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Identification of additional, possible minor deformation zones at Forsmark through a review of data from cored boreholes

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Contents

1 Introduction

This report documents the results of a study, conducted in September and October of 2006, to identify sections in Forsmark cored boreholes that could possibly represent additional minor deformation zones (MDZ). The goal of this study is to look for possible additional zones not already recognized during the single-hole interpretation (SHI) process /SKB 2006c/ or during the deformation zone and rock domain modeling work /Olofsson et al. 2007/. This study was performed at a higher level of resolution than the DZ interpretation completed during the single-hole interpretation workshop.

A draft geological definition of minor deformation zones is proposed in Section 2. This definition was used as the conceptual framework for this study.

Minor deformation zones are hypothesized to occupy a critical section of the range of potential stochastic fractures simulated during SDM efforts. They are structures that are conceptualized as too spatially limited to be included in the deformation zone (model), yet are large enough to be important to site performance assessment criteria (number of rejected deposition holes, total volume available for deposition holes, hydraulic connectivity, and potential displacement during seismic events). As such, further work on the occurrence and characteristics of MDZ has been deemed necessary.

A variety of data were used to delineate additional possible MDZ; 1 metre fracture intensity data from SICADA; the presence of sections of core loss or crushed rock, lithology, and geophysical data as summarized on WellCAD plots, and the BIPS image and data logs available for Forsmark cored boreholes. The data were analyzed, and a series of intervals (delineated by ADJ_SECUP and ADJ_SECLOW) identified as additional possible MDZ are presented.

This work was completed as a component (Task 1) of the Forsmark Interim project, as described in "Activity Plan for Interim Analysis Efforts to Support SDM Forsmark 2.2 GeoDFN", version 1.2, dated 2006-08-08. This report fulfills one of the deliverables listed in Task 6 of the aforementioned activity plan. Project quality assurance (QA) and quality checking (QC) were conducted in accordance with the frame agreement negotiated between SKB and Golder Associates AB, and as described in the project Quality Plan, "Bilaga 3 – Kvalitetsplan", dated 2006-08-08.

2 Methodology

2.1 What is an MDZ?

One of the questions among the different modeling teams is the identification and quantification of minor deformation zones. One of the goals of this document is to initiate discussion to develop a formal definition of minor deformation zones (MDZ).

For the purposes of this analysis, the following definition of an MDZ was used:

"A minor deformation zone is a predominantly brittle geological structure that possesses both a degree of thickness greater than the width of a single fracture, and a three-dimensional spatial extent on the order of tens to hundreds of metres."

No judgment is made as to whether the structure is currently tectonically active (creeping aseismically or exhibiting stick-slip behavior) or if it is hydraulically significant; however, the 'brittle deformation' requirement tends to exclude non-reactivated ductile shear zones or proto-mylonites.

The original goal of this MDZ analysis was to identify brittle deformation features whose size was hypothesized to lie inside a critical size range (trace lengths > 50 m, but less than the 1,000 m minimum trace length cut-off for the deterministic deformation zone model). Fractures and deformation zones within this size range are of key interest, due to the effect that these structures could potentially have on the repository safety case (seismic risk and canister spacing/repository capacity), combined with the probability of their detection through conventional site investigation methods (lineaments, outcrop mapping).

At Oskarshamn, lineament traces shorter than 1,000 m in length have not been modeled in the deformation zone (DZ) model; minor deformation zones were structures that were smaller than 1,000 m in trace length, and were handled as planar structures in the stochastic DFN model. However, the availability of focused, high quality geophysical data combined with key boreholes in strategic locations at Forsmark, has enabled the deformation zone modeling team to incorporate structures with trace lengths (from geophysical lineaments) shorter than 1,000 m. As such, a trace length cut-off of 1,000 m may no longer solely be an appropriate definition for MDZ.

We suggest that, for conceptual models at the scale of the stage 2.2 site descriptions, the most useful definition for MDZ is a functional one; MDZ differ from DZ primarily in the way in which they will be modeled. In the current conceptual understanding, an MDZ and a DZ share a common geological origin and character; they are subsets of a larger population of structures, in which membership is based on model- and scale-dependent parameters.

However, structures interpreted as DZ during site investigations have an areal signature (in boreholes and geophysics) such that they can be represented in geologic models as features with finite thickness. As such, the definition of MDZ should include an additional constraint that, at the current scale of modeling, minor deformation zones must be structures that can be approximated within geologic models as single planar structures with no thickness.

The GeoDFN team requests feedback from other disciplines, particularly the Rock Mechanics, Hydrogeology and Site Investigation teams, as to what their internal conceptualizations of an MDZ are, both at Forsmark and Oskarshamn.

2.2 Methodology for identifying additional possible minor deformation zones in Forsmark

The methodology for identifying additional possible minor deformation zones (MDZ) consists of several steps, each designed to rule out as many 'false positives' as possible, without resorting to physical examination of the core. This study is conducted under the assumption that the avoidance of 'false positive' results, i.e. identification of a section of a borehole as an MDZ when it is in fact not an MDZ, is more important than the avoidance of 'false negatives'; i.e. sections that do contain MDZ that are missed by the re-interpretation. An over-estimation of the number of MDZ could have consequences for site safety cases, especially in the earthquake rupture and displacement scenarios.

This work was completed as a desktop mapping study; however a limited review of sections of drill core was performed at Forsmark. The characteristics of an MDZ are derived from the geological characteristics of the larger-scale deformation zones (DZ) identified during the original single-hole interpretations, and, as such, should be clearly visible in core.

The methodology derived in this report for identifying MDZ reflects a mixture of the unofficial 'operational rules' used during the single-hole interpretation of borehole KLX09 at Oskarshamn /Carlsten et al. 2007/ and the guidelines and instructions presented in the single hole interpretation method description /SKB 2006c/. A member of the DFN modeling team (Aaron Fox) was present during the single-hole interpretation, and developed the MDZ methodology from his observations and participation in the SHI process. It should be noted that the draft version of the KLX09 single-hole interpretation /Carlsten et al. 2007/ does not explicitly identify areas of the borehole as minor deformation zones; rather, all features are referred to as possible deformation zones, regardless of, thickness, size or confidence.

The methodology for identifying additional possible MDZ is as follows:

Step 1: Areas of increased fracture frequency currently not designated as DZ are visually identified in the cored boreholes. The SICADA data table p_freq_1m /SKB 2006b/ was used to construct Microsoft Excel scatter plots of open and sealed fracture intensity. The SICADA data table p_one_hole_interpret /SKB 2006a/ was then used to indicate the existing mapped possible deformation zones on the fracture frequency plots. An emphasis was given on areas with spikes in both sealed and open fracture intensity. Note that during this step, the identified

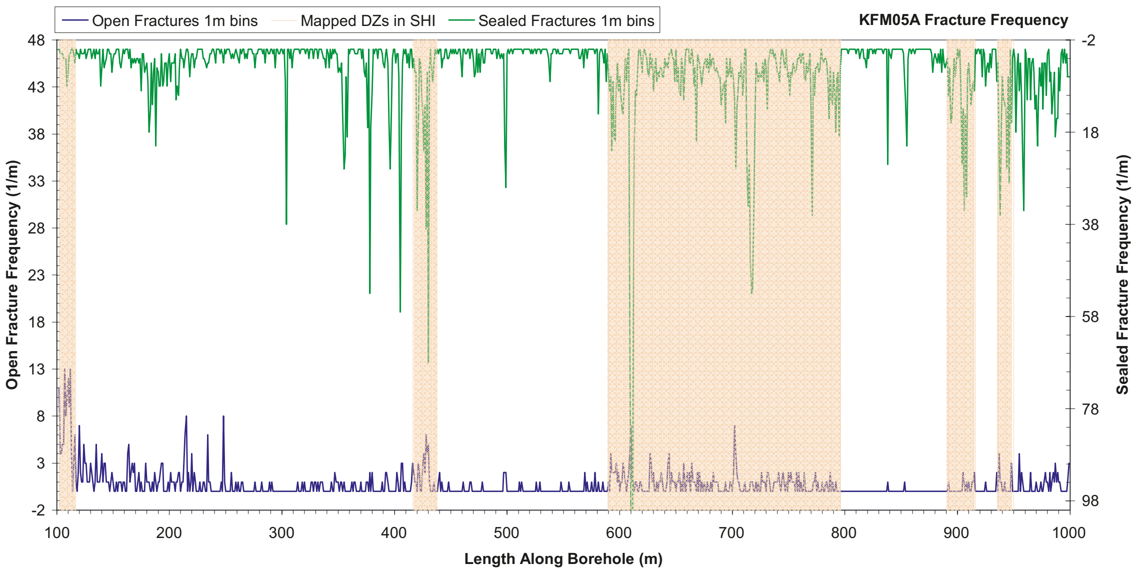

Figure 2-1. *Example fracture frequency plot. The tan-colored bands indicate the possible deformation zones mapped during the single-hole interpretation process. Note that open and sealed fracture are plotted on reversed axes; this makes it easier to locate frequency spikes in both types of fractures.*

additional possible MDZ (Table 3-1) were unusually coarse in resolution. MDZ up to 40 metres borehole length have been suggested. These lengths are 'areas of interest' that warrant further examination; they are not the actual limits of the possible MDZ.

Step 2: Once a list of additional possible MDZ has been made using the fracture frequency plots, the next step is to examine the target areas in the boreholes, using pre-existing WellCAD files completed as part of the single-hole interpretation (Karlberg, personal comm.). The WellCAD images synthesize a wide variety of borehole information (alteration, rock units, sealed fracture networks, core quality, borehole geophysics, fracture frequency, fracture mineralization, fracture morphology) into one (relatively) easy to use document. WellCAD images were available for:

- KFM01A, B, C, and D
- KFM02A
- KFM03A and B
- KFM04A
- KFM05A
- KFM06A, B, and C
- KFM07A and B
- KFM08A, B and C
- KFM09A and B
- KFM10A

The WellCAD image files are used to determine whether other geological attributes characteristic of DZ (moderate to severe alteration, zones of crushed rock or missing core, fault gouge, increased fracture frequency, and, often, evidence of past brittle and/or ductile deformation), are present in the identified additional possible MDZ. Particular attention was paid to the degree and type of rock alteration, the presence or absence of a focused resistivity anomaly, and the presence of crushed zone in the core and/or sealed fracture networks.

Step 3: A third step (largely conducted in parallel with the review of the WellCAD files) in identifying additional possible MDZ is to review the BIPS borehole image logs (.BIP) alongside the Boremap (.BDT) interpreted data files /SKB 2006ae/. The spatial relationship of the fractures, both to other geologic structures in the core (bedding, tectonic foliation, or banding) and to each other (fractures terminating against other fractures, sealed or otherwise) is investigated, as well as the core lithology and physical appearance. This step, by its very nature, is a qualitative assessment, relying on the experience and judgment of a trained geologist to determine whether the rock features represent a larger scale structure or just normal variability within the rock mass.

There are limitations associated with using the BIPS data. The BIPS tool available at Forsmark is limited to a resolution of 360 pixels per revolution (one pixel per degree of angular measurement) /SKB 2002/. This limits the effective identification of fractures to structures approximately 0.5 to 1 mm in width (this number is dependent on the borehole diameter), and makes it very difficult to pick out sealed fracture networks from the image. The BIPS logs are no substitute for a physical examination of the core; the ability to view the fractures simultaneously in the context of rock type, alteration, and in relationship to several metres of core is invaluable. In addition, the resolution of the human eye to resolve rock structural features and relationships is far better than any digital optical sensor.

A 'confidence' rating from 3 (high confidence) to 1 (low confidence) is also assigned to the additional possible minor deformation zone during this step. This parameter is a professional judgment based on how likely it is believed that the observed conditions actually represent a deformation zone, based on the definition presented in Section 2.1, as opposed to being an ‘anomaly’ in the rock mass (a separate rock unit or rock occurrence). For example, quartz dissolution features (the so-called ‘vuggy granite’) appear alongside several additional possible MDZ identified on the fracture frequency logs. Though these sections indicate many of the ‘positive’ geological and geophysical indicators, the structures themselves may not actually have the typical, more or less two-dimensional spatial extent of deformation zones.

Step 4: A series of detailed photographs of core segments inside their core boxes /SKB 2006d/ was next used to determine which borehole sections required further examination. In general, a review of the core box photos was able to remove nearly all of the low-confidence (1) additional possible MDZ candidates, as well as some of the higher-confidence (2) sections. Finally, remaining sections of drill core containing additional possible minor deformation zones were physically examined by a geologist. In most cases, the physical review was limited to sections assigned a level of confidence of 2 or 3.

The end results of the identification steps are a series of tables that document the identification process (Chapter 3). Tables 3-1 through 3-3 are the equivalent of a flowchart; they document the progressive refinement and elimination of suspect borehole sections through the analysis process.

Table 3-4 presents the ‘final’ results as a list of suggested adjusted borehole lengths (ADJ_SECUP, ADJ_SECLOW) within which the authors believe a minor deformation zone exists based on the criteria described in this report.

2.3 Differences between MDZ in Forsmark and Laxemar

The methodology described in Section 2.2 was originally developed for use at Oskarshamn, where minor deformation zones appear to be brittle structures that can be identified based on the presence of increased amounts of alteration with an increase in the open fracture frequency (and not necessarily with a corresponding increase in the sealed fracture intensity). Cataclastic features, such as filled breccias, crushed rock and rubble zones, and mylonite with or without gouge, are not uncommon in deformation zones in Oskarshamn. However, brittle cataclastic features are fairly uncommon at the Forsmark site.

After informal discussions with the Geology team at Forsmark (Michael Stephens, Assen Simeonov and Isabelle Olofsson), it was determined that, in general, open fracture frequency is not the key diagnostic for identifying potential deformation zones and minor deformation zones at Forsmark. The rock at Forsmark is generally very high quality, when compared to Oskarshamn, and is generally free of significant zones of open fractures, crushed rock, and areas of cataclasite (except inside deformation zones). As such, the combination of increased sealed fracture frequency (both as isolated fractures and as sealed networks) with the degree and type of rock alteration within the borehole is a better ‘first cut’ indicator of additional possible minor deformation zones at Forsmark. Also, minor and major deformation zones at Forsmark appear to be associated with dramatically increased sealed fracture network intensities. Whether a similar association at Oskarshamn exists is not known at this time to the authors.

Finally, the occurrence and role of MDZ may be different at Forsmark than in Oskarshamn. Preliminary results of the deformation zone and rock domain models for Forsmark 2.2 (Stephens, personal comm.) and preliminary borehole rock domain (RFM) and fracture domain (FFM) maps seem to indicate that nearly all of the significant areas of brittle deformation are captured within the zones identified in the single-hole interpretation. However, only some of the zones identified in the original single-hole interpretation are able to be matched to regional-scale (> 1,000 m in trace length) structures; this implies that several MDZ have already been captured. Most of the potential areas of MDZ identified in this report contain only a slight increase in open fracture frequency, usually concentrated in what appear to be one to three single fractures associated with a focused resistivity anomaly or the presence of amphibolite or pegmatite rock units.

3 Suggested MDZ in Forsmark cored boreholes

This chapter summarizes the results of the analyses performed on the Forsmark cored borehole data to determine if additional possible minor deformation zones could be identified. The chapter is structured as a 'flowchart'; each section represents an additional refining of the number and locations of borehole sections in which an MDZ is believed to exist.

3.1 Additional possible MDZ noted during the review of available borehole data

The following tables summarize sections of the Forsmark cored boreholes believed to host minor deformation zones (MDZ). A 'first cut' survey (Table 3-1) was completed using the fracture frequency plots, which are based on 1-metre frequency sections taken from SICADA (p_freq_1m).

The second-cut survey (Table 3-2) was completed using the WellCAD summary plots in conjunction with BIPS imagery and high-resolution digital photos taken of the core boxes during the BOREMAP process. Note that, at this stage, the tables contain only *possible* minor deformation zones; their existence should be viewed as a hypothesis for further discussion. Also, note that the level of confidence applied at this stage reflects only the interpretation of the WellCAD plots, the BIPS images, and the fracture frequency plots; the detailed core box photographs have not yet been analyzed, and the core has not been physically reviewed on site. Limits of the possible minor deformation zones presented in Table 3-2 might have been adjusted from those given in Table 3-1.

For reference, Table 3-3 contains several sections that, during the MDZ analysis process, were initially thought to be MDZ. Parallel work, completed as part of the continuing deformation zone modeling work at Forsmark, has placed these sections of the borehole within deformation zones (either by creating a new DZ, or expanding the boundary of an existing DZ). These sections are included for completeness; their identification as areas of interest and subsequent classification as DZ helps confirm that the tentative methodology derived in this report for identifying MDZ may be appropriate.

Table 3-1. Additional possible MDZ identified from fracture frequency plots.

Borehole	ADJ_SECUP (m)	ADJ_SECLOW (m)	Comments
KFM01A	100	300	Refined to 219–225 m during Step 2
KFM01A	270	290	Identified in DZ model (Table 3-3)
KFM01A	840	870	
KFM01B	75	100	
KFM01B	221	228	
KFM01B	255	280	Removed during Step 2
KFM01B	350	370	Removed during Step 2
KFM01C	118	129	
KFM01C	155	175	
KFM01C	200	220	Removed during Step 2
KFM01D	100	170	
KFM01D	225	280	
KFM01D	310	325	Removed during Step 2
KFM01D	345	360	
KFM01D	370	400	Removed during Step 2

Borehole	ADJ_SECUP (m)	ADJ_SECLOW (m)	Comments
KFM01D	470	515	Is DZ3 thicker than mapped (distal effects)?
KFM01D	540	620	
KFM01D	765	785	
KFM02A	225	250	Removed during Step 2
KFM02A	655	675	Removed during Step 2
KFM03A	105	145	
KFM03A	300	333	Removed during Step 2
KFM03A	555	620	
KFM03A	860	905	Removed during Step 2
KFM03A	970	1,000	
KFM04A	110	135	Included in revised DZ1 (Table 3-3)
KFM04A	145	160	Included in revised DZ1 (Table 3-3)
KFM04A	280	370	New DZ identified during modeling process (Table 3-3)
KFM04A	665	720	Removed during Step 2
KFM04A	785	820	Removed during Step 2
KFM04A	870	930	Removed during Step 2
KFM04A	950	960	
KFM05A	160	220	
KFM05A	340	360	Removed during Step 2
KFM05A	375	385	Removed during Step 2
KFM05A	390	415	Included in revised DZ2 (Table 3-3)
KFM05A	950	1,000	Removed during Step 2
KFM06A	360	390	Could the nearby existing DZ4 be larger?
KFM06A	515	550	New DZ identified during modeling process (Table 3-3)
KFM06A	555	585	Removed during Step 2
KFM06C	190	230	
KFM06C	275	310	New DZ identified during modeling process (Table 3-3)
KFM06C	860	EOH	Pattern of fracture intensity strange at bottom of hole; different rock domain?
KFM07A	250	270	Removed during Step 2
KFM07A	330	350	
KFM07A	420	450	Wide zone of increased sealed fractures?
KFM07B	65	89	
KFM07B	150	175	
KFM07B	280	290	Removed during Step 2
KFM08A	395	420	
KFM08A	425	440	
KFM08A	590	630	
KFM08A	720	755	Removed during Step 2
KFM08B	52	68	Removed during Step 2
KFM08B	89	108	Removed during Step 2
KFM08C	240	260	
KFM08C	925	940	
KFM09A	320	340	
KFM09A	380	415	Removed during Step 2
KFM09A	640	675	
KFM09A	680	705	Removed during Step 2
KFM09B	145	155	
KFM09B	158	170	Removed during Step 2
KFM09B	222	232	Removed during Step 2
KFM09B	275	290	
KFM10A	270	280	New DZ identified during modeling process (Table 3-3)
KFM10A	315	350	

Table 3-2. Additional possible MDZ identified through review of WellCAD plots and BIPS imagery.

Borehole	ADJ_ SECUP (m)	ADJ_ SECLOW (m)	Level of confidence (1 to 3)	Geological/geophysical Indicators	BIPS observations/notes	Comment
KFM01A	219	225	2	Increased degree of rock/fracture alteration, increased sealed and open fracture frequency, focused resistivity anomaly, associated with amphibolite.	Vertical sealed fractures visible 220–222 m, strong foliation, diking and veining visible 222.6–224.7 m; related to amphibolite.	FFM02: Teams had difficulty separating DZ from increased background fracture intensity in this rock domain.
KFM01A	838	844	1	Increased degree of rock/fracture alteration, increased sealed and open fracture frequency, focused resistivity anomaly, decreased magnetic susceptibility, increased silicate density, decreased natural gamma.	Appears to be open fractures in association with amphibolite; probably not an extensive structure.	
KFM01B	78	103	2	Increased degree of rock/fracture alteration, increased sealed and open fracture frequency, focused resistivity anomaly, increased frequency of sealed networks.	Several large open fractures, complex small-scale rock unit variance. One big DZ, or 2–3 small ones?	FFM02: Teams had difficulty separating DZ from increased background fracture intensity in this rock domain.
KFM01B	222.5	225	3	Increased degree of rock/fracture alteration, increased sealed and open fracture frequency, strong focused resistivity anomaly.	Two large open fractures, visible aperture with irregular surface.	
KFM01C	117.5	127.5	2	Abrupt change in fracture orientations, increased rock and fracture alteration (oxidization, some laumontite and chlorite?), increased sealed/open fracture frequency, presence of sealed networks.	Appears to be associated with pegmatite/amphibolite intrusions (cooling features rather than shear DZ?).	FFM02: Teams had difficulty separating DZ from increased background fracture intensity in this rock domain.
KFM01C	156	158	2	Abrupt change in fracture orientations with respect to rock structure (foliation), increased rock alteration (weak to medium saussuritization and oxidation), increased sealed and open fracture intensity, presence of sealed fracture networks.	Oxidization and reddish-staining visible in BIPS; structure is between two pegmatite veins/lenses; may be old ductile zone that has re-activated (open fractures visible vertically above sealed fracture network).	
KFM01D	121	135	1	Increased sealed and open fracture intensity; fractures discordant to rock structure (foliation), several small focused resistivity anomalies, increased degree of fracture alteration.	BIPS/Core box photographs not available.	Complex rock structure of pegmatite/amphibolite noted. Section is inside fracture domain FF02.
KFM01D	142	159	3	Increased sealed and open fracture intensity, fractures discordant to rock structure, isolated rock alteration (weak oxidization, epidotization, and albitization), several large and wide focused resistivity anomalies, two sealed fracture networks noted.	BIPS/Core box photographs not available.	Structure cored by amphibolite lens and is inside fracture domain FFM02.

Borehole	ADJ_ SECUP (m)	ADJ_ SECLOW (m)	Level of confidence (1 to 3)	Geological/geophysical Indicators	BIPS observations/notes	Comment
KFM01D	342	357	1	Increased sealed and open fracture intensity, fractures discordant to rock structure, several small focused resistivity anomalies, and a slight increase in the number of fractures exhibiting alteration.	BIPS/Core box photographs not available.	
KFM01D	767	782	2	Frequency of unbroken fractures, distribution of rock alteration and fracture alteration; discordance between fractures and rock structure (foliation).	BIPS/Core box photographs not available.	May be distal effect of DZ5; perhaps a thicker damage/ transition zone.
KFM02A	0	0	–	No changes suggested; possible MDZ visible in fracture frequency plots are not seen on WellCAD or BIPS.		
KFM03A	105	115	1	Slightly increased sealed and open fracture intensity, highly variable silicate density readings, several small focused resistivity anomalies.	BIPS imagery shows complex rock structure associated with amphibolite lens; however, fracturing is also in the surrounding host rock.	
KFM03A	570	578	1	Slightly increased sealed and open fracture intensity, some fractures discordant to foliation, several very small focused resistivity anomalies.	Very complex rock structure (amphibolite and pegmatite veins) visible in BIPS, but poor quality of BIPS imagery makes results inconclusive. May be enhanced fracturing caused by amphibolite pod as stress concentrator, rather than a spatially extensive deformation zone.	
KFM03A	986	994	2	Slightly increased zone of sealed and open fracture intensity that appears to be associated with thicker zone of weak rock alteration (oxidization) near the end of this borehole. Also noted small focused resistivity anomalies.	BIPS shows several visible open fractures and extensive reddish alteration of core.	
KFM04A	952.5	957.5	1	Increased degree of rock/fracture alteration, increased sealed and open fracture frequency, focused resistivity anomaly, sealed fracture network.	Open fractures not visible in BIPS; cooling features along veins/ intrusions?	
KFM05A	163	170	1	Increased open fracture intensity, focused resistivity anomaly. No change in silicate density, minor changes in natural gamma and magnetic susceptibility.	Most likely just open fractures (not MDZ).	FFM02: Teams had difficulty separating DZ from increased background fracture intensity in this rock domain.
KFM06B	0	0	–	Not examined; no anomalies noted on fracture frequency plots.		

Borehole	ADJ_ SECUP (m)	ADJ_ SECLOW (m)	Level of confidence (1 to 3)	Geological/geophysical Indicators	BIPS observations/notes	Comment
KFM06C	203	209	2	Slight change in open and sealed fracture orientations, slightly increased rock and fracture alteration (oxidization), increased open and sealed fracture frequency, focused resistivity anomaly.	Width of resistivity anomaly suggests thickness; appears to be associated with quartz/pegmatite veining.	
KFM06C	860	EOH?	1	The last 140 metres of this hole are geologically distinct from the rest of the hole. Higher overall fracture frequency and more complex geological structure.	Separate/different Rock Domain.	"Problem" already raised by MBS/ASi in SHI.
KFM07A	327	345	1	Increase in open/sealed fracture intensity, very small focused resistivity anomaly, increased small areas of rock alteration (oxidization), presence of sealed networks.	Appears to be associated with amphibolite/quartz veining; BIPS images are not convincing that this is truly a MDZ.	
KFM07B	170	178	1	Increased rock alteration (weak to medium), increased open and sealed fracture frequency, small crush zones, complex natural gamma signature.	BIPS is very inconclusive; no major signs of shear or offset; one large open fracture.	FFM02: Teams had difficulty separating DZ from increased background fracture intensity in this rock domain.
KFM07B	283	287	2	Increase in sealed fracture intensity; slight increase in open fracture intensity, sealed network noted; increased rock and fracture alteration, fractures discordant to foliation.	Strong foliation; possible detachment at 284.4–285. May just be rock structure.	
KFM08A	408	415	2	Increased rock (medium to strong oxidization and albitization) and fracture alteration, increased open and sealed fracture frequency, focused resistivity anomaly, change in orientation of sealed and open fractures, presence of sealed networks.	BIPS logs suggest some quartz dissolution (vuggy granite?); 3 large open fractures visible in BIPS.	This section is outside mapped deformation zones; however, it appears to belong to a special rock type/unit. Perhaps exclude this section from DFN calculations?
KFM08A	428	433	1	Increase in open and sealed fracture intensity; crushed zones, fracture alteration (not rock) zones, and consistency in fracture orientation.	BIPS logs suggest association with amphibolite and pegmatite veins; hard to see fractures on BIPS images.	
KFM08A	597	627	2	Isolated intervals of weak oxidization, chloritization, epidotization in rock mass along fractures, increased sealed fracture intensity and presence of sealed networks, minor focused resistivity anomalies (open conductive fractures?).	Associated with amphibolite veins; very poor quality BIPS images, very hard to see anything.	Special rock unit instead of MDZ? Core examination suggests possible zone is between 623.6 and 624.14 m.
KFM08B	0	0	–	No additional DZ/MDZ suggested.		

Borehole	ADJ_ SECUP (m)	ADJ_ SECLOW (m)	Level of confidence (1 to 3)	Geological/geophysical Indicators	BIPS observations/notes	Comment
KFM08C	240	252	1	Isolated areas of minor increased rock alteration (oxidization), increase in sealed and open fracture intensity, fractures discordant to rock structure, several small focused resistivity anomalies, fluctuating magnetic susceptibility.	No BIPS images available at the time of this report. May be cooling features associated with amphibolite lens.	
KFM08C	928	936	2	Minor to moderate rock alteration (oxidization, laumontization), increase in sealed and open fracture intensity, small mapped sealed network, fractures discordant to rock structure, strong focused resistivity anomaly with several distinct peaks.	No BIPS images available at the time of this report.	
KFM09A	322	362	2	Increased open and sealed fracture intensity (the increase in open intensity is most noticeable), minor isolated areas of rock alteration; some moderate to highly altered fractures discordant to rock foliation, isolated sealed networks, intense veining and small-scale rock structure.	Very complex rock structure with abundant gabbro/amphibolite; mix of open fractures discordant to and aligned with foliation.	FFM05 Section in special rock unit with increased fracture frequency.
KFM09A	650	670	1	Increased sealed fracture intensity, isolated spikes in open fracture intensity, increase in rock alteration (oxidization and albitization), isolated sealed networks, highly variable magnetic susceptibility, natural gamma, and silicate density.	Complex rock structure visible in BIPS; poor quality makes it difficult to determine; old reactivated ductile zone?	FFM04: Section in special rock unit with increased fracture frequency.
KFM09B	146	154	2	Increased open/sealed fracture intensity, small sealed network, zone of weak albitization, very small focused resistivity anomalies, increased fracture alteration, open structures discordant to strong foliation.	One large complex fracture visible in BIPS, other ‘swarms’ of open fractures; alteration rind noted around open fractures.	Rock unit with increased frequency of mainly sealed fractures.
KFM09B	280	290	2	Increased open /sealed fracture intensity, small crush zone, small focused resistivity anomaly, increased rock and fracture alteration.	Lots of open fractures, lithologically complex; alteration visible in BIPS; most may be compositionally related?	Rock unit with increased frequency of mainly sealed fractures.
KFM10A	322	329	2	Increased open/sealed fracture intensity, small sealed network zone noted, several small focused resistivity anomalies, zones of weak to moderate alteration (oxidization, albitization, chloritization), core loss and sealed network noted. Fractures are oriented roughly parallel to rock foliation.	No BIPS images available at the time of this report. This section has a thin (< 0.5’) amphibolite vein in it; intrusion and subsequent fracturing along an old ductile zone?	
KFM10A	339	348	1	Increased open/sealed fracture intensity, large sealed network zone noted, several small focused resistivity anomalies, zones of weak alteration (oxidization, albitization). Fractures are oriented roughly parallel to rock foliation, although the broken fractures tend to be discordant to rock structure.	No BIPS images available at the time of this report. This section may be associated with two amphibolite veins at ~ 344 m and 348 m.	

Table 3-3. Borehole sections of interest remapped as possible deformation zones in the DZ modeling work.

Borehole	Top of zone from fracture freq. plots (m, ADJ_SECUP)	Bottom of zone from fracture freq. plots (m, ADJ_SECLOW)	Top of zone from BIPS/SHI plots (m, ADJ_SECLOW)	Bottom of zone from BIPS/SHI plots (m, ADJ_SECLOW)	Comments
KFM01A	270	290	268	329	Assigned as a new DZ in version 2.2 DZ model.
KFM04A	110, 145	135, 160	110	160	Modified DZ1 in version 2.1 and 2.2 DZ models.
KFM04A	280	370	357.5	362.5	Assigned as a new DZ in version 2.1 DZ model.
KFM05A	390	415	394	408	Modified DZ2 in version 2.1 DZ model.
KFM06A	Not identified in fracture frequency plots.	Not identified in fracture frequency plots.	517	545	Assigned as a new DZ in version 2.2 DZ model.
KFM06C	275	310	283	306	Assigned as a new DZ in version 2.2 DZ model.
KFM10A	267	285	275	284	Assigned as a new DZ in version 2.2 DZ model.

3.2 Investigation of drill core for additional possible minor deformation zones

The final step in the investigation of additional possible minor deformation zones at Forsmark was a physical review of the drill core. An examination of detailed photographs of the core inside the core boxes was used to create a subset of cores for examination; the principal focus of the physical review of the drill core was on additional possible minor deformation zones with a level of confidence of 2 or 3 were selected for further study. However, some lower-confidence intervals were included in the physical review where BIPS or core box photography was judged inconclusive. The physical examination of the core focused on the following characteristics:

- Type and degree of rock alteration.
- Type and degree of fracture alteration.
- The relationship of fracture patterns (orientation with respect to core, orientation with respect to other sets).
- The presence of small-scale indicators of brittle deformation or shear movement (slickensides, striations, mineral lineations).
- Presence or absence of interpreted re-activated ductile deformation features.
- The relationship of fractures to rock structure (foliation, banding).
- The relationship of fractures to rock occurrence (pegmatite veins, amphibolite).

A summary of our observations for each candidate segment of core is presented below. The end result of the physical analysis of the core was to increase the level of confidence of several additional possible minor deformation zones and to reduce the level of confidence of other candidate zones.

3.2.1 KFM01A: 219–225 m

A transitional zone (higher sealed fracture frequency) was noted beginning at 216.4 m, and consisted of reddish oxidized sealed fractures oriented perpendicular to core axis. Fracture intensity (both sealed and open) continued to increase with increasing depth and proximity to a sealed fracture network at approximately 219 m near a rock contact with a small amphibolite lens. A slickensided fracture face was noted at 219.1 m, with minor amounts of gouge and dirt along the fracture plane. The core of this possible additional MDZ ends at 219.7 m at the host rock/amphibolite contact; a lower transition zone is noted to 223.9 m. Level of confidence set to 3; this is a minor deformation zone.

3.2.2 KFM01B: 222.5–225 m

A transitional zone was noted beginning at 223.65 m as an increase in sealed fracture intensity perpendicular to the core axis. Fractures in this zone showed reddish oxidization and quartz sealing. The core of the MDZ began at 224.2 m with medium red rock oxidization increasing with depth. Fracture walls show chlorite, calcite, iron oxide fillings, and potentially some laumontite. The main deformation zone structure occurs from 224.7 m to 225 m. It consists of a wide, open fracture oriented at a high angle to the core axis, with calcite and iron oxide coatings. Slickensides were visible on the fracture face, as well as on a smaller open fracture adjacent to the main fracture oriented at a smaller angle (~ 20°) to the core axis. This smaller fracture appears to be a splay off of the main feature. The transition zone ends immediately below the main fracture contact at 225.1 m. The level of confidence was set to 3; this is a minor deformation zone.

3.2.3 KFM01C: 117–127.5 m

The transition zone appears to begin at approximately 121.15 m, and is marked by an increase in the width of the sealed fractures, reddish oxidation as a fracture infill mineral, and an increasingly complicated rock structure shot through by quartz and pegmatite veins. Fracture frequency increases with depth; there are at least two sets (one oriented approximately parallel to the core axis and one oriented at approximately 60° to the core axis). The core of the MDZ begins at 122.2 m, with major fractures at 122.33 m and 122.76 m. The fracture at 122.76 m has a width of approximately 2 cm, and features a fracture surface coated with epidote, chlorite, and iron oxides. The fracture minerals show lineations and growth along preferred directions. No slickensides were visible. The lower transition zone ends at 123.5 inside amphibolite lens and is marked by the end of the reddish rock alteration. The level of confidence was set to 3; this structure is a minor deformation zone. However, it does not show a significant degree of past displacement, nor of being very 'thick'.

3.2.4 KFM01C: 156–158 m

This section of core featured relatively intense reddish staining/rock alteration beginning at approximately 156.8 m. An increase in the intensity of both sealed and broken fractures intensity was noted. The broken fractures look to be broken along pre-existing thin filled fractures. Also noted from 157.2–157.5 m is a special rock texture featuring open fractures with several generations of mineral infilling, including pyrite, epidote, calcite, (prehnite and laumontite also mapped in WellCAD files). A vuggy texture with fairly strong rock alteration was noted; however, there was no direct evidence of shear or brittle deformation. The level of confidence was reduced to 1; this is not a minor deformation zone.

3.2.5 KFM01D: 142–159 m

This additional possible MDZ is delineated by an increase in sealed fracture intensity adjacent to an amphibolite lens. There is an increased degree of alteration; however, there is no direct evidence of shear or brittle deformation, and the general rock quality is quite high. Fractures show tight sealing with epidote, calcite, and iron oxide fillings. The level of confidence was reduced to 1; this is not a minor deformation zone.

3.2.6 KFM01D: 767–782 m

The limits of this zone were originally defined in Step 3 as 767–782 m. However, the examination of the rock core has resulted in an adjustment of the zone boundaries. The transition zone for this additional possible MDZ begins at 771.35 m and is denoted by increased rock alteration (oxidization and minor albitization) and an increase in open fracture frequency. Sealed fractures in this zone are coated with iron oxide, calcite, and epidote, with minor pyrite in one sealed fracture. The MDZ core begins at 771.6–772.6 m, and consists of parallel open fractures oriented approximately 55° to the core axis. Fractures in the core are broken, open, and a few exhibit parallel lineations on their surfaces (mineral growth aligned to slip direction). One fracture (771.43–771.65 m) showed a slickensided surface. Transition zone appears to end at 773 m, but the higher degree of rock alteration persists to 776 m. This zone has been assigned a level of confidence of 2; this structure is a minor deformation zone, but it is not quite as striking as others observed in Forsmark. The MDZ consists of a diffuse zone of sheared fractures with no fault gouge, very few slickensides, and surrounded by relatively good-quality (low fracture intensity) rock.

3.2.7 KFM03A: 986–994 m

Too much core was initially selected; the actual zone of interesting rock structure here is from 992–994.9 m (the full transition zone). The core of the MDZ begins at 992.6 m, and is denoted by an increased degree of alteration, increased sealed fracture intensity, the presence of iron-oxide stained fractures, and some evidence of small-scale dissolution and vugs along a few fractures. Rock is only weakly altered, but the degree of alteration increases slightly below 993.5 m. A significant set of fractures is located at 994.3–994.5 m; the rock mass appears to have sheared (composite shear plane with 2–3 splays) along a thick zone of biotite mica. There may be some small slickensides visible, but they are very difficult to distinguish from mica crystal structure. Some albitization was visible in small-intervals. The level of confidence in this zone (2) has not changed; however, it has not been selected as an MDZ. The deformation appears to be confined to the biotite.

3.2.8 KFM04A: 952.5–957.5 m

Note that this zone was not examined in core due to time limitations at the site. This zone is delineated by isolated increases in rock alteration (reddish oxidization), a sizeable sealed network, and an increase in both sealed and open fracture intensity. A small crush zone (probably broken during drilling) along an open fracture was noted at approximately 954.8 m. The core of this zone appears to consist of brecciated and highly altered rock that has been re-sealed (quartz?) extending from the bottom of a pegmatite vein at approximately 954.7 m, down to approximately 955.2 m. The transition zone (areas of weak rock alteration) appears to continue down to approximately 956 m. This zone has been assigned a level of confidence of 2. However, based on the visual and geophysical evidence, this structure is an MDZ.

3.2.9 KFM06C: 203–209 m

This section of core exhibited only a minor degree rock alteration and a slight increase in fracture frequency (sealed and open). However, the fracturing appears to be occurring along mica-rich layers within the rock. Minor albitization in small (< 2 cm thick) zones, as well as core disking, was noted across the entire section. Some evidence of shear deformation was noted in fractures surrounding a small amphibolite dyke/mafic enclave at 204.5 m. Both sides of the dyke appeared to have been sheared, but the rock at the contact was rich in biotite mica. The current thinking is that this area of the borehole represents a local concentration of stress along a pre-existing weakness (the mica) and not an extensive MDZ. The level of confidence for this zone was reduced to 1.

3.2.10 KFM07A: 327–345 m

Note that this zone was not examined in core due to time limitations at the site. A review of the core box photography shows a general increase in open, broken fracture intensity. Several of the fractures are quite wide, with a noticeable mineral infilling. Weak to medium oxidization is noted in the core photographs, but it is generally confined to areas surrounding the fractures. This is a different structure than has been seen in the rest of the Forsmark cored boreholes; it looks to be a wide area of increased brittle deformation, but many of the currently open fractures look drilling-induced (but are not marked as such in the core box). The fractures are at a slight angle to the core axis; this zone seems to be dominated by sub-vertical fracturing.

A level of confidence of 2 has been assigned to this zone; it is still uncertain that it actually represents an MDZ due to the lack of extensive alteration.

3.2.11 KFM07B: 283–287 m

Not an MDZ. Good hard intact rock noted in the drill core, with only slight alteration in spots. Confidence reduced to 1.

3.2.12 KFM08A: 325–331 m

This section of core showed fairly normal fracture intensities, with lots of small sealed fractures, but with very few long or open fractures. An increased degree of rock alteration (albitization, oxidization) was noted along sealed fracture networks in this section. Faint slickensides were visible on 2 of the larger open fractures. There is not enough damage, rock alteration, or evidence of shear or brittle failure in this section to suggest an MDZ; the main anomaly is an increase in the sealed fracture intensity. The level of confidence for this zone was reduced to 1.

3.2.13 KFM08A: 334.5–335.2 m

The notes for this section of core are the same as for 325–331 m; the level of confidence for this zone has been reduced to 1. This is not an MDZ.

3.2.14 KFM08A: 428–433 m

This interval is distinguished by a slightly increased degree of rock alteration (reddish oxidization), however, the alteration is concentrated around fractures instead of disseminated through the rock mass (the fracture spacing is such that the rock mass appears altered). There are several sealed fracture networks. The core possesses locally complex lithology; it is a mixture of amphibolite/mafic enclaves, some minor quartz veins, and fine grained granite with metamorphic texture. There is no evidence of shear dislocations, any major brecciation or core loss. The core is generally intact and hard, with very few broken fractures. The increase in fracture intensity appears to be associated with the presence of amphibolite; most of the few open fractures are along mica-rich zones in the amphibolite. The level of confidence was reduced to 1; the current interpretation is that the increase in fracture intensity is associated with the local lithological complexity and not with a deformation zone. Not an MDZ.

3.2.15 KFM08A: 597–627 m

Again, a section of core that was too large was initially selected; further examination delineated a smaller zone from 620–625 m. Rock within this zone exhibited an increased degree of rock alteration (reddish oxidization, epidotization with partial dissolution, chloritization, and albitization) and an increase in the intensity of sealed fractures. A small possible MDZ was identified from 623.6–624.14 m. The zone was composed of a set of open and sealed fractures with orientations at a high angle to the rock foliation in a zone of complex rock structure (amphibolite and metamorphic granite to granodiorite veins). No slickensides were visible, but some small amounts of possible gouge was noted in one of the fractures (might also be dirt from drilling?). The confidence of the smaller interval was increased to 2, and it was labeled an MDZ. The confidence in the surrounding interval (597–623.6 m and 624.14–627 m) was reduced.

3.2.16 KFM08C: 240–252 m

This section does not possess an MDZ. There is a body of amphibolite that swims in and out of this section of core. The section is also associated with pegmatite and quartz veins. The alteration consists of weak reddish oxidization and albitization near the edges of the amphibolite. Fractures in the amphibolite and in the zone between the two amphibolite bodies occur at zones of biotite concentrations. Fracture mineral infillings include chlorite, calcite, and epidote. There is no evidence of gouge, shear movement, brecciation, or of the degree of rock alteration associated with minor deformation zones. The level of confidence of this section was reduced to 1.

3.2.17 KFM08C: 928–936 m

This section of KFM08C is a fairly complex section of rock. On inspection, two different zones of interest were noted. First, from 933.2–934 m, a zone of moderate rock alteration was observed; this appeared to be a mix of albitization and oxidization. The rock mass looked noticeably duller, absorbs water faster than the unaltered rock, and feels slightly lighter when hefted. No quartz dissolution or epidotization was noted. A cause for the different appearance in the core at this location was not identified during this study.

Second, from 934–936.3 m, a zone of stronger rock alteration (largely oxidization, but also scattered albitization) was noted. This section was cored through amphibolite, fine grained granite, and pegmatite. Open fractures were encountered in the pegmatite; the rest of the structure consists of sealed fractures and a single small sealed network. Chlorite, epidote, and calcite fracture infillings were visible. All structures were oriented at a moderate angle (~ 40°) to the apparent foliation. The rock immediately up- and down-core of these sections looked as if it had undergone significant ductile strain (faint boudinage structures, 'pinched-off' quartz lenses, very strong foliation). However, there were no signs of shear or recent brittle deformation (other than a few open fractures in quartz-rich veins and the pegmatite). The level of confidence for this section remains at 2, but it is probably not an MDZ. This area of the borehole may represent a past buildup of pore fluids, perhaps in response to a local weakening of the rock mass by ductile strain.

3.2.18 KFM09A: 650–670 m

The rock structure encountered in this section of KFM09A appears to be a re-activated ductile shear zone. The overall zone is marked by a very strong rock foliation, compositional banding, occasional boudinage texture, lithologic complexity, and a general increase in the degree of rock alteration (reddish oxidization). The entire section is fairly altered. A well-slickensided fracture was noted at 651.6 m.

The core of this zone extends from 666.1 to 667.3 m, and is marked by a drastic increase in rock alteration (reddish oxidization, sassuritization, and epidotization), an increase in the intensity of sealed fractures (some exhibit > 1 cm of width). The sealed fractures are contained within two different sets which are oriented at angles to both the overall rock foliation and the core axis. Some of the sealed fractures inside the sealed fracture networks look not unlike clastic dike or breccia pipes in sheared sedimentary rocks. The WellCAD log for this borehole has recorded brittle/ductile shear zones below this interval (687–695 m). The level of confidence of this zone was increased to 3; it is believed that this zone represents an MDZ created through the re-activation of an older thick ductile shear zone.

3.2.19 KFM09B: 280–290 m

Note that this zone was not examined in core due to time limitations at the site. This section was identified based largely on the increased degree of rock and fracture alteration, combined with an increase in open and sealed fracture intensity with a focused resistivity anomaly. BIPS imagery shows a very lithologically complex section of borehole, as well as a well defined zone of parallel, open fractures with visible apertures from 283.6 to 284.1 m. Core box photos show that the fractures in this zone cut completely across the core axis, and have some degree of thickness. Rock and fracture alteration is clearly visible in the core box photos. Based on the above evidence, this zone is identified as an MDZ with a confidence level of 2.

3.2.20 KFM10A: 322–329 m

This section of KFM10A exhibits a very strong rock foliation with swarms of sealed fractures perpendicular to the foliation. The rock mass exhibits a generally high RQD, with only a slight amount of alteration adjacent to wider sealed fractures (weak reddish oxidization with occasional albitization). The few open fractures are fresh or have a very slight oxidization staining. No slickensides or brecciation was observed. The level of confidence in this section was reduced to 1; it appears to only be a zone of increased fracture intensity, perhaps coupled to the increased rock foliation. Not an MDZ.

3.3 Proposed additional minor deformation zones

Table 3-4 contains a list of the borehole sections where, based on the criteria discussed in this report, MDZ are interpreted to intersect the Forsmark cored boreholes.

Table 3-4. Additional minor deformation zones identified in Forsmark cored boreholes.

Borehole	ADJ _SECUP (m)	ADJ_SECLOW (m)	Level of confidence
KFM01A	216.4	223.9	3
KFM01B	223.65	225.1	3
KFM01C	121.15	123.5	3
KFM04A	953.2	955.8	2
KFM08A	623.6	624.14	2
KFM09A	666.1	667.3	3
KFM09B	283.6	284.1	2

4 Conclusions and recommendations

4.1 Conclusions

The desktop study described in Sections 2 and 3 resulted in the identification of 31 sections (Table 3-2) within the analyzed Forsmark cored boreholes where additional possible minor deformation zones (MDZ) not previously mapped may exist.

However, out of all of the identified candidates, only seven sections (see Table 3-4) stood out as areas of focused brittle deformation with high confidence (2 or 3). Even then, some of the additional possible MDZ given a level of confidence of 2 (see Table 3-2) have not been explicitly declared as MDZ; this is largely due to the lack of evidence of brittle deformation (brecciated core sections, fault gouge, and other kinematic indicators), combined with potential alternative explanations for the observed structures.

A visible increase in fracture intensity (both sealed and open) was noted in nearly all Forsmark cored boreholes near amphibolite rock occurrences. Many of these increases of fracture intensity were suggested as possible additional minor deformation zones; dislocations are occurring along semi-regular planes adjacent to the amphibolite pods. Alternatively, it is also possible that the amphibolite lenses are acting as stress concentrators for joint formation, and that there has not actually been shear movement along the contact. Whether labeled an MDZ or not, it will be important for future site work to remember that both the intensity of fracturing and the degree of rock alteration increases near amphibolite contacts.

A key indicator that was noted during a site visit to the core shed at Forsmark was the angle at which open and broken fractures intersected the rock structure (foliation, banding, and veins). Where fractures intersected the rock structure at high angles, increased degrees of alteration and generally larger open fractures (in the BIPS imagery) were noted. Where fractures were oriented sub-parallel to rock structure they were generally tightly sealed.

4.2 Recommendations

One of the difficulties with the deformation zones and minor deformation zones is how to assess their spatial extent when the zones do not appear to be associated with surface structures or cannot be correlated between boreholes; what is the size and shape of these features? In Oskarshamn, the assumption has been made that MDZ occupy the size range between outcrop-scale fracturing (1–10 m in outcrop trace length) and major deformation zones (1,000 m and larger), assuming that the radius distribution of the associated structures follows a power law. The decision at Oskarshamn in past site models (in particular, SDM Laxemar 1.2) has been made to simulate all features smaller than 1,000 m in trace length (structures with an equivalent-disk radius of less than 564 m) stochastically.

We suggest that a similar MDZ-DZ size cut-off be used as a working hypothesis for SDM Forsmark 2.2 geological modeling. The usage of the same trace-length cutoff at both project sites will enable for direct comparison of the size models between the two sites.

The use of this assumption can add a level of uncertainty to site models; there is no direct evidence (either from hydraulic testing or geophysical data) at Forsmark yet that the sizes of the postulated MDZ are within this range. This uncertainty is largely due to the problem of characterizing a three-dimensional structure of unknown spatial extent using one-dimensional methods (boreholes).

As part of the ongoing characterization of the Forsmark site, deformation zones in cored boreholes have already been mapped and associated with new lineament data with traces smaller than 1,000 m in length. The results of this work are expected to be made available in December of 2006. The lineament data has been derived from high-quality, high-resolution ground magnetic surveys. This introduces the quandary of the existence of structures with trace lengths smaller than 1,000 m that can be modeled deterministically because of the existence of supporting data. We recommend that these smaller deformations zones also be modeled stochastically; i.e. replaced with a single planar fracture whose size and location is determined according to the parameters presented in the Geological DFN. However, we would recommend that, to obtain a discrete-fracture network model that accurately represents existing site conditions to the detail level of available data, that a bootstrapping/trace-map conditioning method be used during DFN generation.

Finally, the GeoDFN team is eager to receive feedback from all other involved disciplines, both with respect to this report and to the concept of minor deformation zones in site models in general.

5 References

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SKB, 2002. Metodbeskrivning för tv-loggning med BIPS, Version 1.0, SKB method document MD 222.006, dated 2002-09-19.

SKB, SICADA table p_one_hole_interpret and BOREMAP image (.BIP) and data (.BDT) files, 2006a. SKB data delivery Sicada_06_162, requested by A. Fox (afox@golder.com) and fulfilled by Margareta Gerlach on 2006-08-02.

SKB, SICADA table p_freq_1m, 2006b. SKB data delivery SICADA_06_164, requested by A. Fox. No data delivery letter available; metadata indicates pull date of 2006-08-02.

SKB, 2006c. Metodbeskrivning för geologisk enhålstolkning, SKB MD 810.003, version 3.0, dated 2006-05-09.

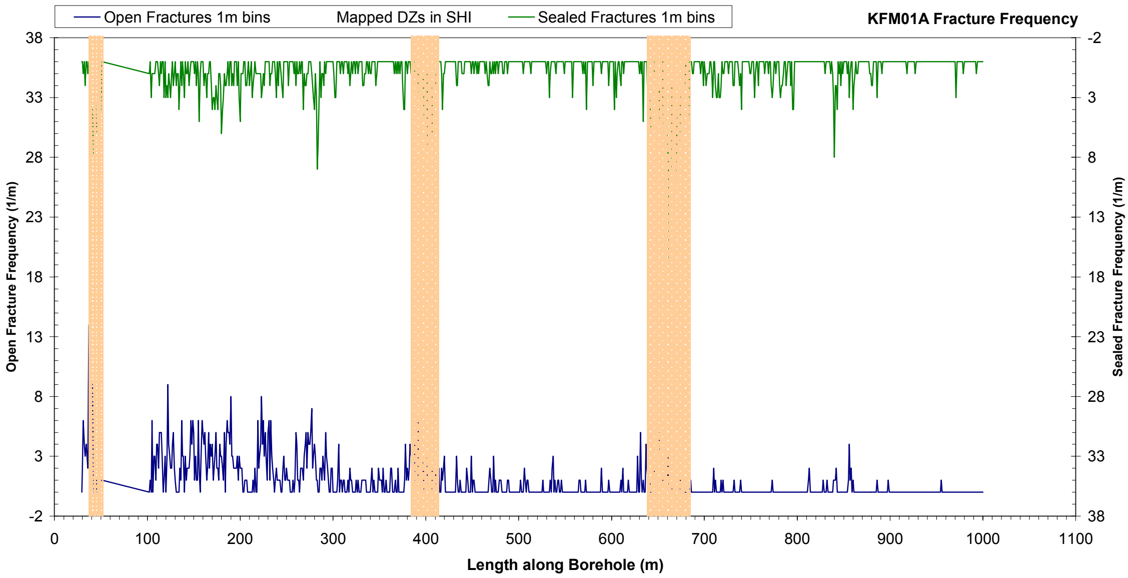
SKB, 2006d. DVDs shipped to Jan Hermanson (GAAB) containing photos of core boxes taken at Forsmark by SKB PFM personnel. No delivery letter was associated with the DVDs, so no formal reference can be made.

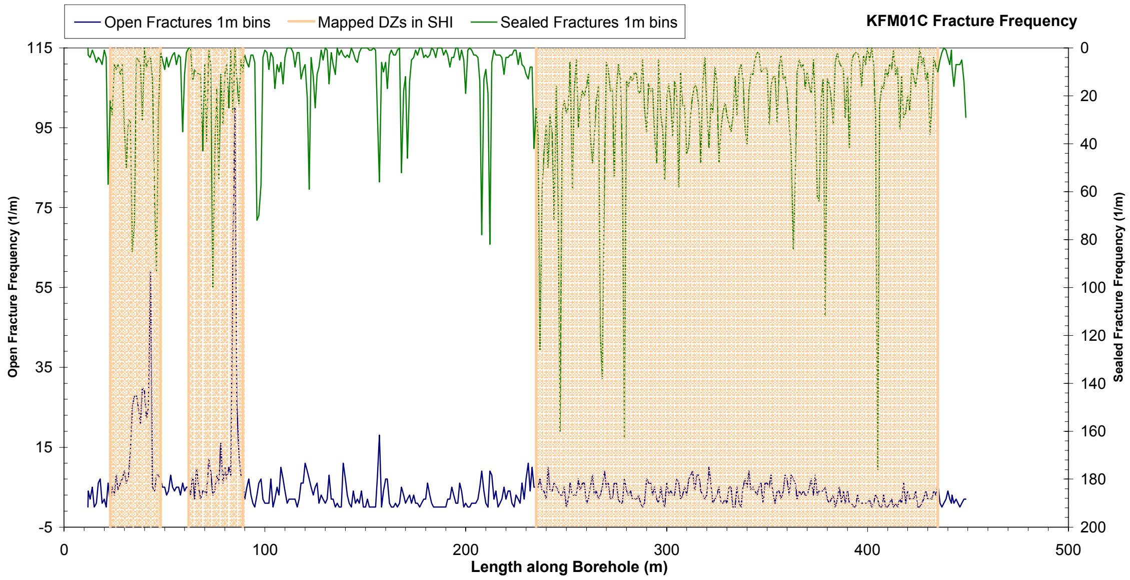
SKB, BOREMAP images (.BIP) and data (.BDT) files, KFM01D, KFM07C, KFM08C and KFM10A, 2006e. SKB data delivery SICADA 06_246, requested by A. Fox, and fulfilled by Veronika Linde on 2006-10-13.

Appendix A

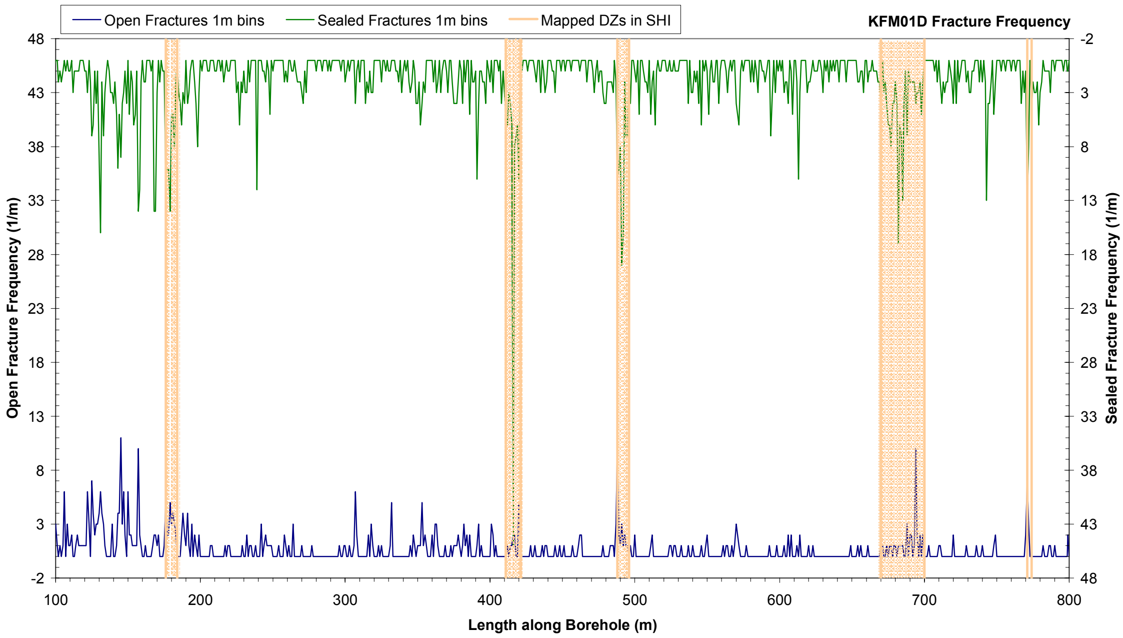
Fracture frequency in cored boreholes

The pink areas represent existing deformation zones (DZs) mapped during the single-hole interpretation process. Note that both Y-axes are labeled as fracture frequency; the left Y axis represents open fracture frequency, while the right Y axis represents sealed fracture frequency. Fracture frequencies on the Y axis begin at negative values (i.e. –2, –5) so that the data series are not drawn directly on the X-axis; this is solely for usability. Sealed fracture intensity is plotted on a reversed axis (intensity increases as Y decreases); again, this was done for usability to make correlating intensity peaks easier.

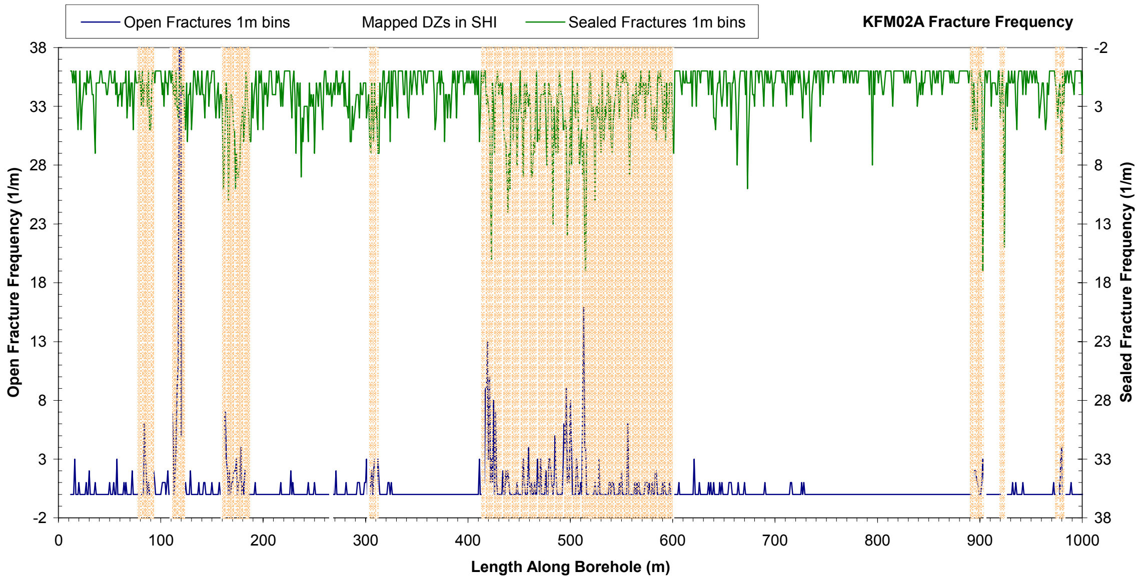




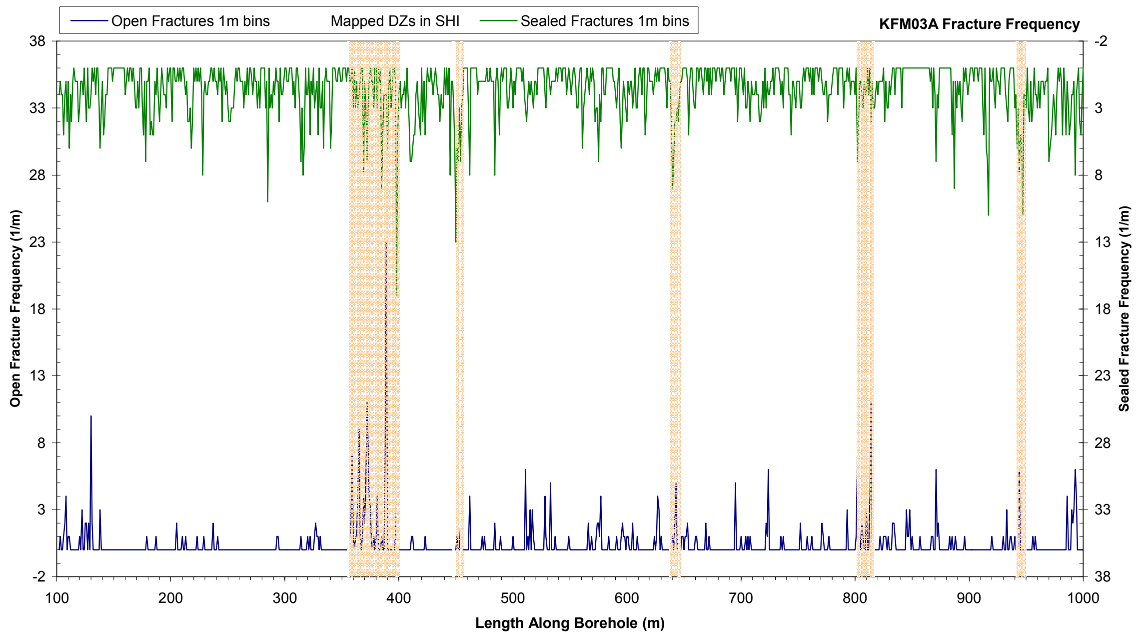
Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM01C Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length along Borehole (m)
115
95
75
55
35
15
-5
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500



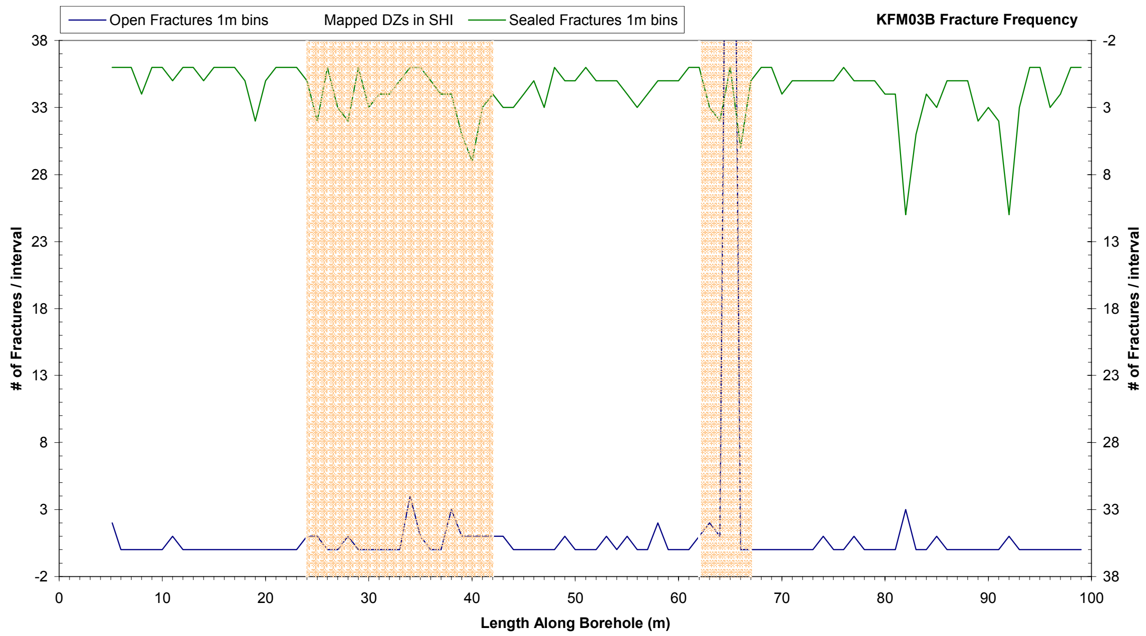
Open Fractures 1m bins
Sealed Fractures 1m bins
Mapped DZs in SHI
KFM01D Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length along Borehole (m)
48
43
38
33
28
23
18
13
8
3
-2
-2
3
8
13
18
23
28
33
38
43
48
100
200
300
400
500
600
700
800

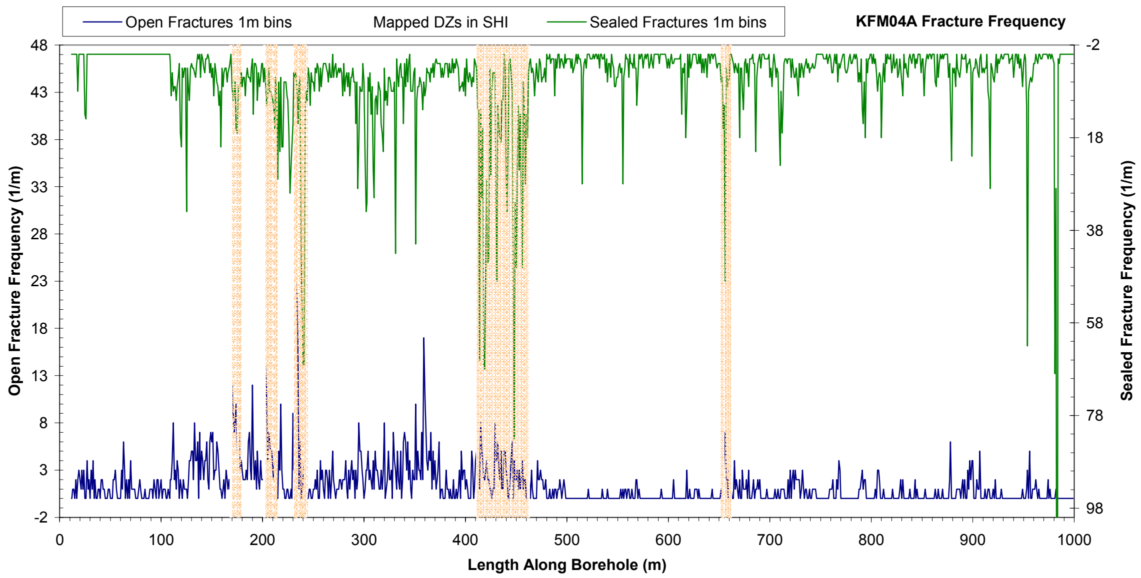


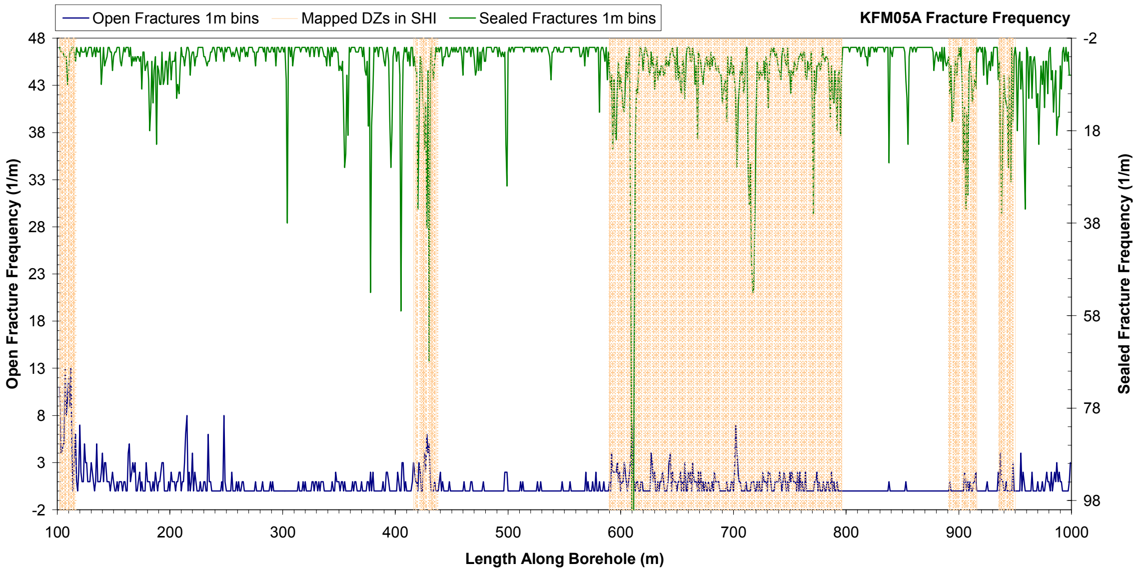
Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM02A Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length Along Borehole (m)

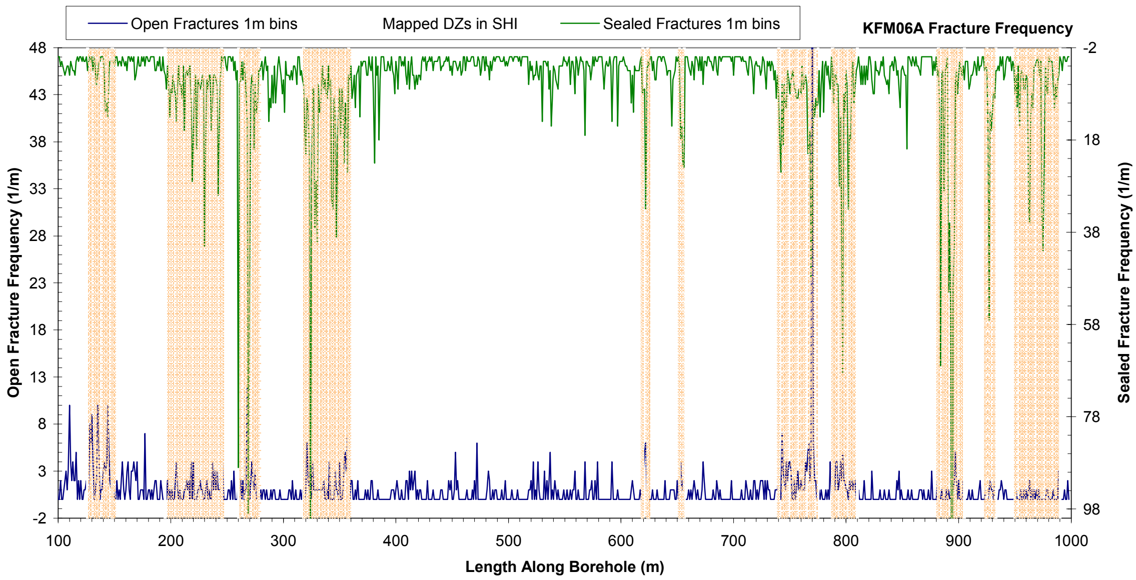


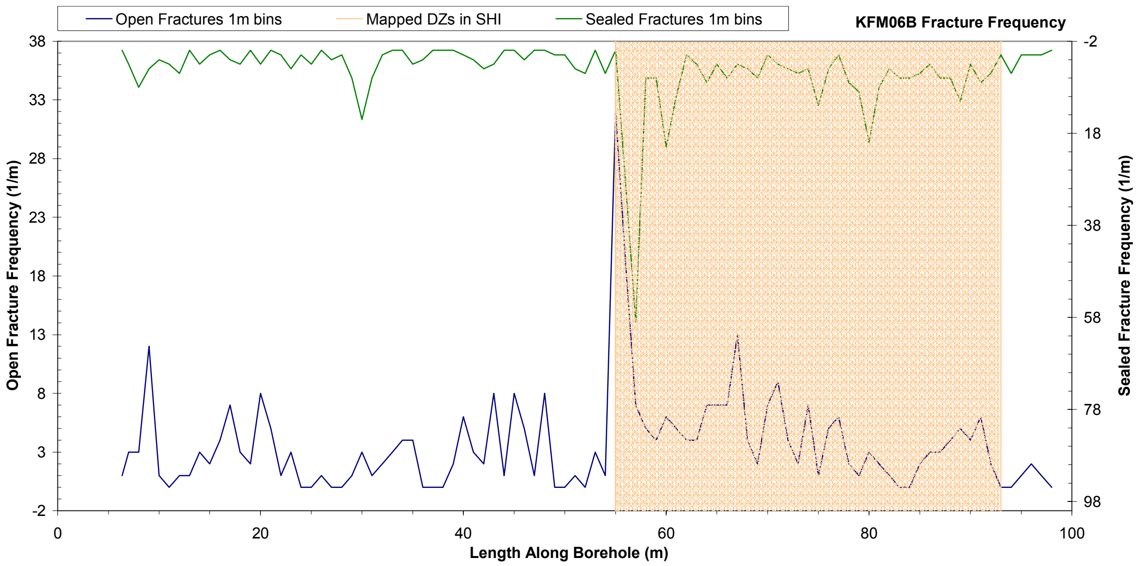
Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM03A Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length Along Borehole (m)


Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM03B Fracture Frequency
# of Fractures / interval
Length Along Borehole (m)

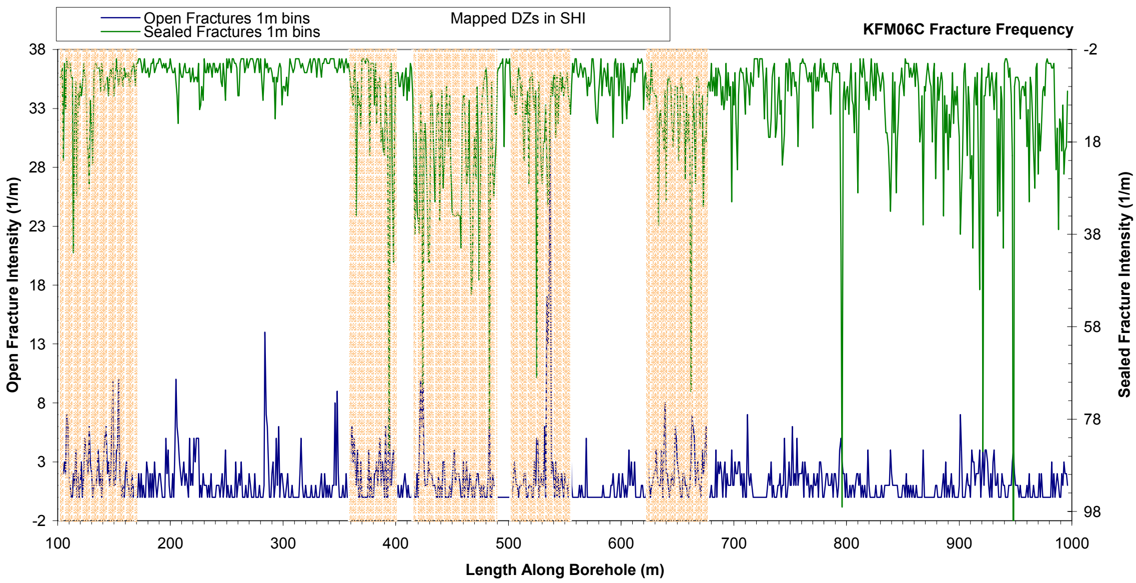

Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM04A Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length Along Borehole (m)


Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM05A Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length Along Borehole (m)
48
43
38
33
28
23
18
13
8
3
-2
-2
18
38
58
78
98
100
200
300
400
500
600
700
800
900
1000

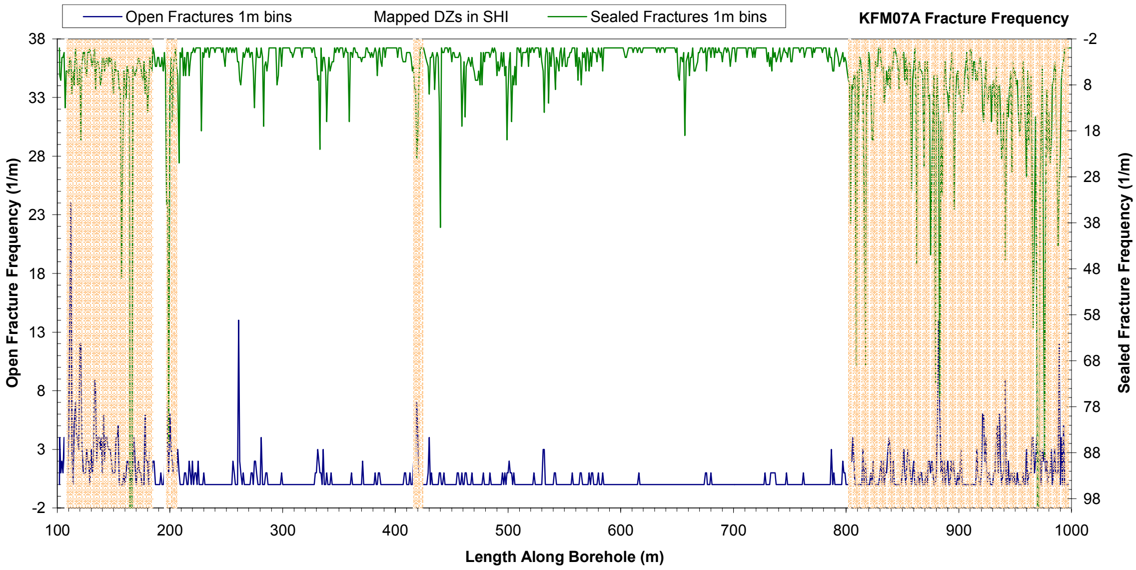

Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM06A Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length Along Borehole (m)
48
43
38
33
28
23
18
13
8
3
-2
-2
18
38
58
78
98
100
200
300
400
500
600
700
800
900
1000



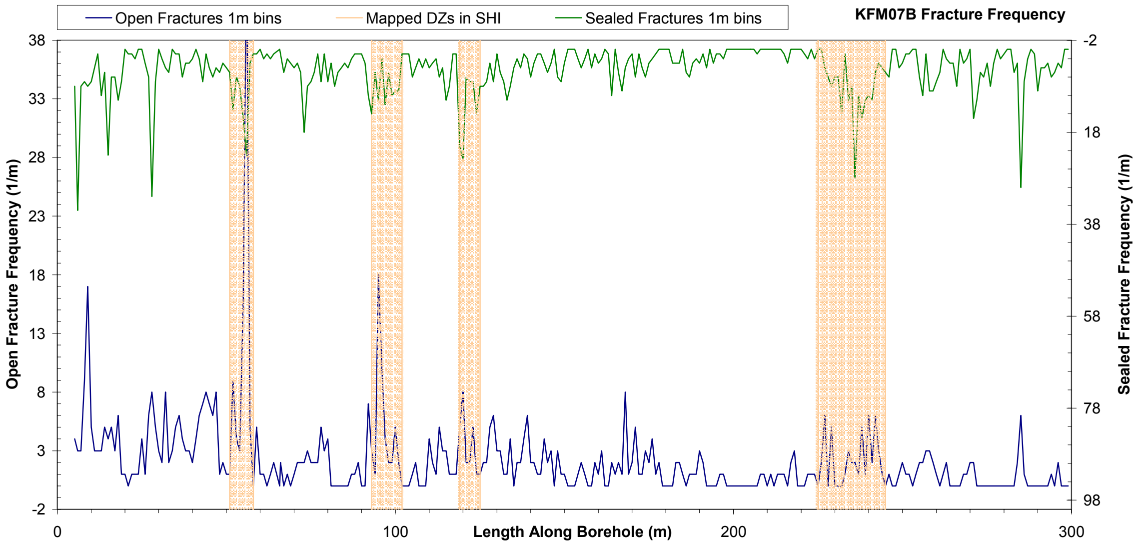
Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM06B Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length Along Borehole (m)



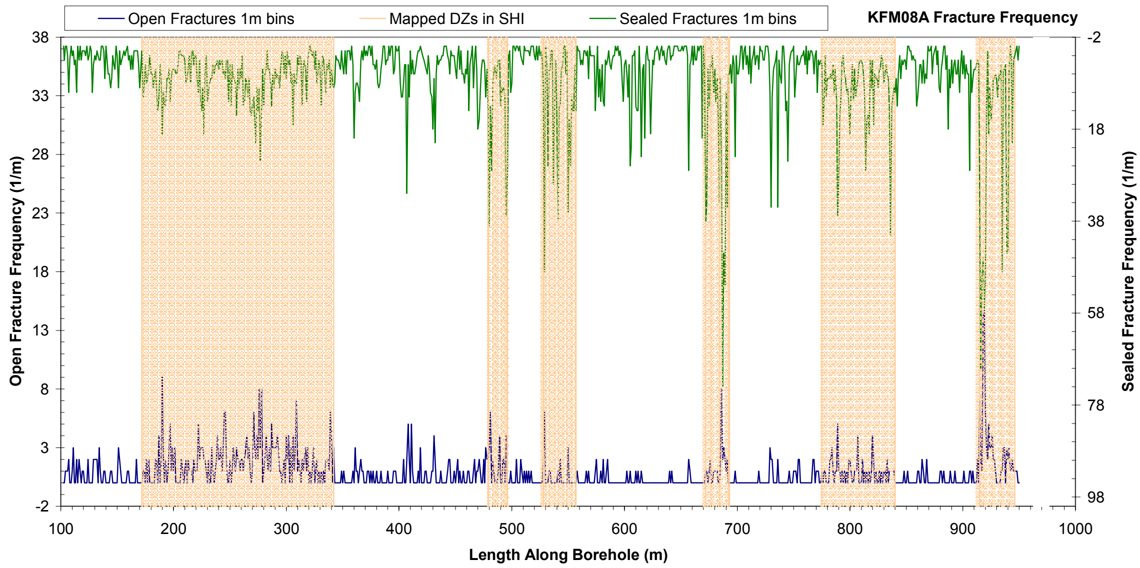
Open Fractures 1m bins
Sealed Fractures 1m bins
Mapped DZs in SHI
KFM06C Fracture Frequency
Open Fracture Intensity (1/m)
Sealed Fracture Intensity (1/m)
Length Along Borehole (m)

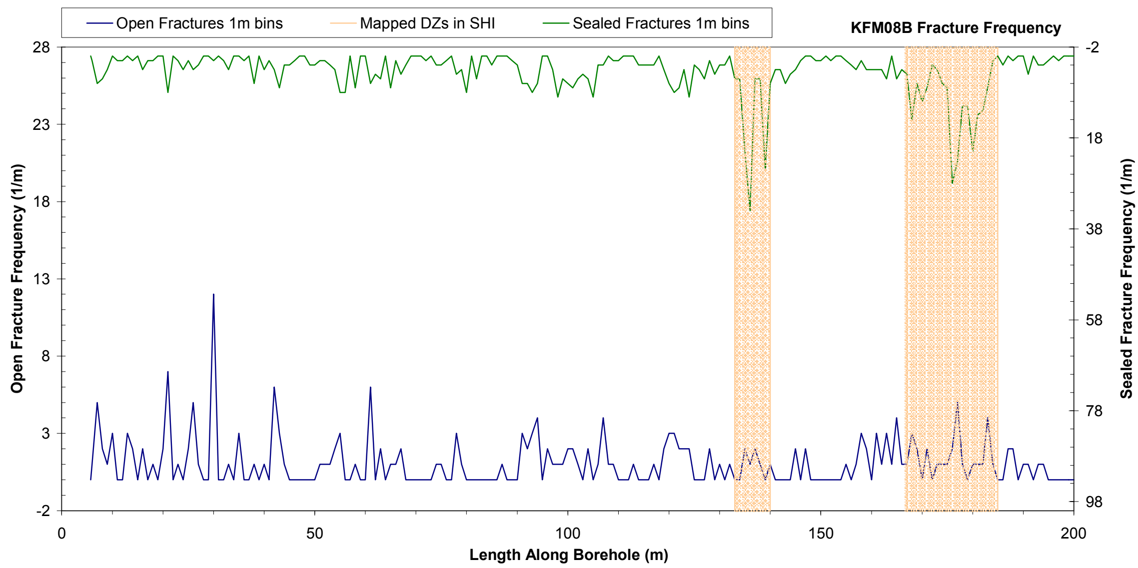


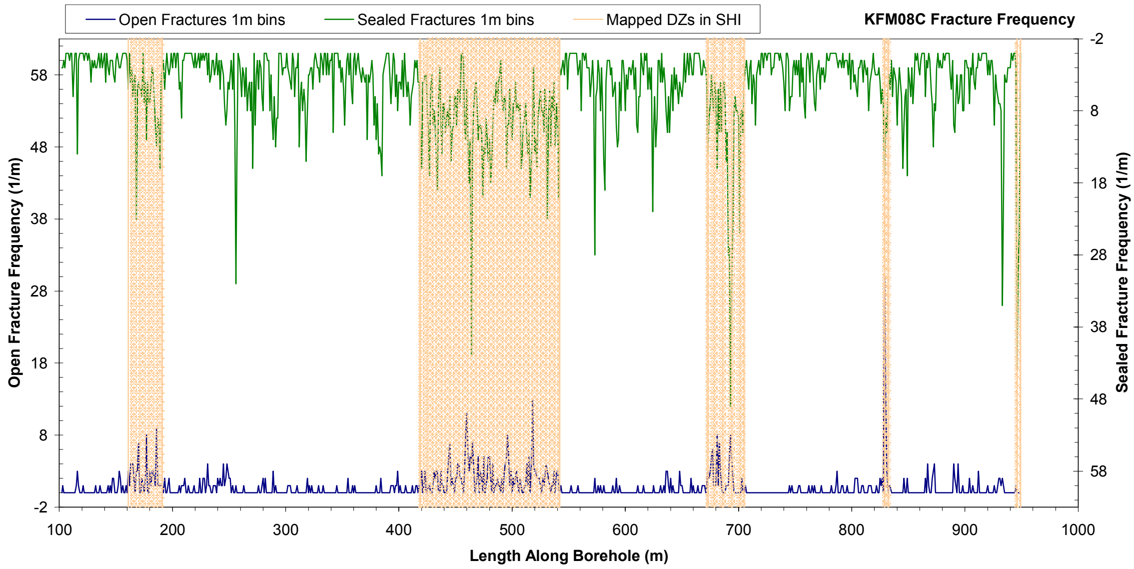
Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM07A Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length Along Borehole (m)



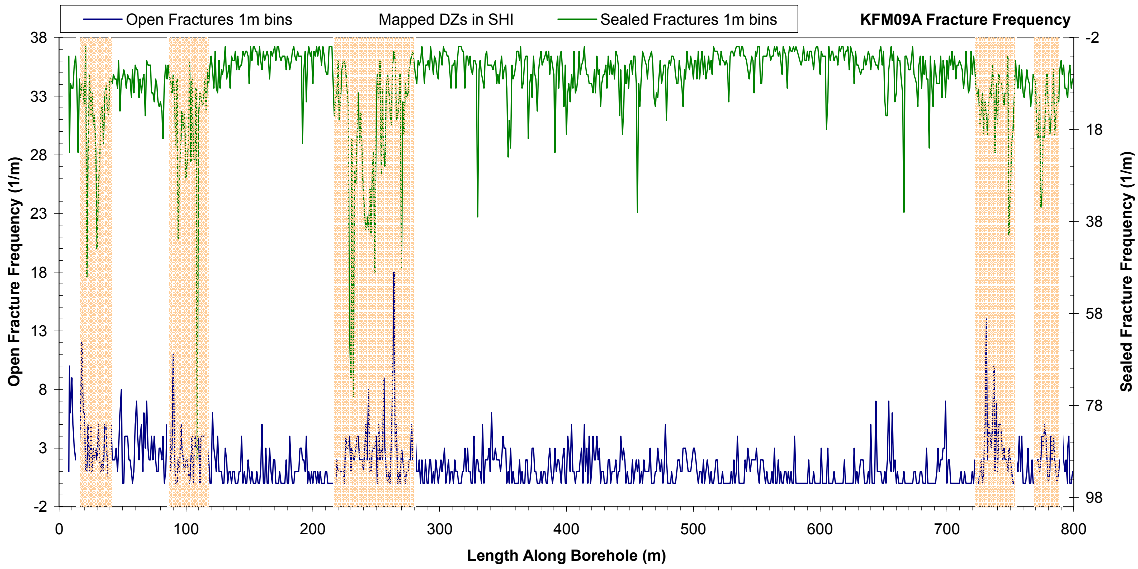
Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM07B Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length Along Borehole (m)


Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM08A Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length Along Borehole (m)

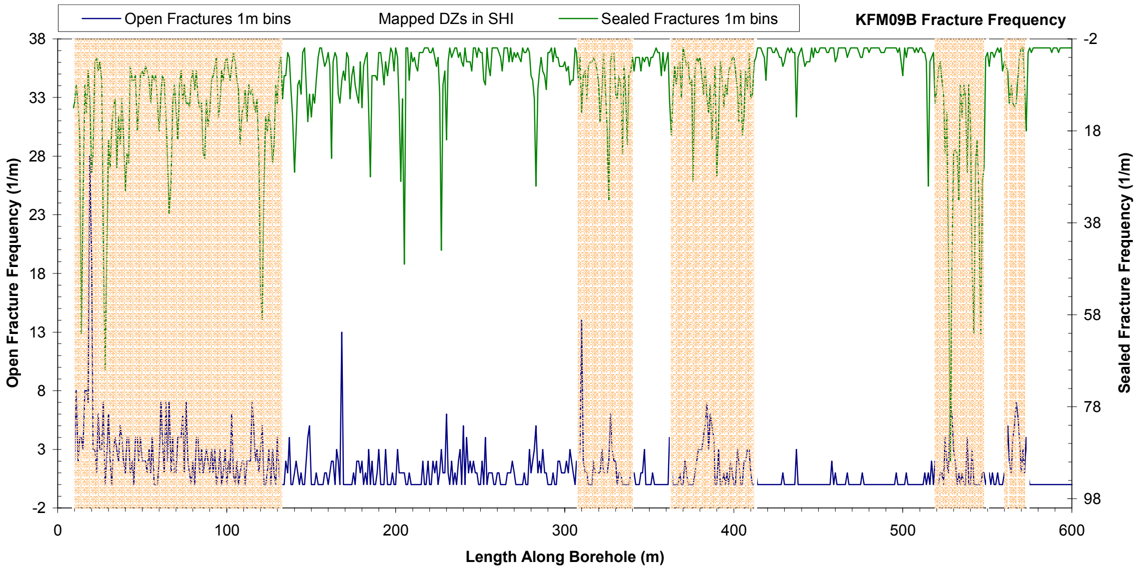

Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM08B Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length Along Borehole (m)

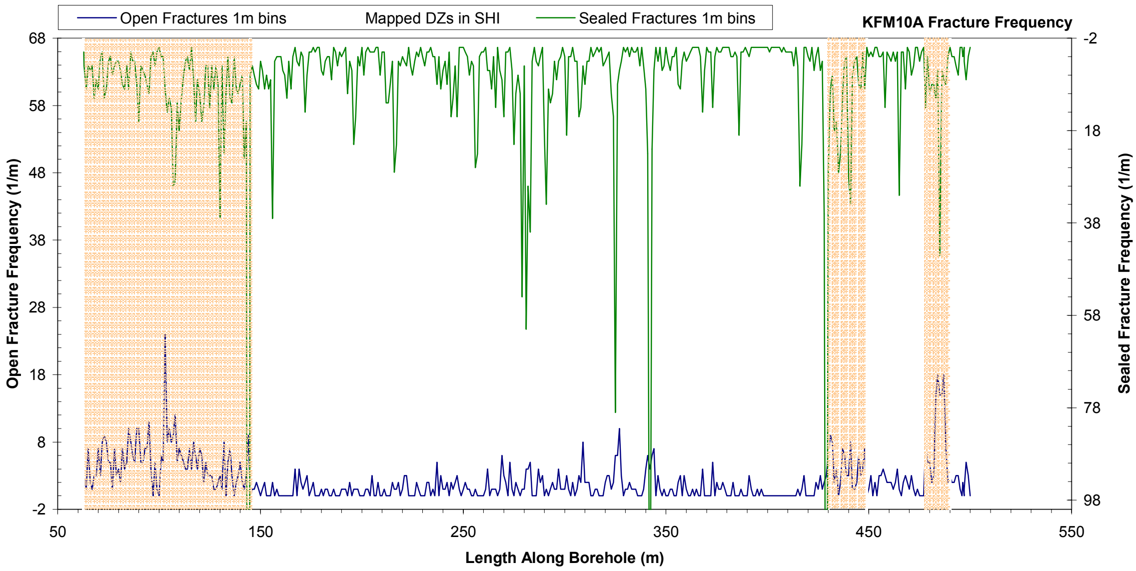


Open Fractures 1m bins
Sealed Fractures 1m bins
Mapped DZs in SHI
KFM08C Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length Along Borehole (m)



Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM09A Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length Along Borehole (m)


Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM09B Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length Along Borehole (m)


Open Fractures 1m bins
Mapped DZs in SHI
Sealed Fractures 1m bins
KFM10A Fracture Frequency
Open Fracture Frequency (1/m)
Sealed Fracture Frequency (1/m)
Length Along Borehole (m)