Rock Stress Orientation from Borehole Breakouts and its Correlation to Drill Parameters and Geology

Results from Boreholes KFM01A and KFM05A of the Forsmark Site Investigation, Sweden

Kenneth Ozaveshe Lawani

Luleå University of Technology

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Environmental Engineering
Department of Civil and Environmental Engineering
Division of Rock Mechanics
Summary

Knowledge of stress orientation is crucial for the understanding of many processes in the Earth’s crust such as tectonic development, earthquake occurrence, and fluid transport along faults. In the Forsmark site investigation; this knowledge plays an important role for engineering decisions with respect to borehole stability and the siting of the future repository for nuclear waste. Breakouts are zones of failure of the borehole wall in response to high compressive tangential stresses. The failures elongate the borehole cross-section from the original circular shape and are observed by geometrical logging tools, for example borehole televiewer (BHTV). Borehole breakouts are reliable indicators of the orientation of the maximum horizontal stress [e.g. Bell and Gough, 1979; Zoback et al., 1985].

The borehole breakout method is a stress method that provides continuous information on stress in intervals where borehole breakouts occur, which makes this method unique in comparison to other existing methods. In other words, this method provides information on the continuation of the stress field along a borehole.

The orientation of borehole breakouts can be measured using mechanical (three-, four- and six-arm caliper), acoustic (BHTV) or electrical resistivity (e.g. Formation MicroScanner (FMS) and Formation MicroImager (FMI)). Optical logging tools such as BIPS and borehole cameras can be used to view borehole breakouts. While BHTV and FMS/FMI tools provide excellent data for breakout analysis, borehole cameras, BIPS, and caliper tools are known to have poorer quality. At the Forsmark Site Investigation, the borehole geometries have been logged using BHTV and BIPS.

This work presents stress orientation data derived from a set of BHTV logs for the core-drilled, approximately 1 km deep, boreholes KFM01A and KFM05A. The two boreholes were drilled by the Swedish Nuclear Fuel and Waste Management Co. (SKB) as part of their site investigation program for storage of nuclear waste in hard rock in Forsmark, Southeast Sweden. The study has the following objectives: (1) determine the downhole orientation of horizontal stresses; (2) correlate borehole breakouts with Measurement While Drilling (MWD) parameters; (3) study the influence of lithology and structures on rock stress orientation; and (4) identify the zones of rock continuum.

The analysis is based on the identification of compressive failures of the borehole wall with the aid of acoustic borehole imaging logs (BHTV). This method for the determination of the minimum stress orientation is found to be highly reliable and capable of delivering detailed and accurate results.

Two different types of breakouts were recognized from the amplitude log with both shallow and deep failure depths. The most dominant occurrence is of the shallow failure type which is observed in both boreholes KFM01A and KFM05A. This study cannot categorically state the full characterization of identified breakouts but previous studies have inferred that they could originate as a result of the differential rock strength, the depth of the borehole and the state of stress [Plumb, 1989].

In borehole KFM01A, 33 borehole breakouts with a combined length of 253 m have been observed from 111 to 1001 meters borehole length (mbl). They suggest a mean orientation of the maximum horizontal stress of about $141\pm8^\circ$N. In borehole
KFM05A, 14 borehole breakouts have been observed between 188 and 996 mbl. They have a combined length of 32 m and a mean maximum horizontal stress orientation of about 159±33°N. According to the World Stress Map quality ranking scheme, boreholes KFM01A and KFM05A are of B- and D quality [Zoback, 1992].

MWD parameters that were used for this analysis were the rotation pressure vs. depth, water pressure vs. depth and the feed speed vs. depth. It was observed that MWD parameters are sensitive to fractures and any kind of opening in the rock as they reveal changes in rock’s mechanical and physical properties of the borehole wall. The variations in the strength of the rock and fracture occurrence in the borehole show changes in the water pressure and also rotation pressure values. Borehole breakouts are associated with changes in the rock quality or rock strength, fractures, mechanical properties and change in lithology. Sections marked as regions without breakouts gradually show minimal changes in MWD parameters and in the rock’s mechanical and physical properties within the depth interval as compared to sections with borehole breakouts that show significant variations in their parameters. Therefore, MWD parameters and borehole breakouts are dependent on the mechanical properties of the rock mass, lithology and the physical properties as well. MWD systems are not absolute rock recognition systems; however, with proper interpretation, changes in rock formations and properties can be inferred.

The observed breakouts in both boreholes KFM01A and KFM05A start within the first 100 m of the core drilled part and this has a significant implication that the horizontal stresses are even high at shallow depth intervals. The fact that the orientation has been very much uniform in borehole KFM01A predicts that the rock domain here have not been influenced much by the lithology and structures which are prominent in the borehole. For borehole KFM05A, the influence of lithology and structures in the stress orientation was observed at depth intervals between 350 – 450 m, 600 – 750 m and 900 – 1000 m. The prominent fractures at these depth intervals result from the gradual changes from one rock units to another and deformation zones that have been detected. It validates that the stress field is not continuous but with influence of previously existing structures on the prevailing stress field in the rock mass.

Borehole KFM01A shows consistency in the minimum stress orientation values along the entire borehole length and this signifies zones of rock continuum without much variance in the rock’s properties; lithology and structures. Borehole KFM05A shows inconsistency in the horizontal stress orientation and intervals with stress re-orientation suggests that there are zones of rock discontinuum which infers that the lithology and structures have a role to play in the changes in stress orientation.
Acknowledgment

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Kenneth Ozaveshe Lawani
Luleå, October 2007.
**List of Symbols and Abbreviations**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$S_{rr}$</td>
<td>Effective radial stress</td>
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<tr>
<td>$S_{zz}$</td>
<td>Effective axial stress</td>
</tr>
<tr>
<td>$S_{θθ}$</td>
<td>Effective circumferential stress</td>
</tr>
<tr>
<td>$S_{rθ}$</td>
<td>Tangential shear stress</td>
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<tr>
<td>$S_{h\min}$</td>
<td>Principal minimum horizontal stress</td>
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<tr>
<td>$S_{h\max}$</td>
<td>Principal maximum horizontal stress</td>
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<tr>
<td>s.d/stdev</td>
<td>Standard deviation</td>
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<tr>
<td>MWD</td>
<td>Measurement While Drilling</td>
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<tr>
<td>FMS</td>
<td>Formation MicroScanner</td>
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<tr>
<td>BIPS</td>
<td>Borehole Image Processing Systems</td>
</tr>
<tr>
<td>BHTV</td>
<td>Borehole Televiewer</td>
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<tr>
<td>CCTV</td>
<td>Computer Controlled Television</td>
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<td>CCD</td>
<td>Computer Controlled Drilling</td>
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<td>mbl</td>
<td>meter borehole length</td>
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<tr>
<td>RU</td>
<td>Rock Unit</td>
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<td>MO</td>
<td>Mean Orientation</td>
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<td>Dxt</td>
<td>Distance</td>
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<td>M</td>
<td>Mean</td>
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<tr>
<td>BOL</td>
<td>Breakout Length</td>
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<tr>
<td>HF</td>
<td>Hydraulic Fracturing</td>
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<tr>
<td>HTPF</td>
<td>Hydraulic test on pre-existing fractures</td>
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1. Introduction

Understanding of the state of stress in the Earth crust is important for different fields of geology and engineering; for example plate tectonics, oil production, seismic hazards, and mining. Tectonic stresses from plate tectonics have a great influence on the global stress field. For example, ridge push from sea floor spreading in the Atlantic is known to control the stress field in Eastern USA and Canada, and in Western Europe [e.g. Zoback 1992]. On the local scale, they may have great influence on stability of boreholes and extraction of hydrocarbons, e.g. for reservoir engineering [e.g. Heffer and Kousabelotis 1996; Heffer et al., 1997] as well as for stability of underground constructions in crystalline rock [e.g. Amadei and Stephansson, 1997].

The phenomenon of borehole breakouts is a reliable indicator of the orientation of the maximum horizontal stress [e.g. Bell and Gough, 1979; Zoback et al., 1985]. Breakouts are intervals where the wall of the borehole has caved so as to produce arcuate extensions on opposite sides.

The borehole breakout method is the only stress method that provides continuous information on stress in intervals where borehole breakouts occur, which makes this method unique in comparison to other existing methods that are measuring the stress in individual points. Furthermore, a large number of observations allow statistical determination of stress orientation and determination of its scatter about the mean stress orientation [Barton et al., 1988; Shamir et al.; 1988]. In other words, this method provides information on the continuation of the stress field.

This work is a detailed study of the occurrence of borehole breakouts in two approximately 1 km deep core-drilled boreholes (KFM01A and KFM05A) at the Forsmark site investigation of the Swedish Nuclear Fuel and Waste Management Co. (SKB). SKB have employed two geophysical logging tools for mapping of the borehole wall: the Borehole Televiewer (BHTV) and the Borehole Image Processing Systems (BIPS) tools. The BHTV gives detailed information about geometry of the borehole wall while the BIPS provides a digitized optical image of the borehole wall. The analyzing programs used are WellCAD version 4.0 to analyze BHTV data and BIPS Image Viewer 3.2 to analyse the BIPS data.

Preliminary investigations on the occurrence of borehole breakouts previously have been carried out in two boreholes, KFM01A and KFM01B, at this site [Ask and Ask, submitted; Ask et al., 2006]. In those studies, the occurrence with depth of borehole breakouts were carefully mapped, but the analyzing program used (WellCAD Reader version 4.0) did not allow detailed mapping of the orientation of borehole breakouts. In this study, I have reanalyzed BHTV data from borehole KFM01A and analyzed data from the additional borehole KFM05A.

The primary objectives of this study are to:

1. determine the downhole orientation of horizontal stresses;
2. correlate relationships between borehole breakouts and Measurement While Drilling (MWD) parameters if any;
3. study of the influence of lithology and structures on rock stress orientation; and
4. identify zones of rock continuum.
2. The Study Area: Forsmark Site Investigation Area

Figure 2.1 shows the location of Forsmark in the South of Sweden with the white arrow from the World Stress Map Project for Scandinavia while Figure 2.2 shows the site investigation area in Forsmark which is situated southeast of the Forsmark Nuclear Power Plant. The candidate area where the final repository can be built is an area of approximately ten square kilometres. SKB is owned by the four Swedish power companies and is tasked with managing and disposing of radioactive waste from the Swedish nuclear power plants in a manner that complies with extremely stringent standards.

Figure 2.1 Stress data from the World Stress Map Project for Scandinavia including topography, Reinecker et al., 2005, with the Forsmark Site Investigation area shown with the white arrow.
Figure 2.2 The Forsmark site investigation area. The red line shows the candidate area within which the Swedish Nuclear Waste Co. (SKB) focuses most of their investigations. Boreholes KFM01A and KFM05A have been included in this study and they were drilled at drill sites DS1 and DS5 respectively. The two boreholes are fairly closely located at the surface and they are located within 500 m from each other [from Claesson et al., 2004a].

In this study, logging and drilling data from boreholes KFM01A and KFM05A have been analyzed. Both boreholes are of telescope type, i.e. the upper 100 m are percussion drilled with a diameter of about 250 mm and then cased, whereas the remaining part of the borehole is core-drilled with a diameter of 77 mm to the full drilling depth (about 1 km). The spatial orientation varies for the two boreholes. In borehole KFM01A, the orientation of the borehole with respect to North (i.e. the borehole azimuth) varies from 318 to 307°N while the borehole inclination from the horizontal (borehole dip) ranges between 85 and 75°, [Claesson and Nilsson, 2004a]. Borehole KFM05A has an azimuth in the range of 81 - 100°N and a dip of about 60 - 52° respectively, [Claesson and Nilsson, 2004b].

2.1 Geology
The rocks in the Forsmark site investigation area can be divided into three main age groups representing different major geological events. The oldest rocks are volcanic rocks and represent an era of volcanic activity, this took place 1.885 Ga. The next big event is when a series of rocks of primarily granitoid composition, including the candidate area’s metagranite, penetrated up into the Earth’s crust between 1.865 and 1.885 Ga. A new magma period followed from 1.845 to 1.865 Ga when small
intrusions, mainly dykes, were formed [SKB Report, 2004 and 2005]. This concluded the “hot” period in the history of the Forsmark bedrock.

Geological mapping of the crystalline bedrock forms one of the major surface activities performed within the initial site investigation program at the Forsmark site. The geochronological work within the context of the bedrock-mapping project suggests the four main groups [Stephens et al.; 2003]:

- Group A, consists of felsic to intermediate metavolcanic rocks
- Group B, meta-intrusive rocks
- Group C, meta-intrusive rocks
- Group D, meta-intrusive rocks

The intrusive rocks that belong to Group B, C and D, form two separate calc-alkaline suites of igneous rocks respectively.

From a structural geology perspective, the investigation area can be divided into contrasting structural domains [Stephens et al., 2003]. SL-tectonites and an inferred higher degree of ductile deformation characterize the areas, for example, to the southwest and northeast of the candidate area. By contrast, LS-tectonites, folding and an inferred lower degree of ductile deformation characterize, for example, the candidate area.

The four bedrock groups have been subjected to different phases of structural deformation, [Page et al., 2004]. The deformation in the bedrock that accompanied the intrusion of the Group D rocks was discrete in character and was restricted to high-strain zones, with combined ductile and brittle or solely brittle character. The most prominent regional deformation zones in the area strike in a north-west direction and include the Forsmark, Eckarfjärden and Singö deformation zones. These zones divide the bedrock into different structural blocks.

The most important structures which run almost perpendicular with the borehole axis in both boreholes KFM01A and KFM05A have been observed to be mostly fractures. A large amount of these steeply dipping fractures were intersected by these boreholes (see Figures 2.3). The fractures in borehole KFM01A are gently dipping. Those considered to be steeply dipping fractures also exist but they are often sealed especially those that strike NE – SE. Fractures shown in borehole KFM05A dip about 30° from the horizontal because borehole KFM05A has an inclination of about 60° from the horizontal.
Figure 2.3 Dynamic colour presentation of WellCAD images of borehole section from 125.60 to 128.80 mbl in KFM01A showing fractures that run across the borehole axis (at 125.40 and 128.80 m) above; while below is the borehole section from 112.45 to 113.70 mbl in KFM05A showing fractures that run across the borehole axis (at 112.50 m, 112.85 m, 113.05 m, and 113.20 m).

Figure 5.2 shows the changes in lithology and structures with depth in borehole KFM01A. It gives a clear picture of the different variations in the rock units and the
possible deformation zones which were observed. See Appendix A for detailed explanations of rock units and potential deformation zones. Most rocks exhibit a medium to severe ductile foliation, striking roughly between NW and NNE. However, a more random orientation due to small scale folding may have occurred adjacent to lithological discontinuities such as veins or minor dykes. With the exception for a highly fractured zone in the depth interval 656–674 mbl; there is a conspicuous concentration of open, gently dipping fractures in the upper 300 mbl in borehole KFM01A. Lithological contacts provide mechanical discontinuities and it is hence reasonable to expect that a high contrast in competence, such as between granitic material and amphibolites, may focus fracture formation.

The far most abundant rock in borehole KFM01A is a medium-grained, reddish-grey to grey metagranodiorite-granite. Other rock units, including finer grained metagranitoids, pegmatitic granites, amphibolites and minor bands, dykes or veins are ubiquitous though volumetrically subordinate.

Figure 5.3 summarizes the downhole variation in lithology and deformation zones in borehole KFM05A. Appendix C gives a detailed explanation of the rock units and deformation zones. The major lithology is metagranite and it grades to granodiorite. Both facies are separated by a sharp intrusive contact at a borehole depth of about 285.8 mbl. Other rock units include metagranitoids, amphibolites, and minor pegmatite dykes. Three fracture sets have been observed in the borehole: They strike NE-SW, dip steeply, and have an increased frequency of occurrence below 580 mbl. Previous studies have shown that these fractures are mostly open and are associated with three minor fracture zones [Claesson and Nilsson, 2004a].

2.2 State of stress

Previous stress investigations that have been carried out in the Forsmark site include indirect stress estimates, geological and tectonic description of the site and regional stress data from nearby locations [see updated reference lists in Sjöberg et al., 2005 and Ask et al., 2006]. The different types of in situ stress measurements that have been conducted in the Forsmark site investigation include overcoring, hydraulic fracturing, hydraulic tests on pre-existing fractures, studies of core discing, and borehole breakout analyses [e.g. Ask et al., 2006]. With exception for the borehole breakout method, these methods provide point-wise estimates of the local stress field, usually, for a small section of the borehole. In contrast, borehole breakout may occur over large sections of the borehole, and within these sections, the borehole breakout method provides continuous information on the orientation of the stress field. Both local stress data from the Forsmark area and regional stress data from Scandinavia propose that the orientation of the major horizontal stress generally is NW-SE, but significant local variations also exist [Reinecker et al., 2004; Sjöberg et al., 2005].

The World Stress Map (WSM) is the global repository for contemporary tectonic stress data from the Earth’s crust [e.g. Reinecker et al., 2004]. The WSM uses different types of stress indicators and they are grouped into four categories [e.g. Zoback, 1992; Reinecker et al., 2004]:

1. Earthquake focal mechanisms
2. Well bore breakouts and drilling-induced fractures
3. In-situ stress measurements (overcoring, hydraulic fracturing, borehole slotter)
4. Young geologic data (from fault-slip analysis and volcanic vent alignments)
The quality of data in the World Stress Map has been ranked according to different ranking schemes [e.g. Zoback, 1992; Sperner, 2003]. For borehole breakouts, the ranking quality depends on the length and standard deviation of obtained borehole breakout intervals.

### 2.3 Measurement While Drilling (MWD)

The drill rig recording of drill parameters is another method that provides physical measurements of the penetrated rock mass, which often is referred to as measurement while drilling (MWD), *Stefan* [1997]. Parameters that are normally recorded are: borehole length, rotation pressure, feed force of the drill bit, feed force of cylinder, feed pressure of cylinder, water flow and water pressure, drill bit position, rotation speed, feed speed, feed position, rod weight and rod pressure, [*Claesson and Nilsson*, 2004a & 2004b].

Historically, the feed speed has been one important parameter to determine the mechanical resistance of the rock mass. This property varies widely between different rock types and also for the same rock type, *Stefan* [1997]. For crystalline rocks, the feed speed also varies as a result of various kinds of weaknesses in the rock mass such as fracture zones, zones of severe weathering, fault intersections, joints etc, *Stefan* [1997].

MWD has some advantages over the conventional geophysical equipment, such as:

- Immediate indication of formation contacts during drilling, with e.g. the feed speed changing at the moment the drill bit penetrates a certain formation.
- MWD does not require any standby time, as other methods do, and it does not normally interfere with drilling.

Major historical disadvantages with MWD in crystalline rock logging have been the lack of reliable equipment and the fact that the recorded data could be difficult to interpret, *Stefan* [1997]. *Schunnesson* [1990] has also interpreted drilling data from percussive production drill rigs, with multivariate techniques.
3. Borehole breakout theory

Bell and Gough [1979] were the first to propose a theory for borehole breakout formation and they predicted that breakouts are spalled areas on either side of the borehole which are centred in the direction of minimum horizontal principal stress (where the compressive stress concentration is the largest). They presented the analytical method commonly used for predicting the theory of borehole breakouts. It uses the Kirsch solution to calculate the stresses around a circular hole in a linearly elastic and isotropic continuum subjected to a three-dimensional stress field. Kirsch [1898] developed a set of equations for calculating the stresses acting in a thick, homogeneous, isotropic elastic plate, containing a cylindrical hole, subject to effective minimum and maximum far field principal stresses. Assuming that the borehole is vertical, the principal stresses at the borehole wall are the effective radial stress ($S_{rr}$), the effective axial stress ($S_{zz}$) and the effective circumferential stress ($S_{\theta\theta}$). The effective radial stress acts normal to the borehole wall. The effective axial stress acts parallel to the borehole axis. The circumferential stress acts orthogonal to $S_{rr}$ and $S_{zz}$ (in the horizontal direction in the plane tangential to the borehole wall).

Zoback et al., [1985] expanded the theory for borehole breakout formation in two aspects: First, they applied the stresses to the Mohr-Coulomb failure criterion with cohesion and angle of internal friction; second, they included the influence of mud pressure in the borehole and the pore pressure in the surrounding formation. The equations for effective principal stresses and shear stresses that are acting perpendicular to the borehole axis at the borehole wall according to Zoback et al., [1985] are:

\[
S_{\theta\theta} = \frac{1}{2} \left( S_{H_{\max}} + S_{h_{\min}} \right) \left( \frac{R^2}{r^2} + 1 \right) - \frac{1}{2} \left( S_{H_{\max}} - S_{h_{\min}} \right) \left( 1 + \frac{3R^4}{r^4} \right) \cos 2\theta - \frac{\Delta P R^2}{r^2} \tag{1}
\]

\[
S_{rr} = \frac{1}{2} \left( S_{H_{\max}} + S_{h_{\min}} \right) \left( 1 - \frac{R^2}{r^2} \right) + \frac{1}{2} \left( S_{H_{\max}} - S_{h_{\min}} \right) \left( 1 - 4 \frac{R^2}{r^2} + 3 \frac{R^4}{r^4} \right) \cos 2\theta - \frac{\Delta P R^2}{r^2} \tag{2}
\]

\[
S_{\theta\theta} = -\frac{1}{2} \left( S_{H_{\max}} + S_{h_{\min}} \right) \left( 1 + 2 \frac{R^2}{r^2} - 3 \frac{R^4}{r^4} \right) \sin 2\theta \tag{3}
\]

where $S_{\theta\theta}$ is the shear stress, $R$ is the radius of the hole, $r$ is the distance from the centre of the hole, $\theta$ is the azimuth measured from the orientation of $S_{H_{\max}}$, $S_{H_{\max}}$ is the effective maximum horizontal stress, $S_{h_{\min}}$ is the effective minimum horizontal stress, and the differential pressure ($\Delta P$) is the difference between mud pressure ($P_{w}$) in the borehole and $P_{p}$ in the surrounding formation. The stress concentration predicted by these equations is illustrated in Figure 3.1 below.

At the borehole wall where $R=r$, Equations 1 and 2 become:

\[
S_{\theta\theta} = S_{H_{\max}} + S_{h_{\min}} - 2(S_{H_{\max}} - S_{h_{\min}}) \cos 2\theta - \Delta P \tag{4}
\]

\[
S_{rr} = \Delta P \tag{5}
\]

\[
S_{\theta\theta} = 0 \tag{6}
\]
The size of $S_{\theta\theta}$ varies with $\theta$ around the borehole wall. Equations (7) and (8) show the maximum and minimum values of $S_{\theta\theta}$, which are obtained at $\theta = 90^\circ$ and $\theta = 0^\circ$, respectively. Borehole breakouts will form parallel to the orientation $S_{\theta\theta,\min}$ if $S_{\theta\theta}$ becomes greater than the rock strength at $\theta = 90^\circ$.

$$S_{\theta\theta,\theta=90^\circ} = 3S_{H,max} - S_{h,min} - \Delta P$$

$$S_{\theta\theta,\theta=0^\circ} = 3S_{h,min} - S_{H,max} - \Delta P$$

The earlier analyses of borehole breakouts were presented for (near-) vertical boreholes [e.g. Bell and Gough, 1979; Zoback et al., 1985]. Later, the theory was expanded to include inclined boreholes as well [e.g. Pëska and Zoback, 1995; Zoback et al., 2003].

Table 3.1 gives a summary of the criteria for quality ranking of borehole breakouts used by the WSM. The quality ranking scheme includes five quality categories, A-E [Zoback, 1992]. Data of best quality (A-quality) is assumed to record the orientation of $S_{h,max}$ within 10 - 15°. Quality B and C record the stress field within 15 - 20° and 25°, respectively. Quality D data give questionable stress orientations for several reasons; the standard deviation for the orientation of recorded borehole breakouts is rather high, and the number of borehole breakouts is small, or their combined length is short (Table 3.1). Data of the worst quality (E-quality) are useless for stress analysis, but are kept in the database for book-keeping purposes.

The mean stress direction inferred from breakouts in two or more boreholes in close proximity may be given a higher quality than would be strictly indicated by the total breakout length (Table 3.1); the rationale being that multiple consistent orientations in different depths intervals in adjacent wells are a significant observation [Zoback, 1992].
Table 3.1 The world Stress Map quality ranking for borehole breakouts; [Zoback, 1992; Sperner et al., 2003]

<table>
<thead>
<tr>
<th>Borehole Breakout (BO)</th>
<th>Ranking Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 10 distinct breakout zones and combined length ≥ 300 m in a single well with s.d. ≤ 10°; Average of breakouts in two or more wells in close geographic proximity with combined length &gt; 300 m and s.d. ≤ 12°</td>
<td>A - quality Believed to be within ± 10-15º</td>
</tr>
<tr>
<td>≥ 6 distinct breakout zones and combined length &gt; 100 m in a single well with s.d. ≤ 20°</td>
<td>B - quality Believed to be within ± 15-20º</td>
</tr>
<tr>
<td>≥ 4 distinct breakouts and combined length ≥ 30 m with s.d. ≤ 25°</td>
<td>C - quality Believed to be within ± 20-25º</td>
</tr>
<tr>
<td>&lt; 4 consistently oriented breakouts or combined length &lt; 30 m in a single well; Breakouts in a single well with s.d. ≤ 40°</td>
<td>D - quality Questionable tectonic stress orientation, s.d. &gt; 25º</td>
</tr>
<tr>
<td>Wells in which no reliable breakouts were detected</td>
<td>E - quality No reliable stress orientation.</td>
</tr>
<tr>
<td>Extreme scatter of orientations, no significant mean determined (s.d. &gt; 40º)</td>
<td></td>
</tr>
</tbody>
</table>

s.d. = standard deviation

Techniques for identification and interpretation of borehole breakouts have been described in numerous publications [e.g. Plumb and Hickman, 1985; Reinecker et al., 2004] and rely on analysis of the cross-sectional shape of a borehole through the use of a magnetically oriented four arm caliper tool (historically the most commonly used tool) or a BHTV [e.g. Plumb and Hickman, 1985]. While many authors [e.g. Plumb and Hickman, 1985; Reinecker et al., 2004] have published criteria for identifying borehole breakouts from four-arm caliper data (Table 3.2), few, if any criteria have been published for identifying borehole breakouts from BHTV data.

Table 3.2 Borehole breakout criteria according to Plumb and Hickman [1985].

<table>
<thead>
<tr>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) The rotation of the logging tool has to stop completely;</td>
</tr>
<tr>
<td>(b) The difference in the caliper readings in breakouts should exceed 6 mm;</td>
</tr>
<tr>
<td>(c) The smaller caliper reading has to be close to bit size, or, if the smaller caliper reading is greater than bit size; it should exhibit less variation than the larger caliper;</td>
</tr>
<tr>
<td>(d) The length of the breakout has to exceed 300 mm, and</td>
</tr>
<tr>
<td>(e) The direction of elongation must not consistently coincide with the azimuth of the high side of the borehole wall when the borehole deviates from the vertical.</td>
</tr>
</tbody>
</table>

Historically, most borehole breakout analysis for breakout detection often has been made using four-arm caliper data and (modified) criteria of Plumb and Hickman [1985]. Although four-arm caliper data can reveal the orientation of borehole...
breakouts, they provide little information about its detailed shape. In contrast, the BHTV may be viewed as a multiple-arm caliper log with much better resolution than the traditional four-arm caliper tool [e.g. Plumb and Hickman, 1985].

Over the last decade the analysis of borehole breakouts is a technique for estimating in situ stress orientation at all depths and all geological conditions and particularly at great depths where direct in situ stress measurements are difficult. Analysis of borehole breakouts is routinely used in deep continental drilling programs such as the German continental deep drilling project (KTB) in Germany, [Brudy and Zoback, 1997; Lund and Zoback, 1999] the borehole for deep-Earth gas in the Precambrian rocks of Sweden [Stephansson, Savilahti and Bjarnason, 1989] and also in the oil industries.
4. Methods

4.1 Borehole breakout logging tools

The orientation of borehole breakouts can be measured using mechanical (three-, four- and six-arm caliper), acoustic (BHTV) or electrical resistivity (e.g. Formation MicroScanner (FMS) and Formation MicroImager (FMI)). Optical logging tools such as BIPS and other borehole cameras can be used to view borehole breakouts. While BHTV and FMS/FMI tools provide excellent data for breakout analysis, borehole cameras such as BIPS, and caliper tools are known to have poorer quality.

At the Forsmark Site Investigation, the borehole geometries have been logged using BHTV and BIPS. These tools are described in greater detailed below, together with briefer description of other logging tools.

4.1.1 Borehole Televiewer (BHTV)

The BHTV is a wireline logging tool that provides a continuous, oriented, ultrasonic image of a borehole wall (Figure 4.1) [e.g. Zemanek et al., 1970]. It consists of a transducer that is mounted on a motor-driven shaft and aimed at the borehole wall. The transducer rotates rapidly and generates multiple ultrasonic acoustic pulses each second.

![Figure 4.1 The high resolution acoustic televiewer probe RG 25 112 000 HiRAT that was used to log boreholes KFM01A and KFM05A [from http://www.geologging.com].](image)

The borehole geometry is recorded while winching the tool up the hole at a constant speed. Both the travel time and amplitude of the reflected waves that return to the transducer are recorded. A bright trace corresponds to a good reflection and a dark trace indicates a scattered or absorbed signal. Successive traces appear on the ray tube as the tool is pulled up the hole. Table 4.1 gives details about the resolution of data sampling in borehole KFM01A and KFM05A.

Table 4.1 Specification for the high resolution acoustic televiewer probe RG 25 112 000 HiRAT, [from http://www.geologging.com]

<table>
<thead>
<tr>
<th>Probe 25 112 000 HRAT</th>
<th>High resolution acoustic televiewer probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>45 mm</td>
</tr>
<tr>
<td>Length</td>
<td>1.98 m including natural-gamma option</td>
</tr>
<tr>
<td>Weight</td>
<td>10 kg</td>
</tr>
<tr>
<td>Construction</td>
<td>Titanium with electrical isolation of verticality sections</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-20 to 70°C (lower and higher ranges available)</td>
</tr>
<tr>
<td>Mac. Pressure</td>
<td>20 MPa</td>
</tr>
<tr>
<td>Transducer type</td>
<td>Focussed piezoelectric</td>
</tr>
<tr>
<td>Transducer frequency</td>
<td>1.5 MHz</td>
</tr>
<tr>
<td>Transducer rotation rate</td>
<td>5-20 revolutions/second</td>
</tr>
<tr>
<td>Firing rate</td>
<td>90/180/270/360 steps/rev (user selectable)</td>
</tr>
<tr>
<td>Down-hole gain</td>
<td>Variable 0 to 80 dB with automatic gain option</td>
</tr>
<tr>
<td>Orientation transducer</td>
<td>3-axis magnetometer, 3-axis accelerometer for true 3D operation</td>
</tr>
<tr>
<td>Communications</td>
<td>Bi-directional digital. Up-hole transmission rate typically 312.5kbits/sec and selectable according to cable length.</td>
</tr>
</tbody>
</table>
Figure 4.2 shows a typical example of data recorded by the BHTV. Planar features such as faults, fractures and joints produce a sinusoidal signature on the log which allows determination of their strike and dip [e.g. Barton et al., 1991]. Zones of low reflectance (dark bands) on the BHTV log correspond to zones of borehole elongation or borehole breakouts.

![Figure 4.2 Typical examples of standard unwrapped BHTV data for borehole KFM01A at depth interval 125 and 190 mbl.](image)
The BHTV has its own limitations; the pulses are reflected and scattered by the particles in the borehole fluid so that such reflections are not observed at the wall of the borehole. An explanation to this could be as a result of the acoustic contrasts at the wall of the borehole. Fractures, voids, soft materials, as well as borehole breakouts have the tendency to absorb or scatter much of the pulse, thereby producing low amplitude and high travel time reflectance or dark zones in the unwrapped images. Tool centralization in the borehole is a major factor that determines the quality of the result of the BHTV. A deliberation on the varying effects of the decentralization of the logging tool has been considered by different authors [e.g. Lofts and Bourke, 1999; Deltombe and Schepers, 2000]. Lofts and Bourke [1999] provide a solid summary of potential logging artifacts for acoustic and resistivity logging tools, Deltombe and Schepers [2000] discuss processing of BHTV data.

RAMBØLL carried out the BHTV measurements in both boreholes KFM01A and KFM05A using a centralized High Resolution Acoustic Televiewer (HiRAT) from Robertson Geologging Ltd, RG 25 112 000 HiRAT, [Nielsen and Ringaard, 2004]. Table 4.2 shows the HiRAT parameters of interest for borehole breakout analysis; typical examples of these parameters are shown in Figure 4.2. The speed of the logging tools was in general 10 m/min for the used geophysical log runs, except the HiRAT Acoustic tool where the speed was 2 m/min and with a sample interval of 2 mm [Nielsen and Ringaard, 2004].

### Table 4.2 Parameters recorded by the High Resolution Acoustic Televiewer (HiRAT) used in borehole breakout analysis [from Ask and Ask, submitted].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CALIPER 3D</td>
<td>This is calculated using both variables of the acoustic travel time and the velocity in the borehole fluid. The velocity in the fluid is calculated using the fluid temperature and fluid conductivity [Nielsen and Ringaard, 2003; 2004].</td>
</tr>
<tr>
<td>CALIPER MEAN</td>
<td>This is calculated using the mean travel time from the acoustical televiewer, the fluid temperature, fluid velocity and the internal travel time in the acoustical televiewer.</td>
</tr>
<tr>
<td>Travel Time</td>
<td>This is a 360º oriented travel time image represented in grey scale. Travel time units are 0.1μs, and reveals the borehole diameter provided if an estimate of the acoustic velocity in the borehole fluid is available.</td>
</tr>
<tr>
<td>Amplitude</td>
<td>This is a 360º oriented amplitude image in colour scale. Amplitude is dimensionless, reveals the acoustic impedance of the borehole wall that is related to geotechnical rock properties.</td>
</tr>
<tr>
<td>Azimuth</td>
<td>This is the orientation of the tool with respect to magnetic North (0-360ºN). The data has been corrected for magnetic declination.</td>
</tr>
<tr>
<td>Dip</td>
<td>This is the borehole inclination form the horizontal and it varies from 0-90º. The Dip reveals the orientation of the tool within the borehole, which may not follow the orientation of the borehole, because of the smaller probe diameter (45 mm) relative to the borehole diameter (76 mm).</td>
</tr>
</tbody>
</table>

### 4.1.2 Borehole camera

The Borehole Image Processing System (BIPS) is a high resolution, side viewing, colour borehole TV system [from www.raax.com, www.geologging.com]. The BIPS method for borehole logging produces a digital scan of the borehole wall. In principle, a standard computer controlled digital (CCD) video camera is installed in the probe in
front of a conical mirror (see Figure 4.3). An acrylic window covers the mirror part and the borehole image is reflected through the window and displayed on the cone, from where it is recorded. During the measuring operation, pixel circles are grabbed with a resolution of 360 pixels/circle. The system orientates the BIPS images according to two alternative methods, either using a compass (vertical boreholes) or with a compass and a gravity sensor (inclined boreholes). BIPS is mainly used for geological surveying of the borehole wall including determination of fracture distribution and orientation.

![BIPS-system diagram](image)

**Figure 4.3 The BIPS-system illustrating the conical mirror scanning, Gustafsson and Gustafsson [2004].**

The borehole camera is a complete computer controlled television (CCTV) inspection system that is used for geological inspection and logging [from http://www.geologging.com]. The system consists of the control unit which controls the winch movement and camera lens rotation; camera with resolution of 0.1 mm (variable); electric winch with cable and a display unit.

### 4.1.3 Caliper

Caliper logging tools are used to generate a profile of the borehole diameter with depth along three, four- or six traces. The caliper tool is pulled up the borehole allowing spring-loaded arms to open as they pass borehole enlargements [e.g. Bell and Gough, 1979; Plumb and Hickman, 1985].

The main drawback of caliper logs is that they do not provide information on the detailed shape of the breakouts. Three-arm caliper measurements may provide reliable data if the borehole geometry is not too irregular; however, poor pad contacts may occur in non-cylindrical holes [Cox, 1970]. Four-arm calipers measure the borehole diameter in two orthogonal directions between two sets of opposing arms. This technique is robust, can be used at great depths, and the evaluation procedure is well established [e.g. Plumb and Hickman, 1985], see Figure 4.4.
4.1.4 Formation MicroScanner / Formation MicroImager

The FMS/FMI tools are four-arm calipers with a ray of microelectrodes mounted on each pad [from http://www-odp.tamu.edu/publications]. The FMI has an additional panel of microelectrodes at each four-arm caliper arm, which result in a better coverage of the borehole wall, Figure 4.5. The FMS/FMI emits a focused current from the four pads into the formation and the variation in current intensity is measured by pads. Processing transforms the current intensity measurements into high resolution images of variable intensity [from http://www-odp.tamu.edu/publications].
4.2 Data Analysis

Two computer programs were used for the analysis of the logging data presented in this thesis, and they were both provided by SKB. The PC based programs WellCAD, version 4.0, and BIPS Image Viewer, Version 3.2, were used to analyse BHTV and BIPS data, respectively. Other analysing programs that were used include Microsoft Excel and KaleidaGraph, version 4.0. Table 4.3 lists the files used in the analysis, which was provided by the SKB database (delivery number Sicada_06_134_1).

Table 4.3 List of data files for analyses provided by the SKB database SICADA (delivery Sicada_06_134_1)

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Name of data file</th>
<th>Data type</th>
</tr>
</thead>
<tbody>
<tr>
<td>KFM01A</td>
<td>KFM01A_HiRAT_up_to_120_run 1.WCL</td>
<td>Geophysical logging data including BHTV, Caliper-1, density, resistivity, etc.</td>
</tr>
<tr>
<td></td>
<td>KFM01A_Presentation_with_SP.WCL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mwd-filtered_data_001.xls-mwd_filtered_data_005.xls</td>
<td></td>
</tr>
<tr>
<td></td>
<td>KFM01A_101-996 bdt</td>
<td></td>
</tr>
<tr>
<td>KFM05A</td>
<td>KFM05A_Presentation.WCL</td>
<td>Geophysical logging data including BHTV, Caliper-1, density, resistivity, etc.</td>
</tr>
<tr>
<td></td>
<td>Mwd-filtered_data_001.xls-mwd_filtered_data_005.xls</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.5 Schematic diagram of the Formation MicroScanner pad, [from http://www.odp.tamu.edu/publications].
4.2.1 WellCAD, Version 4.0

WellCAD is a PC log package that has a combination of graphic editing mechanisms and data processing tool [from http://www.alt.lu/wellcad.htm]. Basic features enable import, edit, process and display of borehole logging data. It incorporates a set of templates and headers, for example 3D Borehole that displays a cross-sectional shape of the borehole. Further details about how borehole breakouts were analyzed are given in section 4.2.5, “Analysis of borehole breakouts data”.

The amplitude images have been plotted using static and dynamic presentation, which are two different color scales. The static colour scale has a partitioned and uniformly changed colour range, which is good for examining large-scale variations. The dynamic colour scale has manually been altered to increase the contrast in interesting intervals to enhance the finer details of the structure, whereas the contrast has been decreased for less interesting intervals. Note that this colour scale has not been generated using the WellCAD processing log normalization functions (Dynamic 1 dim, Dynamic 2 dim).

4.2.2 BIPS Image Viewer, Version 3.2

BIPS Image Viewer, Version 3.2, was used to view the BIPS data for KFM01A in the core drilled part between 100-990 mbl. BIPS data provide a high resolution digitized colour image of the borehole wall. SKB mainly uses BIPS data for geological survey and for determination of fracture distribution and orientation [Gustafsson et al., 2004]. Ask and Ask [submitted] found that BIPS data occasionally can be used for viewing borehole breakouts, namely deep and rugged borehole breakouts with open fractures, and for sections with dark minerals. In the latter case, the light from the BIPS was better reflected in the breakout traces than in other parts of the borehole wall.

4.2.3 Microsoft Excel

Microsoft Excel was used for recording borehole breakout data detected in the WellCAD analyses and appendices B and D show examples of borehole breakout recordings made in Microsoft Excel. For each breakout, a number of recordings are made, including: depth of borehole breakout; orientation of the top, bottom, and mean for each borehole breakout trace; type of borehole breakout; its degree of clarity; and the distances between the diametrical borehole breakout traces. Excel was also used for the calculation of the standard deviation of the minimum horizontal stresses for both boreholes and the weighted mean orientations.

The weighted mean is a mean where there is some variation in the relative contribution of individual data values to the mean. Each data value ($X_i$) has a weight assigned to it ($W_i$). Data values with larger weights contribute more to the weighted mean than data values with smaller weights. The formula used is

$$\bar{X}_w = \frac{\sum W_i X_i}{\sum W_i}$$
4.2.4 KaleidaGraph, Version 4.0

The KaleidaGraph is a graphical plotting tool that was used to make all the plots in this work. It has the functions suitable for making different kinds of plots but it was used mainly for the scatter plots for breakout orientations and line plots for the MWD parameters which were used for all the comparisons and analyses.

4.2.5 Analysis of borehole breakout data

SKBs standard presentations of the BHTV log are used for the analysis of borehole breakouts. The travel time-, amplitude, and CALIPER-3D logs are analyzed. Amplitude image reflects the acoustic impedance of the borehole wall while the travel time image reveals the borehole caliper, *Deltombe and Schepers*, [2001]. Acoustic image tools measure simultaneously two different images, i.e. an amplitude log which is directly related to geotechnical rock properties, and a traveltime log which allows one to derive a very precise borehole caliper, *Deltombe and Schepers*, [2001]. Even though different physical parameters are finally recorded, the two image logs are related to each other. The CALIPER-3D log provides a view of the borehole geometry from plotting cross-sections of the 3D caliper data.

Most analyses were based on the amplitude images. In most cases, the amplitude images were compared with the travel time and CALIPER-3D logs. The depth of borehole breakouts, the borehole breakout orientation at the top, bottom and mean of the trace were recorded. According to borehole breakout theory [i.e. *Bell and Gough*, 1979; *Zoback et al.*, 1985], borehole breakout traces should occur on diametrical sides of the borehole. However, occasionally, only one trace was observed in the borehole. In instances where the trace had the same appearance as those observed for diametrical borehole breakouts and its orientation agreed with closely located borehole breakouts, the trace was registered as a single borehole breakout. Remaining borehole breakouts were recorded as diametrical, and had two traces that were separated by about 180°. The degree of clarity for each borehole breakout was ranked using three scales (high, medium and low) based on how deep, shallow, and visible the breakouts appear. Because most of the breakouts in these boreholes were determined to be of shallow occurrence; it was therefore not too frequent to find a breakout that was of the high degree of clarity except in some very few instances in KFM05A. The high degree of clarity should be deep, well developed, V-shaped and visibly seen without any ambiguity, and be very much consistent at intervals of occurrence. The medium degree of clarity should be easily identifiable and in between the deep and shallow breakouts while the low degree of clarity should be shallow, flat bottomed with limited failure depth, not easily identifiable and its consistency being not continuous along the borehole depth.

To ensure that the readings taken are not mechanically induced features, for example key seats or washouts, a number of criteria for identifying borehole breakouts were proposed.
Table 4.4 Criteria for identifying borehole breakouts from BHTV data

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Borehole breakouts appear as broad parallel grooves that are parallel to the borehole axis. The top and bottom of the breakout should be well marked, by a distinct color change in travel time and/or amplitude images.</td>
</tr>
<tr>
<td>2.</td>
<td>Borehole breakouts consist of two, parallel grooves, separated by about 180°. An offset with depth of ≤ 0.5 m is accepted between the two grooves.</td>
</tr>
<tr>
<td>3.</td>
<td>The length of borehole breakouts should be ≥ 0.5 m</td>
</tr>
<tr>
<td>4.</td>
<td>The orientation of a borehole breakout is determined at the central width of the entire borehole breakout, which is obtained from the average value of the maximum and minimum azimuths of the borehole breakout.</td>
</tr>
<tr>
<td>5.</td>
<td>The direction of the grooves must not consistently coincide with the azimuth of the high side of the borehole wall when the borehole deviates from the vertical.</td>
</tr>
<tr>
<td>6.</td>
<td>If a single groove has similar physical appearance and orientation as the parallel grooves of an adjacent borehole breakout, its orientation is recorded as a single borehole breakout. It is assumed that the diametrical trace has not yet developed or that artifacts from logging or processing even out the second groove.</td>
</tr>
</tbody>
</table>

These criteria have been inspired by those of Plumb and Hickman [1985] and Reinecker et al., [2003] and adapted to the existing data.

The borehole should have a well marked top and bottom to enable the determination of the mean orientation of the breakout and its extent of occurrence taking note of the length and in some cases its average width.

It was observed that some of the breakouts which have grooves occurring 180° do not have their top and bottom starting and ending at the same depth interval. It was therefore reasonable to give room for offsets of ≤ 0.5 m to enable the recording of such borehole breakouts as they have same characteristics and quality as the conventional borehole breakouts.

The length of borehole breakouts ≥ 0.5 m was proposed based on the fact that the BHTV has a very high resolution with a minimum of about 1 mm as compared to four-arm caliper tools which cannot account for shallow and short breakouts because of their pad geometry.

The orientation of a borehole breakout is determined at the central width of the entire borehole breakout, which is obtained from the average value of the maximum and minimum azimuths of the borehole breakout.

Previous investigations do not take single breakouts into consideration and do not give room for offset of such breakouts. However, because of similar orientation and physical appearance of single borehole breakout traces and individual traces of diametrical borehole breakouts, the criteria were enlarged to include single borehole breakouts.
The mean $S_{H_{\text{max}}}$ orientation for KFM01A and KFM05A, and each individual breakout was weighted by its length to enhance the dominant $S_{H_{\text{max}}}$ orientations. The mean $S_{H_{\text{max}}}$ orientation and standard deviation (s.d.) was calculated for each well using Microsoft Excel to ascertain their deviation from the mean and to be able to rank them based on WSM quality ranking scheme [e.g. Zoback, 1992].

4.2.6 Analysis of Measurement While Drilling (MWD) data

The MWD data set for this study was delivered by Sicada in a filtered format. The two boreholes were logged from 100-1001 mbl at intervals of every 1 cm. The different parameters measured during drilling include the borehole length (m), rotation pressure (bar), feed force of drill bit (kg), feed force of cylinder (bar), water flow (l/min), water pressure (bar), rotation speed (rpm), feed speed (cm/min), drill length (cm), and feed position (cm). Because the data set was large, it was difficult to make set of plots for very long range intervals as the plot gets too clumsy and meaningless. The parameters selected for making comparison are the borehole length (m) vs. the rotation pressure (bar), the water pressure (bar) and finally the feed speed (cm/min). These three parameters were chosen as they give clear indication of changes and variations with depth as drilling progressed. Plots for correlation of the MWD parameters with the occurrence of borehole breakouts were made with the KaleidaGraph, Version 4.0.

In making plots for correlation between borehole breakouts and MWD parameters, random intervals were selected from the amplitude log by eye and also using the MWD data set. Intervals with observed breakouts and intervals where breakout was not inferred were picked out for the analysis. In this way, it was possible to make meaningful outputs from the plots. In picking out breakout points for the plots, major focus was at points where there was a good degree of clarity to ascertain that such points were truly representative of regions of inferred breakouts. For zones without breakout, close observation was made to decipher what intervals might be suitable to pick without any major geologic features that will hinder the interpretation.

The method used for comparing MWD parameters with borehole breakouts was based on random selection of intervals from the MWD data set and correlating those sections to the BHTV logs. Two different methods of comparison of the MWD parameters were used for correlation and analysis with the BHTV logs. Points where breakouts were found to be observed were chosen for analysis while points where borehole breakouts were not observed were also considered.

It was observable from the MWD parameters that points which correlate with borehole breakouts had distinct variations in their MWD values used for comparison while points observable without borehole breakouts have their MWD values almost constant within such sections. Parameters observed to follow this trend were then decided to be used for comparisons and they are borehole length versus the rotation pressure, water pressure and feed speed. These three parameters give a clear indication of changes and variations of the MWD parameters as drilling progressed.
5. Results

5.1 Occurrence of Borehole breakouts

Borehole breakouts have been observed to occur primarily as enlargements in the sides of the borehole and as spalled fragments of the borehole wall. Elongations could be a result of failure of the borehole due to brittle fracture (hard but easily broken), or a result of the natural fractures, and most of such elongations are symmetric. These were observed to be of the shallow quality type from the amplitude logs and the CALIPER-3D.

Results from borehole breakouts show that the length of occurrence of the breakouts is stated to be at least ±0.5 m. Most of the borehole breakouts occurred in pairs but with an allowed offset of about 0.5 m for the diametrical type while in some other cases, single borehole breakouts were observed running along one side of the borehole wall.

Basically, two different types of borehole breakouts were observed from the analysis, viz: deep breakouts which appear as very thick dark bands on the borehole wall signifying large fallout of the rock around that zone. They form the minority of breakouts and are well-developed and V-shaped. The shallow breakouts are the most dominantly observed in my own analysis. The shallow borehole breakouts appear slightly blurred in appearance when viewed from the amplitude logs and do not give an exceptional characteristic of the grain fallouts or rock chips from such zones. The overwhelming majority of breakouts in this category have a flat-bottomed shape, with a limited failure depth and the breakouts appear to be more pronounced near existing fractures in the rock. Ability to categorically decipher mechanically induced breakouts in this case is difficult because of the breakout types present in these two boreholes (i.e. shallow borehole breakouts). Figure 5.1 below shows examples of shallow and deep borehole breakouts from boreholes KFM01A and KFM05A. Table 5.1 gives the results of borehole breakouts obtained from both boreholes KFM01A and KFM05A.

Table 5.1 Results for boreholes KFM01A and KFM05A

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Depth (mbl)</th>
<th>LI (m)</th>
<th>TLBO</th>
<th>No. BO</th>
<th>$S_h$±Stdev ($^\circ$N)</th>
<th>BO ratio (%)</th>
<th>Q (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KFM01A</td>
<td>100-1001</td>
<td>901</td>
<td>253</td>
<td>33</td>
<td>51±8</td>
<td>28</td>
<td>B</td>
</tr>
<tr>
<td>KFM05A</td>
<td>100-1002</td>
<td>902</td>
<td>32</td>
<td>14</td>
<td>69±33</td>
<td>4</td>
<td>D</td>
</tr>
</tbody>
</table>

Keys: LI, logged interval; TLBO, total length of borehole breakouts; No. BO, number of borehole breakouts; $S_h$±Stdev, mean orientation and the standard deviation of minimum horizontal stress; BO Ratio, ratio of TLBO over LI; Q, quality according to World Stress Map [Zoback, 1992].
Figure 5.1 Dynamic colour presentation of borehole section from KFM01A showing breakouts of shallow depth with a low degree of clarity at 478 to 482 mbl (top), and dynamic colour presentation of borehole section from KFM05A shows deep breakouts with a high degree of clarity at 611 to 613 mbl (bottom).
5.1.1 Borehole KFM01A

Borehole breakouts occur within the shallow section of borehole KFM01A between 100 mbl and 280 mbl, (Figure 5.2 A). The dominant lithology in this interval is medium grained metagranite – granodiorite with subordinate occurrences of amphibolites and pegmatitic granite with several zones of oxidation. The average breakout lengths are quite short, about ±5 m, and non-continuous along the borehole section. The observable type of borehole breakout within this section is the shallow type. The general trend for the minimum horizontal stress orientation ranges between 45º - 60º and 215º - 245º within this section.

There were no observable borehole breakouts between 290 mbl and 350 mbl (Figure 5.2 A and B). This zone marks the intersection of two different rock units, i.e. rock units RU1 and RU2a, (Figure 5.2 B). The dominant lithology in both units is a medium grained metagranite – granodiorite with minor occurrence of pegmatitic granite, amphibolite and medium grained metagranitoids. The absence of oxidation zones in this interval could be a possible reason for the absence of breakouts but it should also be noted that the type and shape of breakouts vary within the borehole section, because breakout shape and type depend on rock strength, depth, and state of stress.

The borehole section between 350 mbl and 500 mbl has its lithology mainly of medium grained metagranite – granodiorite (Figure 5.2 B). The borehole breakout lengths are quite short, and with an average orientation of about 40º - 60º and 215º - 250º. The presence of deformation zone DZ2 suggests an increased frequency of sealed fractures associated with weak oxidation. The borehole breakouts are shallow, short (±5 m), and non-continuous. Minor scatter observed in the stress orientation values could probably be associated to the presence of the deformation zone.

The borehole interval between 503 mbl and 560 mbl shows no record of borehole breakouts occurring (Figure 5.2 A and B). This borehole section is wholly made up of rock unit RU3 and it is marked by a heterogeneous mixture of medium grained metagranite – granodiorite.

The depth interval of 560 mbl to 670 mbl has a dominant lithology of medium grained metagranite – granodiorite with minor occurrences of pegmatitic granite in the rock unit RU3. The breakout lengths are short, ±5 m, non-continuous and have an average horizontal stress orientation between 40º - 60º and 215º - 250º. Evidence of minor scatter of the stress orientation in this section is likely due to the presence of deformation zone DZ3 (Figure 5.2 B). This deformation zone has a strong increase in the frequency of sealed fractures within this depth interval.

A short interval without borehole breakout exists between 670 mbl and 725 mbl. This section falls within the rock unit RU2b and it is observed just below the deformation zone DZ3, (Figure 5.2 B).

The interval along the borehole length between 750 mbl and 1001 mbl falls within three different rock units RU2b, RU4 and RU2c (Figure 5.2 B). This section is observed to have longer borehole breakout lengths of about ±5 m to ±50 m and they are continuous. The intersection of rock unit RU4 between rock units RU2b and RU2c has been observed to result in the scatter of stress orientation values between 40º - 65º and 215º - 260º. The change in the rock properties at these different rock units stands
to be a possible reason for the scatter in orientation of stresses within this depth section.

Summarily, borehole KFM01A has been observed to have breakout occurrences from a depth of about 112 m to about 1001.6 m. The total length of breakout along the borehole length is about 253 m while the total number of breakouts is about 33. The mean average minimum horizontal stress orientation has been determined to be about 51°N while the ratio of breakout occurrence is about 28%. According to the WSM project quality ranking scheme Zoback, [1992], borehole KFM01A has been determined to have a standard deviation of ±8°N and of B-quality ranking.

Figures 5.2 show the variations in the stress orientations for borehole KFM01A. The plot gives detailed information of the depth versus the mean orientation of borehole breakout. This plot shows the principal minimum horizontal stress orientation along the borehole length of the cored interval. The consistency in the stress orientation suggests the rock’s homogeneity without much influence of geological structures and mechanical properties. The different lithology and structures in this borehole and their depth of occurrence are also shown below. It shows the different rock units and the possible deformation zones that are observed. Refer to Appendix A for detailed explanation of the rock units associated with borehole breakouts and the deformation zones. Appendixes B shows the depth and mean orientations of each breakout points as observed in borehole KFM01A.
Figure 5.2 Plots of the mean depth vs. mean orientation of breakouts with lithology for borehole KFM01A. (Keys: RU1 – 4, rock units 1 – 4; DZ1 – 3, deformation zones 1 – 3).
5.1.2 Borehole KFM05A

Borehole breakouts in borehole KFM05A starts within the very shallow part of the borehole. Basically, seven different rock units are observable in this borehole and with about five different deformation zones. The lengths of the borehole breakouts between 170 mbl and 210 mbl are quite short, in the range of about ±5 m and occur sparsely and with very high scatter. The stress orientation ranges between 45° and 215° - 260° at this depth interval. The breakout type is quite shallow and this falls within the rock unit RU1, (Figure 5.3 A and B).

Between the borehole lengths 210 mbl and 350 mbl, there are no observable breakouts. Two different rock units comprise this section of the borehole i.e. rock units RU2 and RU3a and their major lithology is a medium grained metagranite – granodiorite with minor occurrences of pegmatitic granite and amphibolite (Figure 5.3B).

At a depth of about 370 mbl to 404 mbl, borehole breakouts were recorded in rock unit RU4 with the lithology made up of a heterogeneous mixture of amphibolite and fine grained material with dioritic to quartz-dioritic composition (Figure 5.3 A and B). This section of the borehole has reversed stress orientation and this could be a result of the lithology and the possible deformation zone DZ3 just below it. The stress orientation of about 144° and 150° was observable within this section of borehole KFM05A. The majority of borehole breakouts within this section of the borehole are quite shallow and with some minor specks of deep breakouts in some parts.

Within the borehole section 404 mbl and 610 mbl, no observable borehole breakouts were recorded within rock unit RU3b, though deformation zone DZ2 intersects this lithology at about 416 mbl – 436 mbl, and it is composed of mostly sealed, steeply dipping fractures (Figure 5.3 B).

Borehole breakouts observable between 610 mbl and 710 mbl occur within two different rock units, RU3b and RU5 (Figure 5.3 A and B). The breakout lengths varies within the range of ±5 m, they are non-continuous and occur sparsely but with almost uniform orientation in this section of the borehole. The average stress orientation varies between 45° and 225° and the presence of deformation zone DZ3 does not seem to have influenced the stress orientation.

No borehole breakout was observable between 710 mbl and 900 mbl. The last set of borehole breakouts was recorded in the section between 900 mbl and 1001 mbl. The major rock unit is RU3 with two deformation zones, DZ4 and DZ5, which are inferred to possibly have influenced the stress orientation (Figure 5.3 A and B). The main lithology is medium - grained metagranite – granodiorite with a lower frequency of amphibolite. The length of breakouts is quite short, non-continuous and scattered. The average orientation varies between 45° - 90° and 215° - 270° and this shows a large scatter. The presence of deformation zones DZ4 and DZ5 visibly affects the stress orientation in this section. The breakout type dominant in this section is the shallow borehole breakout type.

Summarily, borehole KFM05A has been observed to have breakout occurrence from a depth of about 118 m to about 996 m. The total length of borehole breakout along the borehole is about 32 m while the total number of breakouts is about 14. The mean
average minimum horizontal stress orientation has been determined to be about 69ºN while the ratio of breakout occurrence is about 4 % of the entire cored borehole section. According to the WSM project quality ranking scheme Zoback, [1992], borehole KFM05A has been determined to have a standard deviation of ±33 ºN and be of D- quality ranking.

Figures 5.3A and B show the plot of orientation versus depth of occurrence of borehole breakouts in borehole KFM05A. Their degree of occurrence, variations with depth and scatter in the principal minimum horizontal stress orientation can be observed from the plot. The different lithology observed in this borehole can be seen from the plots below. The different rock units, their depth of occurrence and possible deformation zones associated with this borehole are duly represented. Refer to Appendix C for detailed explanation of the different rock units associated with the borehole breakouts and deformation zones and how they affect the occurrence of breakout orientations. Appendix D shows the mean depth and orientation of the breakout points in borehole KFM05A.
Figure 5.3 Plots of the mean depth vs. mean orientation of breakouts with lithology for borehole KFM05A. (Keys: RU1 – 5, rock units 1 – 5; DZ1 – 5, deformation zones 1 – 5).
5.2 Variation of Measurement While Drilling data

Results from MWD data for boreholes KFM01A and KFM05A are given below. Basically, the dominant lithology in both boreholes has been identified to cover about 76% of the entire cored interval and this has been observed to be medium grained metagranite to granodiorite.

5.2.1 Borehole KFM01A

Sections selected out for the analysis of borehole breakouts with MWD parameters were randomly picked from the amplitude log and then correlated to the MWD parameters. The lithology is basically a medium grained metagranite grading to metagranodiorite.

5.2.1.1. Variation of MWD within a borehole section with borehole breakout

Interval 139 – 144 mbl is a section with borehole breakout (Figure 5.4A). The breakout is not really consistent with depth but it can be classed into the shallow depth breakouts because of its degree of clarity from the BHTV amplitude logs. The width of the breakout cannot be clearly stated with certainty in terms of its consistency with depth.

The plot of rotation pressure has an average value in the range of about 150 bar and shows a drop between the depth intervals 139.2 - 140 m with the rotation pressure in the range of 100 – 140 bar (Figure 5.4B). Consistent fluctuation was observed between 140 – 140.6 m, where the range of the rotation pressure was about 80 bar. Rapid increase in the rotation pressure (170 bar) was again observed at about 141.8 m and a drop at 142 m to about 90 bar. Between 142 - 144 m, fluctuations in the rotation pressure were again observed between 115 – 150 bar.

Variations in the water pressure are not too evident as compared to the other two parameters (Figure 5.4C). Gradual increase in water pressure from about 18 – 30 bar was observed at intervals between 139 and 143.4 m. The highest point of increase is about 50 bar between 143.4 – 143.8 m.

Considering the feed speed (Figure 5.4D), it maintains the same average value of about 10 – 18 cm/min along the depth interval investigated; 139 – 144 m. Sharp drops in the feed speed were however observed at various points along the depth interval; 140.6 m, 141.25 m and 142.8 m all dropped to 2 cm/min, 142 m dropped to about 5 cm/min while 143.6 m dropped to zero cm/min.

The most significant correlation between these plots can be seen in the rotation pressure and the feed speed (Figures 5.4B and D). At a depth of about 140 – 140.6 m and 142 m, both plots experience a decrease in the rotation pressure and feed speed while at a depth of 141.8 m, a rapid increase in both parameters can be observed.

Because MWD parameters (e.g. Figure 5.4B-D) are sensitive to fractures and any kind of opening in the rock, their variation reveals zones with any form of change in the mechanical- and physical properties of the borehole wall, for e.g. variation in strength and fracture occurrence. This serves as a standard for comparing the signature of the different parameters with points where breakouts were observed and points where no breakouts were detected. It was easily seen from the plots that there was a correlation between variations in the rate at which the water pressure changes with the occurrence...
of fractures and also with the rotation pressure. This rapid change of water pressure in fractured zones is exhibited because the flushing water is always much higher than the groundwater excess pressure in discharging areas of the boreholes. A sudden increase in flushing water may be due to many technical reasons, e.g. increased frictional resistance due to variation in the amount of drilling debris, etc [Pers. Comm. with Lennart Ekman]. From an optical inspection of the BHTV amplitude log, it was observed that the breakouts are associated with regions where we have mostly fractures or a change in the rock quality or rock strength, Figures 5.4B-D. MWD parameters are also good determinants of fractures and changes in the rocks’ mechanical properties also give a similar change in signature of different parameters. Thus, it can be said that MWD parameters and borehole breakouts are both dependent on the mechanical properties of the rocks penetrated, and the occurrence of fractures and fracture zones.
Figure 5.4 Dynamic colour presentation of Amplitude log KFM01A showing the breakout region between 139-144 mbl and plots of MWD parameters showing borehole breakouts, and displaying their correlation to variations in rotation pressure, water pressure and feed speed.
5.2.1.2. Variation of MWD within a section without borehole breakouts

Interval 288 - 293 mbl is a section without borehole breakouts (Figure 5.5A). The plot of rotation pressure versus depth shows a slight variation in the rotation pressure (between 150 – 210 bar) in this depth interval (Figure 5.2.1.2B). A sharp drop in the rotation pressure was however observed at 291.4 mbl to about -1 bar.

The water pressure shows some consistency in its values in the range of about 40 bar but with sharp drops in values at 288.5 m to 8 bar; 290 m to 12 bar; and 290.6 m to 14 bar (Figure 5.5C).

The feed speed has a general trend in the range of between 15 – 19 cm/min (Figure 5.5D). Sharp drops in its values were observed at 288.5 m to 6 cm/min; 289.3 m to 8 cm/min; 290 m to 10 cm/min; 290.6 m to 4 cm/min; 291.4 m to 0 cm/min; and lastly 292 m to 19 cm/min.

The most significant correlation between these plots can be seen in the water pressure and the feed speed. At a depth of about 288.5 m, 290 m and 290.6 m, both plots experience a decrease in the water pressure and feed speed with a strong correlation in their signatures at these depth intervals.
Figure 5.5 Dynamic colour presentation of amplitude log KFM01A showing no breakout zones from 288 – 293 mbl and plots of MWD parameters displaying depth without breakout points and variations in rotation pressure, water pressure and feed speed.
5.2.1.3 Comparison how MWD varies within and without borehole breakout sections

Because MWD parameters are sensitive to fractures and any kind of opening in the rock, their variation reveals zones with any form of variation in the mechanical- and physical properties of the borehole wall, for e.g. variation in strength and fracture occurrence and also variations which reflects the drilling conditions e.g. friction from drill string. Intervals with borehole breakouts exhibit rapid changes in their MWD parameters which signify change in the rocks’ mechanical and physical properties. Zones marked as regions without breakouts show gradually changes in MWD parameters and in the rock mechanical and physical properties within those depth intervals. Observation of the BHTV amplitude log indicates that the breakouts are associated with regions where we have increased fracture frequency or a change in the rock quality or rock strength.

5.2.2 Borehole KFM05A

The fracture frequency in borehole KFM05A is higher in the upper 300 m of the cored borehole length than in the bottom part of the hole. Basically, two facies are dominant here and they are separated by a sharp, intrusive contact at a borehole length of 285.8 m, with the fine to finely medium-grained rock type in the upper part of the borehole.

Sections selected for the analysis of borehole breakouts with MWD parameter are randomly picked and they exhibit almost the same lithology which is a medium grained metagranite to metagranodiorite.

5.2.2.1. Variation of MWD within a borehole section with borehole breakout

The borehole interval 609 - 614 mbl comprises sections of borehole breakouts (Figure 5.6A). Observation of borehole breakouts from the amplitude log can be classed into the shallow breakouts because of its degree of clarity from the BHTV amplitude logs but with variable occurrence of deep breakouts observed also.

The general trend in the plot of the rotation pressure shows consistency of an average value of 150 bar (Figure 5.6B). The plot of rotation pressure shows an increase between the depth intervals 609.4 to 180 bar; 610.2 m to 200 bar; 610.8 to 200 bar and 612.8 m to 210 bar. Consistent fluctuation was observed with some sharp decrease in rotation pressure at intervals, 610.9 m to 70 bar; 611.2 m to 90 bar; 612 m to 110 bar; 612.5 m to 50 bar and 613.8 m to 10 bar.

The average water pressure is in the range of about 44 bar (Figure 5.6C). Variations in the water pressure as compared to the rotation pressure shows some significant correlation also. Gradual increase in water pressure was observed at 612.6 m to about 57 bar. Depth intervals of 610.9 m, 611.2 m, and 612.5 m correlate to the rotation pressure and all have the water pressure decrease to about 39 bar. However, a slight change was observed at 613.8 m where it reduces to 37 bar.

The feed speed has an average value at about 10 cm/min (Figure 5.6D). The feed speed maintains a slight increment in its values which correlates to the other two parameters; it increases at intervals of 610.9 m to 20 cm/min; 611.2 m and 612.6 m to 40 cm/min. However, a decrease was noticed at 613.8 m to about – 90 cm/min which
also correlates to the aforesaid parameters. This decrease also indicates that there was potential interruption in the drilling and the drill string is pulled a bit.

The most significant correlation between these plots can be seen in the rotation pressure and the feed speed (Figure 5.6B & D). At depth intervals 610.9 m, 611.2m, 611.8m, 612.6m and 613.8m for Figures B and D, they show a similar trend in the increment of their values. As the rotation pressure increases, the feed speed also increases. The water pressure has an inverse relationship to these two parameters as it reduces at these depth intervals stated.

Refer to Figure 5.6A-D for correlation of the MWD parameters (rotation pressure, water pressure and feed speed) with the occurrence of borehole breakouts (unwrapped amplitude log). Since MWD parameters used for comparison are sensitive to openings, fractures, changes in the rock’s mechanical properties and any form of deformation; it registers changes in signature in regions with breakouts and prominent fractures, see Figures 5.6A - D. It shows how the fracture formation affects the water pressure, the rotation pressure as well as a little variation in the feed speed. The correlations between MWD and borehole breakouts are therefore dependent on the mechanical properties of the rock mass, geology and physical changes as well (e.g. lithology, fractures, zones of weathering).
Figure 5.6 Amplitude log KFM05A showing breakout zones between 611.75-613.05 mbl and plots of MWD parameters displaying the correlation between borehole breakout and variations in rotation pressure, water pressure and feed speed.
5.2.2.2. Variation of MWD within a section without borehole breakouts

The interval 528 - 533 mbl comprises sections without borehole breakouts (Figure 5.7A). Figure 5.7B-D shows how the MWD parameters rotation pressure, water pressure, and feed speed varies within the zone.

The plot of rotation pressure shows a slight variation (between 130 – 150 bar) in this depth interval (Figure 5.7B). A sharp decrease in the rotation pressure was however observed at 528.2 m to about 50 bar; 528.8 m and 529.9 m to 0 bar; 531.8 m to 10 bar and 532.4 m to 60 bar. Increases in the rate of rotation pressure to 210 bar were also observable at the following intervals; 528.7 m, 529.8 m, 530.4 m, 531 m, 531.2 m, 531.6 m, 532 m, 532.3 m, and 532.7 m.

The water pressure increases at 528.2 m to 80 bar (Figure 5.7C) while the intervals 528.7 m, 529.8 m, 530.4 m, 531 m, 531.2 m, 531.6 m, 532 m, 532.3 m, and 532.7 m shows some decrease in the consistency in its values in the range of about 28 – 38 bar.

The feed speed has a general trend in the range of between 10 cm/min (Figure 5.7D). Decrease was observed at 528.2 m to 0 cm/min; 529.9 m to – 90 cm/min; and 530.2 m to about – 35 cm/min. Increase in the feed speed was observable to about 20 cm/min at the following intervals 528.7 m, 529.8 m, 530.4 m, 531 m, 531.2 m, 531.6 m, 532 m, 532.3 m, and 532.7 m.

The most significant correlation between these plots shows that as the rotation pressure increases, the water pressure decreases, while the feed speed increases accordingly. When the rotation pressure decreases, the water pressure increases and feed speed decreases and these tendencies are seen from the graphs below.
Figure 5.7 Amplitude log KFMO5A showing no breakout zones between 529-530.3 mbl and plots of MWD parameters displaying depth with no breakout points and variations in rotation pressure, water pressure and feed speed.
5.2.2.3 Comparison how MWD varies within and without borehole breakout sections

Because MWD parameters (e.g. Figure 5.6) are sensitive to fractures and any kind of opening in the rock, their variation reveals zones with any form of variation in the mechanical- and physical properties of the borehole wall, for e.g. variation in strength and fracture occurrence and also variations which reflects the drilling conditions e.g. friction from drill string. Intervals with borehole breakouts exhibit rapid changes in their MWD parameters which signify change in the rocks’ mechanical and physical properties. Zones marked as regions without breakouts (Figure 5.7) show gradually changes in MWD parameters and in the rock mechanical and physical properties within those depth intervals. Observation of the BHTV amplitude log indicates that the breakouts are associated with regions where we have increased fracture frequency or a change in the rock quality or rock strength.

5.3 Influence of lithology and structures on rock stress orientation

5.3.1 Borehole KFM01A

The orientations of borehole breakout grooves in borehole KFM01A vary from 37-64°N and 215 - 250°N. However, most grooves range in orientation from 43-59°N, and from 223 - 239°N. Exceptions was observed near 500, 600, 790, and 870 mbl (Figure 5.2B).

In general, the borehole breakouts are evenly distributed with depth in borehole KFM01A. Exceptions from this trend are observed for the deeper part (750-1001 mbl) that is characterized by longer borehole breakouts. The smallest scatter in borehole breakout orientation within a rock unit is observed in the shallowest and deepest sections of the borehole, rock units RU1 and RU2c (Figure 5.2B). No borehole breakouts were recorded in rock unit RU3.

It appears that the upper deformation zone (DZ2) has little influence on the orientation of stress, if any (Figure 5.2B). Only one borehole breakout was found in the lower deformation zone (DZ3). However, inspection of borehole breakouts in RU2b indicates that DZ3 might cause re-orientation of borehole breakouts (Figure 5.2B). There is a general decrease in borehole breakout orientation above DZ3, from 59°N and 239°N at 560 mbl, to 37°N and 217°N near the top of DZ3 (~640 mbl). Below DZ3, there is a general increase in borehole breakout orientation, from 50°N and 222°N near 725 mbl, to 61°N and 250°N near 800 mbl. The borehole breakout within DZ3 has a Shmin orientation of 46°N.

5.3.2 Borehole KFM05A

The orientations of borehole breakout grooves in borehole KFM05A vary from 40 - 90° N and 215 - 270° N. Most of the grooves range in orientation from 40 - 55° N and from 215 - 235° N. Exceptions were however observed at depth intervals of 375 – 410, 900 and 970 mbl (Figure 5.3B).

The occurrences of borehole breakouts are not evenly distributed with depth in borehole KFM05A. Borehole breakouts in borehole KFM05A are generally
characterized by short lengths. Scatter was however observed in the shallow parts of the borehole in rock units RU1 and RU4. The deepest section of the borehole also experiences some scatter in rock unit RU3c. No borehole breakouts were recorded in rock units RU2 (237 – 286 mbl), RU3a (286 – 349 mbl), the upper section of RU3b (460 – 600 mbl) and RU3c (720 – 890 mbl), (Figure 5.3B).

Deformation zone DZ1 in the shallow section of the borehole has little influence in the change in stress orientation in rock unit RU1. However, deformation zone DZ2 is suspected to have influenced the stress orientation in rock unit RU4. Deformation zone DZ3 also influences the stress change in rock units RU3b and RU5 while deformation zones DZ4 and DZ5 influences the stress change in rock unit RU3c.

Average stress re-orientation observed for the different rock units and deformation zones observed are; RU1 and DZ1 (260° N), RU4 and DZ2 (150° N), RU3b and RU5 for DZ3 (235° N) while RU3c for DZ4 and DZ5 (270° N).

Borehole breakouts were not observed in rock units RU2, RU3a, RU3b (420 – 570 mbl) and RU3c (730 – 870 mbl). The overall breakout orientation has been observed to be averagely 69 – 225° N for the minimum horizontal stress.

5.4 Identify Zones of Rock Continuum

5.4.1 Borehole KFM01A

Borehole KFM01A has a regular occurrence of borehole breakouts with depth. The average minimum horizontal stress orientation was deciphered to be in the range of 43 – 59 °N and 223 – 239 °N.

Basically, six different rock units with very little changes in stress orientation were observed. The entire borehole length reveals continuity in the rock stress orientation with very little variations. Rock unit RU1 shows consistency in the average stress orientation as seen from (Figure 5.2A). Rock units RU2a, RU3, RU2b, RU4, and RU2c all exhibit an average stress orientation from 37 – 64 °N and 215 – 250 °N.

Sections without borehole breakouts along the borehole depth are at rock unit contacts between RU1 and RU2 (670 – 720 mbl), Figure 5.1.1.B.

Generally, the rock units in this borehole have been observed to have a fairly uniform minimum horizontal stress, continuous and homogeneous.

5.4.2 Borehole KFM05A

Borehole KFM05A has an irregular occurrence of borehole breakouts with depth and also the orientation of the minimum horizontal stress varies along the borehole.

Seven different rock units with variable changes in stress orientation were observed. The entire borehole length reveals discontinuity in the rock stress orientation with major variations in its values.

Rock units RU1, RU4, RU3b, RU5 and RU3c show major variation in the orientation of the minimum horizontal stress (Figure 5.3B). They show signs of heterogeneity in the different depth sections of the borehole. Rock units RU2, RU3, and the upper
section of RU3b and RU3c do not have borehole breakout occurring. Generally, the rock units in this borehole have been observed to have a non-uniform minimum horizontal stress orientation, to be non-continuous and inhomogeneous.
6. Discussion

6.1 Borehole breakout analysis

The analysis of borehole breakout using the BHTV log for boreholes KFM01A and KFM05A has been observed to yield the result that the most commonly observed breakouts are the shallow type of borehole breakout. This was observed from the analysis of the amplitude logs and the other associated logs of travel time and CALIPER-3D. Problems of tool decentralization were minimal in both boreholes but it was observed that the quality of the logs was not excellent making it a bit difficult to have a clear and distinct picture of the structures present in the boreholes. Tool wobbling/ indentations were the most observable borehole artifacts in borehole KFM05A and this is inferred to occupy about ±5% of the entire cored section of the borehole.

6.2 Orientation of horizontal stress

Table 5.1 gives a summary of the mean orientation of the minimum horizontal stress for boreholes KFM01A and KFM05A. Figures 5.2 and 5.3 give a graphical representation of the downhole distribution of the orientation of the minimum horizontal stress with depth for both boreholes and their variations. Boreholes KFM01A and KFM05A both have a mean orientation of about 51 ± 8 ºN and 69 ± 33 ºN respectively. Borehole KFM01A has breakouts observable over extended intervals along the borehole with a quite consistent orientation with depth. The low standard deviation for the orientation of the breakout and the combined length of borehole breakouts in borehole KFM01A results in B- quality ranking according to Zoback [1992]. Borehole breakout orientation in borehole KFM05A has shown some evidence of significant deviation between 350 - 450 m and 900 - 1000 m of the cored interval. The standard deviation for the orientation of the breakout in KFM05A was determined to be averagely ±33ºN and has been observed to fall into the D – quality ranking which gives vital information about the local state of stress, or as a result of the variation in the mechanical properties according to Zoback [1992], see appendix D. This results in the fact that the different rock units have different strength and are inhomogeneous and therefore exhibit different material properties. Sjöberg et al. [2005] have shown that a combined assessment of the local (site-scale) and regional stress data for Forsmark support that the major stress is orientated NW – SE [140ºN], however, with a significant local variation for different measurement levels, boreholes and measurement sites. Compilations by the WSM [Reinecker et. al., 2004] showed that the regional stress field in Fennoscandia is primarily E- W to NW – SE. Data from WSM reveal a major stress orientation of around 130ºN based on focal mechanism. Therefore, the maximum horizontal stress for borehole KFM01A and KFM05A is about 141±8 ºN and 159±33 ºN approximately as determined from the downhole orientation of the horizontal stresses using the weighted mean.

6.3 Relationship between borehole breakouts and MWD

Within the analyzed section with borehole breakouts in borehole KFM01A, the rotation pressure and the feed speed both have direct relationship at some intervals. Direct correlation between rotation pressure and feed speed is the normal condition, regardless of rock properties, because increased energy supply entails increased rotation pressure, which results in increased feed speed. As the rotation pressure
increases, the feed speed increases and vice versa. The water pressure gradually increases while the other two parameters decrease, Figure 5.4. The water pressure was observed to vary in its values in the sections of the borehole where fractures are observed to be prominent and this therefore suggests the changes in the rock’ mechanical properties and rock strength.

In analyzed sections without borehole breakouts, the rotation pressure varies slightly at the observed intervals but the water pressure shows a decrease in its values in some intervals as well as the feed speed, Figure 5.5. This decrease in water pressure at such intervals may signify the presence of fractures. Also, the variation of MWD parameters in analyzed breakout intervals were quite high as compared to their variations in zones where no borehole breakouts were observed.

Within sections in borehole KFM05A with borehole breakouts, the rotation pressure and feed speed exhibit same variation in values at the observed intervals, i.e. direct relationship. The rotation pressure and feed speed shows significant correlation in their values while the water pressure exhibit the inverse relationship at depths where the rotation pressure and feed speed increases, Figure 5.6.

At intervals where no borehole breakouts were observed for borehole KFM05A, the rotation pressure and the feed speed both have direct relationship while water pressure has an inverse relationship to both parameters. As the rotation pressure and feed speed increases, the water pressure decreases, Figure 5.7.

MWD parameters are mostly useful for the determination of the mechanical properties of the formation, determination of the deformation of the borehole, defining the physical properties of the rock mass such as hardness or structures as they vary with depth. Rock characterization using MWD parameters aims at refining and defining accurately the properties of the subsurface as the drill bit propagates. The geology and structural geology of the boreholes are determinants of breakout formation and MWD parameters. Borehole breakouts and MWD parameters are both subjective to changes in the rock properties, fracture formation and their relationships could be tied to these factors but that does not infer that MWD parameters can be used to determine borehole breakouts or vice versa.

### 6.4 The influence of lithology and structures on rock stress orientation

The present study reveals that borehole KFM01A has breakouts evenly distributed with depth. However, it was also observed that the occurrence of borehole breakouts was not observed in rock unit RU3. The influence of the observed deformation zones on rock stress orientation in this borehole is very limited though this might, theoretically, cause re-orientation of the stress field and, hence, the borehole breakouts. Therefore, different rock units and structures do not have any adverse effect on the orientation of the borehole breakouts in borehole KFM01A.

Borehole KFM05A has its breakouts less evenly distributed with depth compared to borehole KFM01A. Breakouts in borehole KFM05A are generally of short length and with major scatter. The stress orientation is not consistent and it was observed to vary with depth in the different rock units. It was also observed that borehole breakouts were not recorded in some of the rock units but clear influence of the deformation
zones on the re-orientation of the stresses were observed in this borehole irrespective of rock unit. The different material properties of the rock units might as well be a factor that has led to the stress re-orientation along the cored section of the borehole.

6.5 Zones of rock continuum

The in situ stress field orientation obtained from the study of breakouts is very homogeneous within the Forsmark area. It shows a regular trend in lateral variation of mean minimum horizontal stress orientation observed; the breakouts data reveal values with an NE – SW orientation of mean minimum horizontal stress orientation in both boreholes KFM01A and KFM05A but with some scatter in the upper 350 – 450 m and lower 900 – 1000 m in borehole KFM05A.

Borehole KFM01A has a stress orientation determined from the image logs analysis of BHTV which is very consistent vertically and laterally along the borehole length. Twentyeight percent of the total borehole length were identified as intervals with borehole breakouts in this borehole. The dominant rock type found in borehole KFM01A is a foliated metagranite – granodiorite (76%) followed by massive or lineated pegmatite or pegmatitic granite (12%) and foliated amphibolite (6%). Other subordinate rock types are also present in this borehole. Three major sets of deformation zones have been documented with high confidence of occurrence at the Forsmark area. A regional trend in the lateral variation of mean minimum horizontal stress orientation is observed and the minimum horizontal stress orientation in this group seems to be homogeneous and fall within the category of the observed data for Scandinavia, i.e. NE- SW directions and it validates that the stress field is continuous with little or not much influence of previously existing structures on the prevailing stress field in the rock mass.

Borehole breakout orientation in borehole KFM05A has shown some evidence of major deviation between 350 – 450 m and 900 – 1000 m from the plot of the mean orientation against borehole depth. This could probably be a result of the prominent fractures at these depth intervals resulting from the deformation zones that have been detected there, see Figure 5.3. A heterogeneous mixture of rock units between amphibolite and fine – grained material with dioritic to quartz composition and increased frequency of mostly sealed fractures might have contributed to the change in the stress orientation in the upper part of the borehole. Between 900 – 1000 m where a variation was observed in the stress orientation, it could probably be affected by increased frequency of both open and sealed fractures. The breakout intervals in this borehole occupy about 4% of the entire cored interval measured in this borehole. This group is characterized by medium – grained metagranodiorite – granite. Other rock units including finer – grained metagranitoids, pegmatitic granites, and amphibolites are subordinate. A regional trend in the lateral variation of mean minimum horizontal stress orientation observed in this borehole is not completely homogeneous and experiences some major deviation when compared to borehole KFM01A. It validates that the stress field is not completely continuous but with some influence of previously existing structures on the prevailing stress field in the rock mass where stress orientation changes were observed. The decoupling in the stress directions could be due to the influence of the deformation zones or the dominance of local stresses.
7. Conclusions

The analysis of the two borehole image logs KFM01A and KFM05A from the Forsmark Site Investigation yielded information on downhole orientation of stress in these boreholes. The data were provided by SKB (Sicada delivery 06_134_1; Table 4.3).

The objectives of this study were to:
1. Determine the downhole orientation of horizontal stresses;
2. Correlate relationships between borehole breakouts and Measurement While Drilling parameters if any;
3. Study the influence of lithology and structures on rock stress orientation; and
4. Identify zones of rock continuum

In general, the quality of BHTV log is good, with exception for existence of borehole artifacts in borehole KFM05A. The most common artifacts in borehole KFM05A include tool wobbling/indentation. However, the borehole artifacts only had minor influence on the further analysis. The amount of data for the MWD parameters was enormous, because both boreholes were logged at a 1 cm frequency. This therefore resulted to the constraint of not been able to analyze large intervals of the cored sections of the borehole distinctly. The analysis of MWD data was based on random selection of intervals that have been identified from the amplitude logs to have the occurrence of breakouts and sections without borehole breakouts.

Borehole KFM01A has breakout occurrences from a depth of about 122 m to about 1001 m. The total length of borehole breakout is about 253 m while the number of breakouts is about 33. The mean average minimum horizontal stress orientation and standard deviation is about 51°N ± 8°N and this falls in the B – quality ranking according to the WSM ranking scheme. The ratio of breakout occurrence is about 28 % of the entire cored section of the borehole. The consistency in stress orientation suggests the rock’s homogeneity without much influence of geological structures and mechanical properties.

Borehole KFM05A has borehole breakout occurrences between 118 m and 996 m. The total length of breakout occurrence is about 32 m of the entire cored section while the number of breakouts is about 14. Mean average horizontal stress orientation and standard deviation is about 69°N ± 33°N and this falls in the D – quality ranking according to the WSM ranking scheme. The ratio of breakout occurrence is about 4 % of the entire cored section. Generally, distinct scatter in the minimum horizontal stress orientation marks this borehole and with short breakout lengths, non-continuous orientation and non-homogeneous rock properties.

Conclusively, the average maximum horizontal stress orientation for boreholes KFM01A and KFM05A is approximately 141±8 °N and 159±33 °N.

MWD parameters that were used for this analysis were the rotation pressure vs. depth, water pressure vs. depth and the feed speed vs. depth. It was observed that MWD parameters are sensitive to fractures and any kind of opening in the rock as they reveal changes in rock’s mechanical and physical properties of the borehole wall. The variations in the strength of the rock and fracture occurrence in the borehole show
signs and changes in the water pressure and also rotation pressure parameters. Borehole breakouts are associated with changes in the rock quality or rock strength, fractures, mechanical properties and change in geology. Sections marked as regions without breakouts gradually show minimal changes in MWD parameters and in the rock’s mechanical and physical properties within the depth interval as compared to sections with borehole breakouts that show significant variations in the MWD parameters. MWD parameters and borehole breakouts are dependent on the mechanical properties of the rock mass, geology and the physical properties as well. MWD systems are though not absolute rock recognition systems; however, with proper interpretation, changes in rock formations and properties can be inferred. The rock mechanical properties also affect the occurrence of breakouts and it has been observed that the higher feed force and the lower drill rate in Forsmark results in a higher friction at the rock-drill bit contact, which leads to increases in the rock temperature, heat expansion, and induced thermal stress of the rock. The impact of this transient, 3D thermo-mechanical effect has not been fully understood [Ask & Ask, submitted].

The observed breakouts in both boreholes KFM01A and KFM05A start within the first 100 m of the core drilled part and this has a significant implication that the horizontal stresses are high even at shallow depth intervals. The fact that the orientation has been very much uniform in borehole KFM01A predicts that the units of rock here have not been influenced much by the lithology and structures which are prominent in the borehole. For borehole KFM05A, the influence of lithology and structures in the stress orientation was observed at depth intervals between 350 – 450 m, 600 – 750 m and 900 – 1000 m. The prominent fractures at these depth intervals result from the changes in the rock units and deformation zones that have been detected. It validates that the stress field is not continuous but has been influence by previously existing structures on the prevailing stress field in the rock mass.

Borehole KFM01A shows consistency in the minimum stress orientation values along the borehole length and this signifies a zone of rock continuum without much variance in the rock’s properties; lithology and structures. Borehole KFM05A shows inconsistency in the horizontal stress orientation and intervals with stress re-orientation suggests that there are zones of rock discontinuum which infers that both the lithology and structures have a role to play in the change in stress orientation. The different rock units have different stiffness variations and this could as well be a possible reason for the change in stress orientation. Changes in stress orientations are possible to vary with different material properties of the different rock units. It is believed that the observed short-wavelength variations of breakouts azimuth in KFM05A with amplitudes up to 150º reflects stress perturbations in the vicinity of active fractures.
8. Recommendations for future studies and Remarks

Further study needs to be conducted to assess the state of stress in the Forsmark area, and also to determine the occurrence of borehole breakouts in the drilled holes. This will give valuable information for the siting of the final repository in the proposed investigation area.

Re-logging of all deep boreholes in this area using FMS/FMI and BHTV will improve the result of the detection of borehole breakouts. In general, BIPS data provide little additional information to that obtained from BHTV and FMS/FMI tools, with the exception for inspection of filling material in open fractures. Hence, BIPS data are of subordinate importance for further borehole breakout analysis.

Finally, it is recommended that the boreholes should be logged multiple times to study time effects. The first suite of logs should be collected immediately after completion of drilling. It is important to have a high resolution logging and well centralized logging tools to favour collection of high quality data.
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10. Appendices

**APPENDIX A: Geological single-hole interpretation for borehole KFM01A**

The detailed results of the geological single-hole interpretations are presented for KFM01A.

**KFM01A**

The borehole consists of three rock unit types, RU1–RU3. Further division on the basis of degree of fracture frequency has also been carried out for one of these rock units. In all, the borehole has been divided into eight sections of distinct rock character.

29-51m RU1: Medium-grained metagranite-granodiorite. Percussion-drilled part of the borehole contains a possible deformation zone and a generally increased fracture frequency relative to the remaining borehole outside the possible deformation zones.

51-100m RU1: Medium-grained metagranite-granodiorite and percussion-drilled part of the borehole.

102-290m RU1: Medium-grained metagranite-granodiorite with subordinate occurrences of amphibolite, pegmatitic granite and fine to medium-grained metagranitoid. Several zones of oxidation are also present.

290-503m RU2a: Medium-grained metagranite-granodiorite with minor occurrences of pegmatitic granite, amphibolite and fine to medium-grained metagranitoid.

503-560m RU3: Heterogeneous mixture of medium-grained metagranite-granodiorite, fine to medium-grained metagranitoid with granitic to granodioritic composition, pegmatitic granite and subordinate amphibolite.

560-808m RU2b: Medium-grained metagranite-granodiorite with minor occurrences of pegmatitic granite, amphibolite and fine to medium-grained metagranitoid.

808-865m RU4: Fine to medium-grained metagranitoid (granitic to granodioritic composition), with subordinate amphibolite, pegmatitic granite, medium-grained metagranite-granodiorite and calc-silicate rock.

865-1001m RU2c: Medium-grained metagranite-granodiorite with subordinate occurrences of pegmatitic granite, amphibolite and fine to medium-grained metagranitoid.

Three possible deformation zones have been recognised:
36-48m DZ1: One three decimetre-wide and one two decimetre wide crush zone and an increased frequency of open fractures in the upper part and of sealed fractures in the lower part of the zone.

386-412m DZ2: Increased frequency of sealed fractures associated with a weak oxidation. Predominant infilling minerals are chlorite and laumontite.

639-684m DZ3: Strongly increased frequency of sealed fractures, mostly filled by laumontite. Distinct concentration of fractures striking NE and dipping steeply towards SE; a weak zone of oxidation is observed.
## APPENDIX B: Table showing detailed information for borehole KFM01A

Table for borehole KFM01A showing the depth, orientation, type, clarity, distance apart, breakout length and the rock types for each individual breakout occurrence.

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**ROCK TYPE IN FORSMARK**
- **G1**: Granite, fine to medium-grained
- **G2**: Pegmatite, pegmatitic granite
- **G3**: Granitoid, metamorphic
- **G4**: Granite, granodiorite and tonalite, metamorphic, fine to medium grained
- **G5**: Granite to granodiorite, metamorphic, medium-grained
- **G6**: Amphibolite
- **G7**: Calc-silicate rock (skarn)
Table for borehole KFM01A showing the depth, orientation, type, clarity, distance apart, breakout length and the rock types for each individual breakout occurrence.

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ROCK TYPE IN FORSMARK
G1: Granite, fine to medium-grained
G2: Pegmatite, pegmatitic granite
G3: Granitoid, metamorphic
G4: Granite, granodiorite and tonalite, metamorphic, fine to medium grained
G5: Granite to granodiorite, metamorphic, medium-grained
G6: Amphibolite
G7: Calc-silicate rock (skarn)
APPENDIX C: Geological single-hole interpretation for borehole KFM05A

The detailed results of the geological single-hole interpretations are presented for KFM05A.

KFM05A

The borehole can be divided into four different rock units, some of which are reoccurring in the borehole. For this reason, the borehole was further subdivided into seven rock sections:

102–237m RU1: Fine- to medium-grained variety of medium-grained metagranite-granodiorite, with minor occurrences of pegmatitic granite and amphibolite, and one occurrence of fine- to medium-grained metagranitoid. Generally increased fracture frequency relative to the remaining part of the borehole, outside possible deformation zones.

237–286m RU2: Fine- to medium-grained variety of the otherwise medium-grained metagranite-granodiorite, with minor occurrences of pegmatitic granite and amphibolite.

286–349m RU3a: Medium-grained metagranite-granodiorite, with minor occurrences of pegmatitic granite and amphibolite.

349–362m RU4: Heterogeneous mixture between amphibolite and fine-grained material with dioritic to quartz-dioritic composition. Subordinate occurrences of medium-grained metagranite-granodiorite and pegmatitic granite.

362–676m RU3b: Medium-grained metagranite-granodiorite, with minor occurrences of pegmatitic granite, amphibolite and in the interval 570–620 m fine- to medium-grained metagranitoid.

676–720m RU5: Fine- to medium-grained metagranitoid of granodioritic to tonalitic composition with subordinate medium-grained metagranite-granodiorite and pegmatitic granite. Amphibolite is absent in the fine- to medium-grained metagranitoid.

720–1,000m RU3c: Medium-grained metagranite-granodiorite with subordinate occurrences of pegmatitic granite and fine- to medium-grained metagranitoid. Lower frequency of amphibolite compared to the remaining part of the borehole.

Five possible deformation zones are indicated in KFM05A:

102–114m DZ1: Marked increase of flat-lying, open fractures, with apertures ranging up to more than 1 cm. Two crush zones. Mostly clay minerals, calcite and some fractures filled with fine-grained, clay-dominated material, inferred to be a clastic sedimentary rock.

416–436m DZ2: Increased frequency of mostly sealed, steeply dipping fractures, apertures generally less than 0.5 mm.
590–796m DZ3: Increased frequency of mostly sealed, steeply dipping fractures, with a sharp contact on both sides to a very little fractured bedrock. Two distinctive intervals, 609–616 m and 712–720 m, with dense fracture network and faint to weak oxidation.

892–916m DZ4: Increased frequency of mostly sealed, steeply dipping fractures. Open fractures with apertures less than 1 mm and faint to weak oxidation are concentrated in the lower part of the interval.

936–950m DZ5: Increased frequency of both open and sealed, steeply dipping fractures. Part of the interval shows faint to weak oxidation.

APPENDIX D: Table showing detailed information for borehole KFM05A

Table for borehole KFM05A showing the depth, orientation, type, clarity, distance apart, breakout length and the rock types for each individual breakout occurrence.

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G2: Pegmatite, pegmatit granite
G3: Granite, granodiorite, and tonalite, metamorphic, fine-to medium-grained
G4: Granite to granodiorite, metamorphic, medium-grained
G5: Amphibolite
G6: Felsic to intermediate volcanic, metamorphic
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**APPENDIX E: Dynamic colour presentation for borehole KFM01A with diametrical breakouts.**

Dynamic colour presentation of borehole section from KFM01A showing diametrical breakouts with shallow depth and with a low degree of clarity at 478 to 482mb.
APPENDIX F: Tool wobbling in borehole KFM05A.

Dynamic colour presentation of borehole section from borehole KFM05A showing tool wobbling at 279.35 to 279.95mbl
APPENDIX G: Single breakout in borehole KFM05A

Dynamic colour presentation of borehole section from KFM05A showing single breakouts at 670.50 to 671.15mbl
Dynamic colour presentation of borehole section from KFM05A showing diametrical breakouts at 611.75 to 613.70 mbl