM08B	35.7	42.5	No PFL-logging in section
KFM08B	61	66	No PFL-logging in section

KFM08C – total drill core length 17.7 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM08C	461.3	465.0	462.3
KFM08C			464
KFM08C	469.7	471.7	470.7
KFM08C	479.0	481.0	480
KFM08C	498.0	500.0	499
KFM08C	517.8	519.8	518.8
KFM08C	520.4	522.4	521.4
KFM08C	523.6	525.6	524.6
KFM08C	682.6	684.6	683.6

KFM08D – total drill core length 70.8 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM08D	74.8	78.8	75.8
KFM08D			77.8
KFM08D	79.9	83.4	80.9
KFM08D			81.4
KFM08D			82.1
KFM08D			82.4
KFM08D	92.5	97.5	No PFL-anomaly
KFM08D	102.9	104.9	103.9
KFM08D	106.3	110.2	107.3
KFM08D			107.6
KFM08D			109.2
KFM08D	116	118	117
KFM08D	124.6	126.6	125.6
KFM08D	130.1	132.1	131.1
KFM08D	140.6	142.6	141.6
KFM08D	146.4	150.8	147.4
KFM08D			148
KFM08D			149.8
KFM08D	186.1	189.6	187.1
KFM08D			188.3
KFM08D			188.6
KFM08D	200.2	202.2	201.2
KFM08D	204	208.2	205
KFM08D			205.3
KFM08D			207.2
KFM08D	308.5	313.5	No PFL-anomaly
KFM08D	386.7	390.2	387.7
KFM08D			389.2
KFM08D	391.2	394.3	392.2
KFM08D			393.3
KFM08D	552.2	557.2	No PFL-anomaly
KFM08D	675.2	678.9	676.2
KFM08D			677.9
KFM08D	684.5	686.5	685.5
KFM08D	694.8	696.8	695.8
KFM08D	733.8	735.8	734.8
KFM08D	831.2	833.2	832.2
KFM08D	924.1	926.1	925.1

KFM10A – total drill core length 86.1 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM10A	59.3	63.3	60.3
KFM10A			62.3
KFM10A	70.1	73.3	71.1
KFM10A			72.3
KFM10A	75.2	77.2	76.2
KFM10A	81.1	83.1	82.1
KFM10A	83.4	104.9	84.4

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM10A			85.9
KFM10A			87.7
KFM10A			87.9
KFM10A			89.6
KFM10A			90.5
KFM10A			92
KFM10A			93.8
KFM10A			94.8
KFM10A			95.1
KFM10A			96.5
KFM10A			98.3
KFM10A			99.9
KFM10A			101.6
KFM10A			103.3
KFM10A			103.9
KFM10A	105	109.3	106
KFM10A			107.3
KFM10A			108.3
KFM10A	112	119.7	113
KFM10A			114.6
KFM10A			115.2
KFM10A			116.9
KFM10A			118.7
KFM10A	119.9	123	120.9
KFM10A			122
KFM10A	143.3	145.7	144.3
KFM10A			144.7
KFM10A	253.9	255.9	254.9
KFM10A	298.5	300.5	299.5
KFM10A	307.8	309.8	308.8
KFM10A	314.3	316.3	315.3
KFM10A	321	323	322
KFM10A	326.3	329.8	327.3
KFM10A			328.1
KFM10A			328.8
KFM10A	331.9	335.5	332.9
KFM10A			334.5
KFM10A	359.5	361.5	360.5
KFM10A	367.4	369.4	368.4
KFM10A	372.6	374.6	373.6
KFM10A	375	377	376
KFM10A	430.9	432.9	431.9
KFM10A	435.3	439	436.3
KFM10A			437.3
KFM10A			438
KFM10A	479.3	481.8	480.3
KFM10A			480.8
KFM10A	482.8	485.4	483.8
KFM10A			484.4

KFM11A – total drill core length 61.1 m.

Borehole	Adjusted Secup (m)	Adjusted Seclow (m)	Location of PFL-anomaly
KFM11A	72.8	83.3	73.8
KFM11A			74.6
KFM11A			75.3
KFM11A			75.9
KFM11A			77.4
KFM11A			79.4
KFM11A			80.3
KFM11A			82.3
KFM11A	87.9	101.5	88.9
KFM11A			90.4
KFM11A			91.7
KFM11A			92.4
KFM11A			92.9
KFM11A			93.3
KFM11A			95.1
KFM11A			95.6
KFM11A			96.4
KFM11A			97.3
KFM11A			98.4
KFM11A			100.3
KFM11A			100.5
KFM11A	145.7	147.7	146.7
KFM11A	150	153	151
KFM11A			152
KFM11A	153.2	159.5	154.2
KFM11A			155.4
KFM11A			157.1
KFM11A			158.5
KFM11A	255.9	258.6	256.9
KFM11A			257.4
KFM11A			257.6
KFM11A	260.5	263	261.5
KFM11A			262
KFM11A	265.8	267.8	266.8
KFM11A	268	270	269
KFM11A	270.7	277.5	271.7
KFM11A			273.4
KFM11A			275
KFM11A			276.5
KFM11A	375.2	377.8	376.2
KFM11A			376.8
KFM11A	378.3	380.3	379.3
KFM11A	466.6	468.6	467.6
KFM11A	473.6	476.7	474.6
KFM11A			475.7

Nonconformities from selected drill core sections

Borehole	PFL section (adjusted length in m) Secup	Seclow	Causes of data loss
KFM01C	23.5	28.5	Fractures at 26.437, 26.450 missing due to sampling. Fractures at 28.262, 28.331 not mapped (unavailable core boxes).
KFM02A	436	439.5	No open fractures mapped in previous mapping.
KFM02A	440.2	442.2	No open fractures mapped in previous mapping.
KFM02A	476.8	482.2	Fractures at 476.976 , 476.994 missing due to sampling.
KFM02A	494.5	502.4	Fracture at 500.046 missing in core.
KFM02A	511.3	514.6	Crush at 413.492–413.751 is missing due to sampling.
KFM02B	87.6	89.6	The section has not been mapped in previous mapping.
KFM02B	409.8	416.1	Fractures at 414.556, 414.570, 414.602 missing due to sampling.
KFM02B	418.4	424.3	Fractures at 421.052, 421.073, 421.086, 423.160, 423.165 missing due to sampling.
KFM02B	469.2	472.5	Crush missing at 471.461–471.478, 471.582–471.669 due to sampling. Fracture missing at 471.512 due to sampling.
KFM02B	499	503	Crush at 499.954–500.015 missing due to sampling. Crush at 501.001–501.021 missing in core. Fractures at 500.721, 500.760, 500.779 missing due to samping. Fracture at 500.466, 500.990, 501.022 missing in core.
KFM03A	304	309	Fracture at 308.537 missing in core.
KFM03A	641.2	644.9	Fractures at 643.887, 643.908, 643.944 missing due to sampling.
KFM03A	802.8	804.8	Fractures at 803.687, 803.783 missing due to sampling.
KFM03A	812.7	814.7	Fractures at 813.746, 813.803 missing due to sampling.
KFM03A	943.2	945.2	Fracture at 943.648 missing due to sampling.
KFM04A	108.6	114.9	Fractures at 11.586, 112.437 missing due to sampling.
KFM04A	356.8	360.8	Fractures at 359.532, 359.667 missing due to sampling. Crush at 359.700–359.849 missing due to sampling.
KFM05A	107.9	114.3	Fractures at 109.878, 112.295, 112.313, 112.326, 112.349, 112.374 missing due to sampling.
KFM05A	701.7	703.7	Fracture at 702.467, 702.697, 702.764, 702.774 missing due to sampling.
KFM06A	105.4	107.4	Fracture at 106.251 missing due to sampling.
KFM06A	108.3	112.5	Fracture at 110.512, 110.761. 111.453 missing due to sampling.
KFM06A	207.3	209.3	No open fractures mapped in previous mapping.
KFM06A	214.6	219.2	Fracture at 218.083 is missing due to sampling.
KFM06A	302	304	No open fractures mapped in previous mapping.
KFM06B	6	90	Fracture at 9.714 missing in core Crush zone at 55.666–56.255 is missing due to sampling and core loss A flexit-plate covers the crush zone. Fracture at 91.310 missing due to sampling.
KFM07A	969	971	Fracture at 969.798 is missing due to sampling.
KFM07C	97.4	99.4	Fracture at 98.623 is missing due to core loss.
KFM07C	107.1	109.9	Fracture at 108.288 is missing due to core loss.
KFM08A	686	688	Fracture at 686.606, 686.756, 686.837 missing due to sampling.
KFM08B	35.7	42.5	Fracture at 42.037 missing due to sampling.
KFM08C	469.7	471.7	Fracture at 470.516 missing due to sampling.
KFM10A	59.3	63.3	No mapping available for this interval.
KFM10A	105	109.3	Fractures at 106.004, 106.015 missing in core. Fracture at 107.310 missing due to sampling.
KFM10A	143.3	145.7	Fracture at164.625 missing due to sampling
KFM10A	253.9	255.9	No open fractures mapped in previous mapping.
KFM10A	298.5	300.5	The only fracture in the PFL anomaly at 299.403 is missing due to sampling.
KFM10A	326.3	329.8	Fractures at 327.256, 327.260, 327.264, 327.266, 327.267, 327.280 missing due to core loss.
KFM10A	430.9	432.9	Fractures at 431.643, 431.719, 431.809, 431.815, 431.830, 431.841, 431.892, 431.915, 432.063, 432.109, 432.121, 432.496 missing due to mechanical crush.

Image analysis of mineral coverage

Borehole	Adj sec up	Mineral*	Estimated coverage (%)	Analytical coverage (%)
KFM01D	319.262	Chlorite (hem)	55	51
		Calcite	<1	<1
KFM01D	307.343	Chlorite	40	35
KFM01D	196.887	Chlorite	35	29
		Calcite	2	1
KFM01D	145.757	Chlorite	20	14
		Calcite	30	28
		Clay Mineral	50	42
KFM01D	129.506	Calcite	10	12
		Clay Mineral	70	66
KFM01D	101.992	Laumontite	3	1
		Hematite	5	3
KFM01D	352.543	Calcite	10	13
KFM01D	130.681	Chlorite	80	84
KFM01D	151.997	Calcite	10	15
KFM01D	736.322	Calcite (hem)	70	63

* (hem) means the mineral is impregnated with hematite

Appendix 4

Analysis of hematite-impregnated minerals

Sample ID	Hematite content (area-%)*	FeO (normalised) **
H1	0.4–0.7	7–13%
H2	1.2–1.9	4–17%
H3	0.4–0.6	5–11%
H4	0.6–0.8	8–18%
H5	0.3–0.6	7–13%

* The hematite content was calculated by running two profiles across the sample at 50× magnification. Each profile consisted of approximately 15 area measurements where the hematite content was estimated. Area measurements consisted of a combination of manual analysis and BSE-intensity mapping over the surface. Hematite was generally associated with chlorite and analysis of these grains (generally <spot size) yielded chlorite + hematite. In these cases BSE-intensity was lower than for pure hematite and was therefore counted as c. 20% hematite or 30–50% hematite depending on the addition of Fe to the chlorite analysis. Due to this the average hematite content for each sample is presented as a range, depending on what hematite content is designated in the mixed analysis.

** A chemoanalysis (normalised to 100%) was also executed for each area measurement. The column presents the average FeO content as a range depending on what hematite content is designated in the mixed analysis.