RESEARCH ARTICLE

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Key Points:

- Borehole breakouts develop sporadically and indicate NW-SE maximum horizontal stress orientation aligned along the 2.5 km borehole
- Breakout growth is observed in overlapping logging intervals
- Natural fracture strike orientations are generally aligned with the maximum horizontal stress orientation

Supporting Information:

- Supporting Information S1
- Table S1
- Table S2
- Table S3
- Table S4

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Image log analysis of in situ stress orientation, breakout growth, and natural geologic structures to 2.5 km depth in central Scandinavian Caledonides: Results from the COSC-1 borehole

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Abstract Stress-induced borehole deformation analysis in the Collisional Orogeny in the Scandinavian Caledonide deep scientific borehole establishes in situ stress orientation in a poorly characterized region in central Sweden. Two acoustic televiewer logging campaigns, with more than 1 year between campaigns, provide detailed images along the full length of the 2.5 km deep borehole for breakout, drilling-induced tensile fracture (DITF), and natural occurring structural analysis. Borehole breakouts occur in 13 distinct zones along total length of 22 m, indicating an average maximum horizontal stress, S_{Hmax} , orientation of $127^\circ \pm 12^\circ$. Infrequent DITFs are constrained within one zone from 786 to 787 m depth (S_{Hmax} orientation: $121^\circ \pm 07^\circ$). These S_{Hmax} orientations are in agreement with the general trend in Scandinavia and are in accordance with many mechanisms that generate crustal stress (e.g., ridge push, topographic loading, and mantle driven stresses). The unique acquisition of image logs in two successions allows for analysis of time-dependent borehole deformation, indicating that six breakout zones have crept, both along the borehole axis and radially around the borehole. Strong dynamic moduli measured on core samples and an inferred weak in situ stress anisotropy inhibit the formation of breakouts and DITFs. Natural fracture orientation below 800 m is congruent to extensional or hybrid brittle shear failure along the same trend as the current S_{Hmax} . Analysis of foliation in the image logs reinforces the interpretation that the discontinuous seismic reflectors with fluctuating dip observed in seismic profiles are due to recumbent folding and boudinage.

Plain Language Summary Knowledge of the in situ stress state gives information on dynamic processes, for example, earthquakes within the Earth, and is also applied to various geotechnical drilling and excavation projects. This paper analyzes stress-induced deformation features in image logs that span the length of the 2.5 km deep borehole in Central Scandinavia, to address the subsurface stresses in the region. We identified a stress orientation in the borehole that is oriented parallel to the general trend in Scandinavia. This orientation is compatible with many drivers of stresses including pushing and pulling forces on the sides from the crust, gravitational loading from mountain ranges, and driving below due to flow of the mantle. A unique observation from this study is that some breakouts have grown both along and radially around the borehole wall. Such radial breakout growth around the borehole will affect how the magnitude of subsurface stresses is estimated.

1. Introduction

Deep scientific boreholes present unique opportunities to study stresses in underexplored rock types and crustal regions at intermediate depths between the surface and the seismogenic zone. In summer 2014 the Swedish Scientific Drilling Program, with support from the International Continental Scientific Drilling Program, drilled the first Collisional Orogeny in the Scandinavian Caledonide scientific borehole (COSC-1) near Åre, Sweden [Lorenz et al., 2015]. The 2.5 km borehole penetrates through a seismically reflective limb of the Seve Nappe Complex, an amphibolite grade metamorphic sequence.

One of the primary goals of the COSC-1 wellbore is to establish the stress orientation in the central Jämtland region and address the structural relationships from logs and core. This contribution analyzes wellbore stress indicators, foliation, and natural fractures from ultrasonic televiewer logs to provide a vertical profile of horizontal principal stress orientations to 2.5 km. Analysis of borehole image logs for stress-induced deformation to estimate the orientation of the stress regime has been well developed over the past 30 years [e.g., Schmitt *et al.*, 2012; Tingay *et al.*, 2008; Zoback *et al.*, 2003], which gives information on dynamic processes within the Earth and is also applied to various geotechnical drilling and excavation projects. The use of ultrasonic borehole telev viewers has become one of the principal methods worldwide to identify deformation structures downhole related to in situ stress. Stress-induced deformation structures are the only existing method that shows the semicontinuous variation in orientation of in situ stress; all other methods offer point-wise determinations or constraints on various parts of the in situ stress tensor.

In this assessment of the ultrasonic televiewer logs we analyze stress-induced borehole breakouts and drilling-induced tensile failures (DITFs) to determine the orientation of the horizontal principal stresses. In central Scandinavia, the seismic activity is infrequent and deep boreholes (e.g., >1 km) are rare, leaving few present-day stress indicators in the area. Thus, COSC-1 provides an opportunity to study in situ stresses where few stress orientation and focal mechanism data are available [Heidbach *et al.*, 2008]. The stress orientation observations from COSC-1 are contextualized with respect to tectonic drivers of crustal stresses from the ridge push hypothesis [e.g., Gregersen, 1992; Zoback, 1992], mantle-driven stresses [e.g., Bird and Baumgardner, 1984; Forsyth and Uyeda, 1975], glacial unloading after the last glacial maximum [e.g., Keiding *et al.*, 2015], and gravitational loading due to the influence of topography [e.g., Pascal and Cloetingh, 2009].

Additionally, the COSC-1 borehole remains open with no casing or cementation, allowing for the acquisition of the ultrasonic televiewer logs in two separate campaigns during and after drilling the COSC-1 borehole, which took place over a year apart from each other. In overlapping logged sections we investigate the time-dependent growth of the breakouts. Data sets with overlapping logs separated by extended periods of time are not common in literature [cf. Berard and Cornet, 2003; Moore *et al.*, 2011]; however, observations of breakout growth will have implications on horizontal stress magnitude interpretation [Barton and Zoback, 1988]. Finally, rock strength estimates from laboratory velocity measurements on core samples [Wenning *et al.*, 2016] and relationships to seismicity in the region to provide constraints on the nature of borehole breakouts in high-grade metamorphic rocks. The observed orientation of in situ stresses is framed in a structural context by using foliation and natural fracture analysis from the image logs.

2. Geologic Setting

The mid-Paleozoic Caledonian orogeny is preserved in present-day Scandinavia, Greenland, and Scotland [Gee *et al.*, 1985]. The Scandinavian Caledonide thrust sheets, which formed during the closure of the Iapetus Ocean and subsequent underthrusting of Baltica beneath Laurentia, are divided into four parts (Figures 1a and 1b): Lower, Middle, Upper, and Uppermost Allochthons [Gee *et al.*, 1985]. The COSC-1 borehole penetrates the amphibolite grade Lower Seve Nappe Complex of the Middle Allochthon, located near Åreskutan mountain in Central Jämtland, Sweden (lat: 63.401629°, long: 013.202926°). The topography is highest northwest of the drill site at Åreskutan mountain (1420 m) and slopes down to 523 m at the COSC drill site [Lorenz *et al.*, 2015], which is located on the eastern flank of the mountain ~4 km from the peak (Figure 1b). The proximal topography reaches a low of ~370 m in the nearby Indalsälven river valley. The borehole location was placed along the site investigation 2-D reflection seismic profile [Hedin *et al.*, 2012], and subsequent 3-D seismic investigations (see 2-D subsection in Figure 1c) around the borehole have produced detailed subsurface reflectivity images [Hedin *et al.*, 2016].

The Middle and Lower Seve Nappes display an inverted metamorphic gradient, where the base consists of greenschist to amphibolite meta-sedimentary and meta-igneous rocks [Gee *et al.*, 2010]. Metamorphic grade increases from the lower to middle part of the nappe into granulite and locally eclogite in Central Jämtland. A detailed core description of COSC-1 is reported in Lorenz *et al.* [2015]. In the upper 1700 m, the borehole penetrates a succession dominated by felsic and calc-silicate gneisses, amphibolites, and metagabbros with sporadic marble, pegmatite dykes, and microkarst. Ductile deformation is pervasive in the same interval and develops a continuous foliation within all rock types. At depth of ~1700 m, layers of mica-rich mylonites

Figure 1. (a) Regional geologic map in the vicinity of the COSC-1 wellbore (after Strömberg *et al.* [1984]). (b) Enlarged geologic map showing the extent of the seismic profile line in "c" (after Strömberg *et al.* [1984]). (c) Seismic cross section (inline 1045) near the COSC-1 borehole (after Hedin *et al.* [2016]).

appear, indicating signs of increasing strain with depth. The occurrence and thickness of the mica-rich mylonites, which are often garnet-bearing, increase between 1900 and 2000 m, and eventually, mylonites become the most abundant lithology below 2100 m. At the base of the well, mylonites transition into lower grade meta-sedimentary rocks with white mica and chlorite, as well as meta-sandstones.

3. Stress Setting

The COSC-1 borehole is located in an area where few stress indicators are available. Figure 2 shows the location of the COSC-1 well in relation to other stress indicators from the World Stress Map (WSM) in Scandinavia [Heidbach *et al.*, 2008]. While the North Sea has a plethora of stress indicators due to extensive oil and gas exploration, drilling, and production, the coverage in continental Scandinavia is significantly sparser. A general NW-SE maximum horizontal stress S_{Hmax} orientation is the prevailing trend across most of on- and offshore Scandinavia.

Figure 2. Map depicting the location of the COSC-1 borehole with respect to (a) generalized tectonostratigraphic map of the Scandinavian Caledonides (after Gee *et al.* [2010]) with the location of the COSC-1 borehole, locations of the Gravberg-1 and Stenberg-1 deep boreholes [Lund and Zoback, 1999], stress indicators from the WSM (after Heidbach *et al.* [2008]), and location of seismic activity in Scandinavia including a recent 4.1 event near the COSC-1 borehole [FENCAT, 2011]. Earthquake events are between magnitudes 1.3 and 5.9. Active topographic fault scarps in Scandinavia are displayed in brown [Mikko *et al.*, 2015].

This first-order NW-SE trend has been attributed to “ridge push” from spreading at the Mid-Atlantic Ridge [Gregersen, 1992; Richardson, 1992; Zoback, 1992]. In one of the few studies on deep scientific boreholes in continental Scandinavia, Lund and Zoback [1999] found S_{Hmax} -oriented NW-SE in two ~6 km deep wells ($288^\circ \pm 7^\circ$ in Gravberg-1 and $307^\circ \pm 9^\circ$ in Stenberg-1) drilled in the Siljan Ring area of the Baltic Shield located 300 km toward the south of COSC-1. The authors show that local variations in stress orientation in both deep wells occur along the borehole due to faulting. Lindblom [2011] shows that principal stress orientation

changes along the lateral length of a fault from analysis of focal mechanism observed in northern Sweden. Local changes in stress orientation in southern Sweden from the prevailing NW-SE trend to an NE-SW trend have also been attributed to regional horst and graben extension structures [Stephansson and Ångman, 1986]. Additionally, changes in borehole stress orientation can be attributed to anisotropy in formation and angle of layering [Amadei, 1996; Bruno and Winterstein, 1994; Lee et al., 2013].

Central Jämtland is situated in a relatively quiet seismic setting. Figure 2 shows the location of the COSC-1 borehole with respect to seismic activity monitored via the FENCAT catalogue from 1965 to 2013 [e.g., FENCAT, 2011]. The earthquake events shown in Figure 2 range from magnitude 1.3 to 5.9, with most being less than 3.0. Earthquake activity in this intracontinental interior setting is low, especially in the Swedish Caledonides (Figure 2). However, a magnitude 4.1 oblique strike-slip earthquake (strike: 040°, dip: 69°, rake: −160°), consistent with regional S_{Hmax} orientations, occurred in September 2014 about 250 km to the south of the drill site near the town of Lillhärdal (61.668°N, 14.362°E) according to the Swedish National Seismic Network. In addition to the seismicity, majority of active postglacial fault scarps in northern Scandinavia have a prevailing NNE-SSW trend (Figure 2). These NNE-SSW fault scarps are oriented subperpendicular to the regional NW-SE S_{Hmax} direction, which produce reverse or transpressional faults [Lindblom, 2011; Slunga, 1991]. Stress inversion from earthquake fault plane solutions on these faults has shown local variation of S_{Hmax} orientation from E-W to NNW-SSE [Lindblom, 2011; Slunga, 1991].

The location of the COSC-1 well in Central Jämtland provides the first analysis of the orientation of in situ stress at depth in the region. Stress magnitude estimates are not the scope of this study.

4. Stress Orientation Analysis Methods

4.1. Theory

Coupling modern borehole imaging techniques with mathematically known derivations of stress concentrations around boreholes allow for the determination of stress orientation (see reviews: Moos and Zoback [1990], Schmitt et al. [2012], and Zoback et al. [2003]). When material is removed during drilling, stress concentrations are redistributed around the void. Determining stress concentrations around a borehole in the simplest 2-D case follows the [Kirsch, 1898] solution for a cylindrical hole that maintains equilibrium by redistributing the stresses in the surrounding rock along a horizontal plane when subjected to “far-field” stress. Anisotropy in the far-field stress results in anisotropy in the tangential stress concentration at the wellbore, with highest and lowest tangential stress concentrations in the direction parallel with the minimum far-field stress and parallel with the maximum far-field stress, respectively. Compressional failure around the borehole is expected along the minimum far-field stress direction if the stress concentrations around the borehole are greater than the mechanical strength of the rock [Bell and Gough, 1979]. Two types of stress-induced borehole failure are commonly observed by using standard borehole imaging tools (Figure 3): borehole breakouts and drilling-induced tensile failures (DITFs).

In the case of a vertical well where the stress regime is stable with depth and one principal stress is vertical, borehole breakouts will form as enlargements of the wellbore cross section on diametrically opposite sides of the well where the local compressional stress at the borehole wall is at a local maximum and exceeds the compressive strength of the rock [Zoback et al., 1985]. In ultrasonic acoustic televiewer logs, borehole breakouts are distinguished by diametrically occurring longer travel times on transit-time logs and low amplitude zones in the amplitude logs because both return signals are attenuated by the broken borehole wall [e.g., Loftis and Bourke, 1999].

Tensile failure in the wellbore may develop during drilling where the local stress concentrations around the borehole exceed the tensile strength of the rock [Aadnoy, 1990], which is aided by a large temperature difference between the surrounding rock mass and the drilling fluid [Brudy and Zoback, 1999]. In this case, the magnitude of induced thermal stresses may be sufficient to produce tensile failure in the direction of maximum horizontal far-field stress, where the tangential stress concentration is smallest around the borehole wall. Two types of DITF form in the wellbore [e.g., Valley and Evans, 2009]: (1) axial DITFs (referred to as A-DITFs), which form diametrical pairs of fractures along the borehole axis if the borehole is drilled parallel with one principal stress direction [e.g., Aadnoy and Bell, 1998]. They typically form as thin fractures and display sharp contrast with the surrounding formation. A-DITFs are best visualized in the amplitude

Figure 3. Example stress indicators from COSC-1 with amplitude image on the left and interpretation on the right of each. (a) Breakout from logging campaign 2 (October 2015). (b) Logging campaign 1 (July 2014) A-DITF example. (c) Logging campaign 1 E-DITF example bounded by two foliation parallel fracture planes (FPs).

log as diametrical thin vertical low amplitude signals. (2) En-echelon DITFs (referred to as E-DITFs), which form more complex stacks of en-echelon fractures if the principal stresses are oriented oblique to the borehole axes [e.g., Zoback *et al.*, 2003]. E-DITFs can appear similar to stacks of parallel natural fractures; however, there is a tendency for E-DITFs to have a weak trace along the crests of each “sinusoid”, while natural fractures are often strongly defined near the crest [Valley and Evans, 2009].

Petal-centerline fractures (PCFs) form due to complex stress concentrations ahead of the drill bit due to the weight of the bit, mud weight, and removal of rock mass [e.g., Davatzes and Hickman, 2010; Li and Schmitt, 1998; Massiot *et al.*, 2015]. PCFs are characterized by curved chevrons, with the tips merging with diametrical pairs of axial parallel centerline fractures, and are observable in both core and image logs. Clear development of PCFs in image log and core is not observed in the COSC-1 borehole.

4.2. Image Log Acquisition and Analysis

The COSC-1 borehole was logged by using acoustic borehole televewers during pauses in drilling and immediately after drilling in June and July 2014 and again in a second campaign in October 2015 (Table 1). The borehole was drilled with 5 to 15°C drilling fluid, and subsequent logging has indicated that the formation temperature at the base of the borehole is ~55°C [Lorenz *et al.*, 2015]. Image logs in COSC-1 from 2014 were acquired by using a Robertson Geologging High Resolution Acoustic Televewer (HRAT). Measurements were made by using a single tool string consisting of only the HRAT sonde from the base of the casing at 105 to 1605 m. The logging tool is limited to 1605 m due to

Table 1. Logs Acquired in This Study

Logging Expedition	Date	Depth Range (m)	Logging Tool	Resolution Radial/Vertical (mm)
Campaign 1	June–July 2014	105–1605	Robertson Geologging-HRAT	1/2
Campaign 2	October 2015	103–2485	Mount Sopris and ALT-QL43 ABI	4/3

temporary casing being installed in the deeper borehole section. Throughout the logged interval the well was drilled with HQ3 diamond impregnated drill bits, 96 mm diameter [Lorenz *et al.*, 2015], well within the range of optimum functionality of the HRAT sonde [Ask *et al.*, 2014]. The second campaign furthered the interpretation depth by logging a section from 103 to 2485 m with a Mount Sopris and Advanced Logic Technology (ALT) QL43 Acoustic Borehole Imager (ABI) tool (total depth of the borehole is 2496 m). From 1616 m to the total depth of the borehole was drilled by using N-size (76 mm hole diameter). Using logging retrieval speed, as well as the rotational speed and firing rate of the ultrasonic transducer, the radial and vertical resolutions for campaigns 1 and 2 are approximately 2 mm² and 12 mm², respectively (Table 1).

Borehole breakouts, DITFs, foliation, and natural fractures are analyzed from the image logs by using WellCAD version 5.0. Before interpreting the image logs, a thorough review of the logs for quality assessment was performed. *Lofts and Bourke* [1999] describe various artifacts in borehole image data that can hinder analysis. The most common artifacts in the campaign 1 HRAT travel time and amplitude image logs are tool decentralization and stuck/sticking zones caused by stick-slip movement of the tool in the borehole. Decentralization occurred even though tool centralizers were used during logging. The decentralization is most pronounced in the travel time logs, which are mitigated by using the WellCAD centralization function. The amplitude logs did not require centralizing.

A similar quality assessment of the second logging campaign revealed that the logs spanning the deeper section of the well have increased logging artifacts. Again, the most common artifacts are tool decentralization and stuck/sticking zones. Centralization of the travel time and amplitude logs produced a moderate “woodgrain” effect in the images. Additionally, a revolving low-amplitude streak (~10° radial width) trends along the image log throughout the section. Breakout is still clearly observed in overlapping sections with campaign 1 logs, so there is little doubt in the clarity of these features. For steeply dipping (>75°) natural fractures, the limb of the fracture sinusoid often disappears from trough to crest due to the logging artifacts, making vertical fractures difficult to identify and trace.

Stress-induced wellbore failures, foliation, and natural fractures are interactively identified from the logs in WellCAD. It should be noted that the breakout and DITF interpretation criteria are defined for the COSC-1 borehole, but it is clear that breakout and DITF development (i.e., length and frequency) vary from borehole to borehole [cf. *Valley and Evans*, 2009; *Moore et al.*, 2011]. For the interpretation of the acoustic televiewer logs, we followed the criteria that a breakout trend (Figure 3a) must be >0.4 m in total length and display diametrical low amplitude reflections and/or long travel times that are separated by 180° at the same depth interval. Variations in individual breakouts are discretized into intermittent individual elements within the overall trend based on their observed characteristics. A-DITFs (Figure 3b) appear as vertical hairline low-amplitude trends with a diametrical conjugate separated by 180°. Individual A-DITFs must be >20 cm in length or be in a trend of individual A-DITFs of >0.5 m. In addition, core scans help distinguish possible A-DITFs from near vertical fractures in the core. Zones of E-DITFs (Figure 3c) are recorded by fitting a sinusoid through the parallel en-echelon fracture sets.

In general stress-induced features, breakouts and DITF are infrequent in the COSC-1 borehole. When occurring near potential natural structures, breakout observations are less ambiguous compared to DITF, since breakouts are easily distinguished from fractures or veins due to their characteristic shape. However, when drilling-induced fractures are in the vicinity of previously existing natural fractures, the identification characteristics between the two can be equivocal, especially when cores depict near vertical or steeply dipping natural fractures or in zones where the core is heterogeneously fractured. In performing the analysis, core scans were cross checked with the fractures to see if the fracture was observed in the core, and if so, it was omitted from the stress orientation assessment. Moreover, the suspect DITFs are few in number. In the rare event that a fracture had characteristics of DITF the reasons for omission were the following: (1) image

Table 2. Sample List of Laboratory Velocity Measurements, Where the International Geo Sample Number (IGSN) Is Specified For Each Sample With Corresponding Depth and Rock Type [Wenning *et al.*, 2016]

Sample	Depth (m)	IGSN	Rock Type
C193-2	659.8	ICDP5054EXL6601	Amphibolite
C243-2	729.5	ICDP5054EXN6601	Calc-silicate gneiss
C487-1	1492.6	ICDP5054EXS6601	Felsic gneiss
C556-2	1691.9	ICDP5054EXU6601	Amphibolite
C631-1	2100.4	ICDP5054EXY6601	Amphibole-rich gneiss
C691-1	2460.3	ICDP5054EX27601	Garnet-bearing micaschist (mylonitic)

log and core scan indicate similar features at the same depth interval and (2) chaotic fracture pattern near foliation changes or natural fractures did not develop a clear depiction of stress orientation. Thus, the results depict the most confident breakout and DITF picks.

The image logs are oriented to magnetic north, but the orientation measurements of the stress indicators, foliation, and natural fractures have been converted to true north by using the magnetic declination at the time of logging (004°E). Mean preferred orientation and standard deviation of breakouts and DITFs are calculated by using circular statistics for bimodal data [Mardia, 1972].

4.3. Elastic Moduli From Core Samples

Understanding the elastic and mechanical properties of rocks is of fundamental importance when addressing stress state in the subsurface, especially in borehole stability analysis [Zoback, 2007], where anisotropy plays an important role [Amadei, 1996; Bruno and Winterstein, 1994; Vernik and Zoback, 1990]. Laboratory measurements of P and S wave seismic properties at ultrasonic frequency were conducted under increasing hydrostatic confinement on samples from the most common lithologies encountered in the COSC-1 borehole (Table 2) [Wenning *et al.*, 2016]. These measurements were performed along the three main structural directions (parallel to lineation and foliation and perpendicular to foliation), and they constrain the anisotropic seismic properties of the most common lithologies: amphibolite, felsic gneiss, calc-silicate gneiss, amphibole-rich gneiss, and mylonitic micaschist (i.e., phyllonite). A simplified lithology log (Figure 4a) depicts the occurrence of mafic, felsic, gneiss with increasing amounts of micaschist, and mylonites toward the bottom of the borehole. The dynamic elastic moduli are calculated from velocity measurements at 40 and 70 MPa, which roughly correlate to the vertical stress magnitude in the middle and at the base of the borehole based on integration of the core density log. The P and S wave moduli are represented in the general form as $c_{xx} = \rho * V_{p/s}^2$. Thus, the P wave moduli are calculated from the corresponding sample density (ρ) and P wave velocity (V_p) for the parallel to foliation and lineation (c_{11}) and perpendicular to foliation (c_{33}) experiments. Similarly, the S wave moduli, known as the shear modulus, calculated by using the density and S wave velocity (V_s) in the foliation perpendicular (μ_3) and maximum foliation parallel (μ_1) samples, are represented by c_{44} and c_{66} , respectively. The elastic moduli are estimated by applying the isotropic equations to the parallel and perpendicular components separately in order to estimate the P and S wave moduli [Mavko *et al.*, 2009]. In the absence of a measurement with a sample oriented 45° from the others, due to borehole sample dimension limitations, the use of independent isotropic equations does not follow the precise derivation for a vertically transverse isotropic medium. However, Sone and Zoback [2013] show the error in this estimation to be negligible. The dynamic Young's moduli are approximated for the foliation parallel (E_1) and foliation perpendicular (E_3) components by using the following equations:

$$E_1 = \frac{c_{66}(3c_{11} - 4c_{66})}{(c_{11} - c_{66})}$$

$$E_3 = \frac{c_{44}(3c_{33} - 4c_{44})}{(c_{33} - c_{44})}$$

Figure 4. Borehole logs, stereographic projections, and rose diagrams of breakouts, A-DITF, foliation, and fractures. (a) Lithology log (after Hedin et al. [2016]). (b) Breakout (red with black bars indicating breakout width) and A-DITF (green) occurrence along the borehole. (c) Azimuth and (d) dip of measured foliation sinusoids in the image logs. (e) Azimuth and (f) dip of the measured natural fracture sinusoids in the image logs. (g) Rose diagram of the orientation of the breakouts. The arrows indicate the S_{Hmin} direction parallel to breakout orientation with S_{Hmax} perpendicular to the breakout direction. (h) Lower hemisphere Schmidt equal area projection of the poles to the foliation planes (black circles) with Kamb contours. The diamond markers show pole maxima of the two high-density clusters from contouring. The planes from the poles of the two high-density colors depict the primary shallow (0–500 m) and deep (500–2500 m) foliation trends (Stereonet 9 software [Allmendinger, 2014]). (i) Lower hemisphere Schmidt equal area projection of the poles (black circles) to the natural fracture planes with Kamb contours. (j) Rose diagram of the orientation of the natural fractures.

The dynamic Poisson's ratio for the foliation parallel (v_1) and foliation perpendicular (v_3) sample is calculated by using the isotropic equation:

$$v_{1,3} = \frac{1}{2} \frac{(V_p/V_s)^2 - 2}{(V_p/V_s)^2 - 1}$$

The dynamic bulk modulus for the foliation parallel (K_1) and foliation perpendicular (K_3) sample is calculated by using the isotropic equation:

$$K_{1,3} = \rho \left(V_p^2 - \frac{4}{3} V_s^2 \right)$$

5. Results

5.1. Breakouts

The interactive breakout analysis produced a total of 50 orientation measurements (Table 3). The longest breakout or DITF trend has been assessed in this analysis, which typically is a result of the image logs from campaign 2. However, some picks utilize the campaign 1 logs because of visualization clarity from these higher quality logs (see individual picks in Data S1 in the supporting information). The breakout trends are typically composed of individual breakouts that form approximately 0.1 to 1.0 m along the borehole axis (e.g., Figure 3a). The total length is reported as the sum of the depth intervals where breakouts occur. The cumulative length of the borehole breakouts is 22 m, which is ~1% of the total borehole length. Breakouts occur in 13 distinct zones throughout the borehole (Figure 4b), which form intermittently from ~600 to 2200 m depth. Breakouts develop where the tangential stress concentration around the borehole is at a maximum, which is aligned with the minimum principal horizontal stress (S_{hmin}) [e.g., Zoback *et al.*, 1985]. In order to be consistent when discussing stress regimes and maximum stress directions, we report the inferred S_{Hmax} direction from breakouts, which is assumed to be perpendicular to the breakout orientation (Figure 4g). The orientation analysis of the stress-induced deformation features in the COSC-1 borehole yields an S_{hmin} orientation of $37^\circ \pm 12^\circ$ (true north), corresponding to an inferred S_{Hmax} orientation of $127^\circ \pm 12^\circ$.

5.2. Time-Dependent Evolution of Borehole Breakouts

In the depth range of overlapping logged sections (105 to 1605 m) six breakout zones overlap and four show appreciable width growth during the time window of over a year between logging runs, but new breakout sections have not formed (Table 4). The growth in breakout width is assessed by comparing the maximum extent of breakout width from a given depth interval in campaign 1 with the maximum breakout width in campaign 2. In addition to growth in breakout width, elongation along the axis of the borehole can also be significant (Figure 5) but stays within ~1 m of the previously formed breakout. Growth along the axis of the borehole is observed except for the breakout growth zone 5. The axial growth can either directly stem from a previously formed breakout or form as an individual component nearby (within ~1 m) the extent of the original breakout. The growth stemming from individual breakout trends does not elongate more than 20 cm from the original breakouts. The width of the newly formed borehole breakouts remains closely within the maximum bounds of the previously formed breakout, but this is not always the case (Table 4). Breakout width growth of up to $20^\circ \pm 3^\circ$ is observed in some instances (e.g., Figure 5), which will influence S_{Hmax} magnitude estimation depending on rock strength and S_{hmin} magnitude [Barton and Zoback, 1988].

5.3. Drilling-Induced Tensile Fractures

Separate analysis of both A-DITFs and E-DITFs indicates that drilling-induced fracturing of the borehole wall is markedly infrequent. The interactive image log analysis produced only one distinct diametrical set of A-DITFs and E-DITFs, respectively. The A-DITF pair occurred along 1 m with an orientation of $121^\circ \pm 07^\circ$ (Figure 4b and Table 3). In a few cases, axial fractures appear on the image logs where core scans indicate the presence of natural fractures or filled veins. These fractures are not considered to be formed due to stresses during drilling. The E-DITFs shown in Figure 3c are the only set observed in COSC-1. Sinusoidal fits to the fracture pattern measure a mean strike of approximately 26° , which is almost perpendicular to the A-DITF orientation. We do not consider the E-DITFs to be reliable stress indicators due to their infrequency and ambiguity in formation mechanism and because they appear to be bounded by two potential natural fractures (Figure 3c), which likely perturbs the stress field locally.

5.4. Foliation and Natural Fractures

Foliation strike and dips were selected every few meters where differences in amplitude between layering marked clear lithological contacts (e.g., Figures 3c and 5). The foliation is parallel to the lithological contacts due to the highly strained nature of rocks in the COSC-1 borehole. A foliation analysis has been reported by Wenning *et al.* [2016]; here it is extended beyond 1600 m depth with the logs from the second campaign in October 2015. Both foliation and fracture planes are measured by fitting a sinusoid to the unwrapped image

Table 3. Results From Image Log Analysis

Stress Indicator	Count	Number of Distinct Zones	Combined Length	S_{Hmax} Orientation (True North)	WSM Quality Ranking	Coverage Percent of SIs
Breakouts	50	13	22 m	$127^\circ \pm 12^\circ$	C	~1%
A-DITF	2	1	1 m	$121^\circ \pm 07^\circ$	E	<1%

log, and the dip azimuth is corrected for borehole diameter and to represent orientation with respect to true north. Much like an outcrop, not every single layer is measured as many of the layers within a few meters have the same or similar dip direction and dips. However, in some zones the strike and dip of the foliation varied markedly within a narrow depth window. In these zones multiple foliation measurements were made. A total of 1074 foliation measurements were acquired from combined analysis of the image logs. Figures 4c and 4d show the dip direction and dip of the beds along the borehole. Above 500 m the dip direction is centered around 270° with shallow dips $\sim 30^\circ$. This corresponds to the cluster of poles in the NE quadrant of the stereographic projection (Figure 4h), where the diamond marker shows that the pole center and the best fit plane (0–500 m) are dipping to the SW. Below 500 m the foliation alternates with one cluster between 0 and 90° and one between 180 and 360° . A cluster of poles in the SW quadrant of the stereographic projection (Figure 4h) has a best fit plane (500–2500 m) dipping to the NE.

Natural fractures are observed as low-amplitude planes that are especially clear when they crosscut an observed foliation plane. It is worth mentioning that foliation parallel fractures are observed in the core and there are intervals with very low amplitude sinusoids following the foliation trend. However, these foliation parallel fractures are not part of this fracture analysis due to ambiguity in distinguishing between low-amplitude foliation planes and low-amplitude foliation parallel fractures. Additionally, the foliation parallel fractures are also not likely to be indicative of the far-field stresses as their formation mechanism is different than cross-cutting fractures (i.e., flexural slip along foliation parallel fractures versus mode I/II for cross cutting fractures). A total of 249 fractures were identified in the image logs (Figures 4e and 4f). The orientation of the fractures is sporadic until ~ 800 m. Below ~ 800 m the orientation of the fractures becomes concentrated along a dip direction of $\sim 45^\circ$ with some falling outside this trend. The stereographic projection (Figure 4i) and the rose diagram (Figure 4j) show a distinct concentration of fractures with an NW-SE strike orientation.

5.5. Dynamic Elastic Moduli

Dynamic elastic moduli calculated from measured velocities and densities are summarized in Table 5. The seismic velocities measured on the samples, especially the sample perpendicular to foliation, are in agreement with sonic logs and the seismic velocity model used in the reflection seismic profiles [cf. Hedin *et al.*,

Table 4. Maximum Breakout Width (w_{BO}) and Change in Breakout Width in Breakout Zones in Overlapping Logged Sections From Campaigns 1 and 2^a

Zone	Depth (m)	Campaign 1 w_{BO} (deg)	Campaign 2 w_{BO} (deg)	Δw_{BO} (deg)	Axial Growth	Rock Type and Breakout Observation
1	612–616	63	64	1	Yes	Calc-silicate gneiss with intermittent micaceous layers. Breakouts in unfractured rock.
2	794–796	31	51	20	Yes	Fine-grained mafic gneiss with more developed foliation in the less mafic parts. Breakouts in unfractured rock.
3	850–853	52	62	10	Yes	Banded mafic and felsic gneisses with deformed quartz lenses and calcite veins. Breakouts in homogenous rock and associated with filled fractures in the core.
4	1177–1178	53	54	1	Yes	Mainly felsic gneisses with cm thick mafic bands. Breakouts correspond to the transition between two core runs where cores fracture parallel to foliation.
5	1538–1539	67	74	7	No	Alternating bands of felsic gneiss and mafic layers. High-amplitude breakouts occur in a mica-rich layer bounded by a fracture at the top of the unit.
6	1598–1599	28	37	9	Yes	Thin alternating quartz rich, calc-silicate, micaceous and mafic layers. Shallowest breakout occurs in between foliation parallel fracture planes. Other couplets in homogeneous rock.

^aThe interpretation error in w_{BO} can be approximated to be $\pm 2^\circ$; therefore, following classical error propagation, the change in breakout (Δw_{BO}) error is $\pm 3^\circ$.

Figure 5. Example of breakout growth with amplitude image on the left and interpretation on the right of each. (a) Breakout from logging campaign 1 in July 2014. (b) Breakout from logging campaign 2 in October 2015. Breakout growth is observed at the same depth level as Figure 5a and deflected growth at the foliation plane (labeled FP).

2016; Hedin *et al.*, 2012; Wenning *et al.*, 2016]. A range of moduli magnitude is reported where the 40 MPa confining pressure measurement represents the middle of the borehole and the base of the borehole is given by the 70 MPa confining pressure measurement. The foliation parallel x_1 and foliation perpendicular x_3 moduli are upper and lower bounds for each anisotropic sample. Figures 6a–6d summarize x_1 – x_3 anisotropy of the S wave (shear) modulus, Young's modulus, bulk modulus, and Poisson's ratio. The plot shows the mean modulus values with bars depicting the range of values reported in Table 5. The elastic moduli μ_{dyn} , E_{dyn} , and K_{dyn} are always greater in the x_1 direction and in some cases $x_3 \geq 0.75 * x_1$. The amphibolite (C193-2 and C556-2) and amphibole-rich gneiss (C631-1) samples are elastically the strongest, although minor variations occur between each elastic modulus. While the amphibole-rich samples are the strongest in this data set, the gneiss and micaschist samples are still comparatively strong with respect to noncrystalline rocks [cf. Chang *et al.*, 2006]. Poisson's ratio measured along x_1 and x_3 scatters around the 1:1 correlation.

6. Discussion

6.1. Orientation of In Situ Stress

The COSC-1 well is drilled nearly vertical permitting the use of borehole breakouts and A-DITFs as direct indicators of the in situ principal horizontal stress. The total deviation of the wellbore is $\sim 2^\circ$ from the surface to the base of the 2496 m borehole [Lorenz *et al.*, 2015]. The breakout and A-DITF analysis produced a limited number of stress indicators from the COSC-1 wellbore (Table 3). Even though the number and length of stress indicators are small in the COSC-1 wellbore, the orientation of the breakouts (Figure 4g) shows a preferred orientation along the borehole signaling a mean inferred S_{Hmax} orientation of $127^\circ \pm 12^\circ$. The A-DITF pair also suggests a similar S_{Hmax} orientation of $121^\circ \pm 07^\circ$.

Table 5. Dynamic Elastic Modulus Results From Laboratory Testing^a

Sample	Shear Modulus (GPa)		Young's Modulus (GPa)		Bulk Modulus (GPa)		Poisson's Ratio	
	μ_1	μ_3	E_1	E_3	K_1	K_3	ν_1	ν_3
C193-2	56–57	52–52	136–140	120–122	81–85	60–63	0.22–0.22	0.17–0.18
C243-2	37–39	36–37	92–96	89–92	56–60	56–60	0.22–0.23	0.23–0.24
C487-1	34–37	31–34	84–93	76–84	54–63	48–55	0.24–0.25	0.23–0.25
C556-2	53–56	44–48	127–135	95–109	71–79	37–49	0.20–0.21	0.07–0.13
C631-1	47–54	36–37	107–126	81–92	48–63	36–58	0.13–0.17	0.13–0.24
C691-1	46–47	32–33	106–111	77–79	52–58	42–44	0.16–0.18	0.20–0.20

^aIn the range of values, the lower value comes from the 40 MPa confining pressure measurement and the higher value represents the 70 MPa confining pressure measurement.

Figure 6. Dynamic moduli measured from core samples parallel to the foliation plane (x_1) and perpendicular (x_3). Correlation lines of 1:1, $x_3 = 0.75 * x_1$, and $x_3 = 0.5 * x_1$ depicted in black. (a) Shear modulus (μ), (b) Young's modulus (E), (c) bulk modulus (K), and (d) Poisson's ratio (ν). The markers show the mean x_1 and x_3 values from the 40 to 70 MPa confining pressure measurements. The black bars indicate the range between 40 and 70 MPa confining pressure measurements in Table 5.

The WSM quality assessment for stress indicators [Tingay *et al.*, 2008] is applied individually to both borehole breakouts and A-DITFs (Table 3). The borehole breakouts form in 13 distinct zones with a low standard deviation but occur only over a total length of 22 m. The limited combined length of the borehole breakouts reduces the quality ranking to "C". The complementary A-DITFs rank "E" (unreliable) because they occur as only one distinct zone with a total length of approximately 1 m. Even though the poorer quality of the data in the deeper part of the borehole might hinder the detection of A-DITFs, we think that their paucity is a function of the environmental conditions in the borehole. Although the combined length of the borehole breakouts is restricted, the distinct zones form sporadically over a more than 1.5 km depth range in the borehole (Figure 4b), giving confidence that the inferred horizontal stress directions are consistent with depth. We note that in previous WSM ranking schemes [Zoback, 1992], which establish the quality ranking on the basis of occurrences along the borehole and length and/or low standard deviation of measurements, the low standard deviation in breakout orientation and distribution of breakouts along the COSC-1 borehole would result in a higher quality ranking.

The S_{Hmax} inferred from borehole breakouts and A-DITFs in the COSC-1 borehole are aligned with the regional NW-SE S_{Hmax} trend observed from boreholes, overcoring, and focal mechanisms across on- and offshore Scandinavia (Figure 2a). The borehole is drilled in a mountainous area, near the local topographic high at Åreskutan Mountain (1420 m), and even though local topography is known to cause stress perturbations in the subsurface, this is typically reserved for the upper few hundred meters [Hergert *et al.*, 2015]. Therefore, local topographic effects are probably minimal at the depth of breakout occurrence. The results from the COSC-1 well are also in good agreement with the prevailing trend in two ~6 km deep boreholes drilled near Siljan in central Sweden [Lund and Zoback, 1999].

Since COSC-1 is nearly vertical, if the vertical stress is a principal stress, breakouts and DITFs should be preferably aligned with the borehole axis, and deviations of these stress-induced structures from vertical traces indicate that the principal stress is not vertical [Brudy and Zoback, 1993]. Local perturbations in the stress

field have been observed to rotate breakouts [Barton and Zoback, 1994; Lund and Zoback, 1999; Shamir and Zoback, 1992] and incline drilling-induced fractures forming E-DITFs [Brudy and Zoback, 1999; Brudy et al., 1997] that are attributed to faults that crosscut the borehole. Additionally, planar anisotropy and anisotropic rock properties can have pronounced influence on borehole stress orientation [Amadei, 1996; Bruno and Winterstein, 1994; Vernik and Zoback, 1990].

While most borehole breakouts and DITFs in COSC-1 follow axial traces along the borehole and display characteristic trend and shape of isotropic breakouts consistent with the NW-SE S_{Hmax} , the influence of foliation or fault angle locally perturbs the stress field around both breakouts and E-DITF formation. Figures 5a and 5b show an example of breakout that occurs across a dipping lithological contact (labeled FP for foliation plane) at ~795.2 m. The breakout orientation is deflected approximately 30° to the east just below the contact and returns to the initial orientation within ~0.2 m of the foliation plane. The rotation of breakouts near the observed discontinuity is consistent with previous observations of breakout rotations associated with faulting [Barton and Zoback, 1994; Lund and Zoback, 1999; Shamir and Zoback, 1992] and rotation due to dipping lithological contacts [Bruno and Winterstein, 1994]. In this case, there is no clear indicator that slip has occurred along this dipping lithological contact. Stress orientation analysis from E-DITFs is more difficult to interpret [Valley and Evans, 2009] due to complexities in their formation. However, the en-echelon pattern of fractures wedged between two foliation planes depicted in Figure 3c provides further evidence that the foliation or fault angle with respect to the borehole can cause the principal stresses to rotate from near vertical to inclined around dipping layers. The dipping planes that bound the E-DITF display much lower amplitude when compared to similar foliation trends in the vicinity. Therefore, these are interpreted as fault planes striking NNE-SSE, which are pseudoperpendicular and preferentially oriented for slip to the general NW-SE S_{Hmax} orientation. Similar types of en-echelon fracture pattern have been attributed to rotation of the principal stresses around faults in the German KTB (Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland) and the European geothermal research project at Soultz-sous-Forêts, France [Brudy and Zoback, 1999; Brudy et al., 1997]. The strike of the E-DITF sinusoids at 026° is perpendicular to the A-DITF direction and the S_{Hmax} direction observed from borehole breakouts. The E-DITFs could potentially be formed as shear failure, which could explain the mismatch in orientation with respect to the A-DITF. However, with just one set of each structure we cannot reach definitive conclusions. In COSC-1 the rotation of the stress orientation appears to be localized and the overall breakout orientation remains consistent with depth, having a low standard deviation. Local deflection of the stress orientation in COSC-1 is minimal (<30°), when compared to the fault-related rotation (>45° rotation) near Siljan crater in Central Sweden [Lund and Zoback, 1999] and postglacial faults (~90° rotation) in northern Sweden [Lindblom, 2011]. These observations corroborate the importance of careful interpretation of breakout or DITF formation in and around pre-existing structures and across changes in lithology.

6.2. Sources of Stress in Scandinavia

Analysis of the stress-induced deformation features in the COSC-1 borehole yields an inferred S_{Hmax} orientation of $127^\circ \pm 12^\circ$. Most of the stress data in Scandinavia come from earthquake focal mechanisms, borehole breakouts, hydraulic fracturing, and overcoring and are located offshore in the Atlantic passive margin or in the Precambrian basement, mainly in the northern and southern parts of the Baltic Shield (Figure 2). Our new measurement provides a coherent orientation of the state of stress in the upper 2.5 km of the crust and fills an existing gap in Central Sweden and in the Caledonian nappes.

The WSM database suggests a first-order control of the intraplate stress pattern from boundary forces that drive plate motion with an additional second order on shorter wavelength being influenced by flexure and density contrasts in the lithosphere [Heidbach et al., 2010; Zoback, 1992]. In that regard, Scandinavia offers a complex setting where mechanisms such as ridge push, isostatic compensation from deglaciation, and topography may interact to influence the present-day stress pattern.

The NW-SE maximum horizontal stress orientation found in this study is in good agreement with the expected stress direction originating from ridge push, a mechanism that has been long recognized as the main force influencing the stress field of the Baltic Shield [Gregersen, 1992; Zoback, 1992]. From focal mechanism analysis, Slunga [1991] deduces a principal horizontal compression in the direction N120°E for Finland, as well as southern and northern Sweden, which is consistent with our measurements. In their study, Slunga notes a scattering of the orientations in northern Sweden that they attribute to the different pattern of fault

strikes in this area. Alternatively, this scattering in northern Sweden could be explained by the rotation of the stress pattern in the vicinity of postglacial faults as shown along the Pärvie fault by Lindblom [2011] with S_{Hmax} variations from E-W to N-S.

Regarding the influence of deglaciation, Keiding *et al.* [2015], through analysis of strain rate derived from horizontal GPS data, propose that the glacial isostatic adjustment decreases the NW-SE compressional stress due to the Mid-Atlantic Ridge. However, the absence of a radial pattern in stress orientation in the WSM database and its homogeneity on the Scandinavian scale shows the greater effect of far field forces rather than viscoelastic rebound in the present day. The postglacial scarps observed in Northern Sweden [Mikko *et al.*, 2015] are the main tectonic scars left by the glacial isostatic adjustment, and some authors [e.g., Gregersen, 2002] used them to argue in favor of a change in dominating stress orientations during the last 9000 years. The pattern of the strain rate field modeled by Craig *et al.* [2016] at 11–10,000 years does not look so different from the present-day strain rate field calculated from geodetic observations [Keiding *et al.*, 2015], except that it is 1 order of magnitude lower today. However, the recent mapping of postglacial fault scarps in Sweden by Mikko *et al.* [2015] shows a remarkably homogeneous NE-SW orientation of these reverse faults that are consistent with the dominance of a linear rather than radial stress pattern in Scandinavia also at that time. The orientation of these thrust faults is in agreement with the S_{Hmax} in the COSC-1 borehole with $\sim 90^\circ$ difference in the trend of the 9000-year-old faults and the present-day maximum horizontal stress.

The influence of topography on the stress field has been investigated in southern Norway by Pascal and Cloetingh [2009]. By means of numerical modeling, they show that moderately elevated landmass can produce stresses competing with far-field-induced stresses. However, if the Scandinavian topography could have an effect on the stress field in the COSC borehole, its NE-SW orientation is perpendicular to the ridge push forces and will only change the magnitude of the stress, but not its orientation.

These effects on crustal stresses are all derived from pushing or pulling on the sides of the plates or gravitational loading in the crust. Driving forces from below plates, such as mantle drag, could also play an important role in driving the plates. Forsyth and Uyeda [1975] show that both side-driven and bottom-driven forces can explain surface plate motion and suggest that mantle drag is stronger under the continents than under the oceans. Bird and Baumgardner [1984] suggest that mantle drag can have an important role on the stress field and the strength of brittle faults in Southern California. By analysis of P wave delays due to anisotropy, Bokelmann [2002] suggests that the mantle plays an important role in driving the plates in North America. Assuming that the lithosphere deforms approximately in simple shear, in a normal mantle flow fabric, olivine crystal a axes will align parallel with the direction of flow [Nicolas and Christensen, 1987]. The fast shear wave will polarize parallel to the dominant a axis orientation distribution and hence provides an indirect indicator for mantle flow or direction of shear in the mantle. Eken *et al.* [2010] show seismic anisotropy below Scandinavia from body wave analysis in the upper mantle (including the lithospheric mantle) with fast shear waves that align semiparallel with S_{Hmax} in our study, as well as many other stress studies in Scandinavia. Depending on the coupling between crust and lithospheric mantle this could drive plate motion and generate crustal stresses. A problem with this interpretation is that it becomes hard to distinguish what part of the shear wave splitting is related to current mantle flow and what is related to a pre-existing “frozen in” mantle fabric, since the splitting measurement in the end is an indirect indicator of the finite strain in the upper mantle.

6.3. Time-Dependent Breakout Development

A limited number of downhole observations, as well as laboratory and numerical modeling efforts, show that breakout growth can occur along the axis of the borehole and penetrate into the borehole wall with minimal appreciable breakout width growth [Cuss *et al.*, 2003; Haimson and Herrick, 1986; Zoback *et al.*, 1985]. Previous observations in crystalline rocks suggest that borehole growth is instantaneous and stress-induced deformation ceases in a matter of hours as is the case in the Kola Super Deep Borehole [Vernik and Zoback, 1992] after [Guberman *et al.*, 1988; Vernik and Zoback, 1992]. In the Kola borehole, a section of the well from 7000 to 9500 m was drilled and left without casing for several years, which showed no addition elongation of the breakouts in caliper logs. Studies with image logs separated by a time period of 1 year are quite rare in literature; in one of them Berard and Cornet [2003] observe that breakouts have formed in the Soultz geothermal project in Eastern France after about 1 year. In COSC-1, three breakout zones show breakout width growth of 7° to 10° , and one zone has up to 20° growth over the course of a year (Table 4 and Figure 5). Such a breakout

growth would influence S_{Hmax} magnitude estimation by using breakout width, unconfined compressive strength (UCS), and known S_{Hmin} magnitude [Barton and Zoback, 1988].

While growth along the borehole and penetration of the breakout into the formation is expected, the cause for breakout radial growth is less clear. The effect of pore pressure has been shown to have time-dependent effects on breakout enlargement in sandstones and shales [Moore *et al.*, 2011], but pore pressure effects in low porosity and permeability rocks, such as crystalline and high-grade metamorphic rocks, are typically negligible [Vernik and Zoback, 1992]. Commonly, breakout forms in continuous trends for several tens of meters or more in porous sedimentary rocks that are weak [e.g., Moore *et al.*, 2011; Valley and Evans, 2009] or at depth in stronger crystalline or high-grade metamorphic rocks where stress magnitude is high [e.g., Cui *et al.*, 2009; Valley and Evans, 2009]. Schoenball *et al.* [2014] implemented a time-dependent brittle creep mechanism into a finite element model of stresses around boreholes. The authors show that the breakout growth can be significant enough to alter stress magnitude estimations from breakout width. In COSC-1, breakouts formed intermittently throughout the borehole and there is no correlation linking rock type to zones of breakout growth, since the growth is observed in zones of mafic, felsic, and mica-rich lithologies (Table 4). Since the rocks in COSC-1 have very low porosity and permeability, it is unlikely that pore pressure plays a significant role in breakout growth [Vernik and Zoback, 1992], whereas time-dependent brittle creep could explain the observations of growth in COSC-1. In COSC-1 the breakout zones formed immediately after drilling, as they are imaged in the first logging campaign. The observed growth after the second logging campaign suggests that under conditions where the stress exceeded the strength of the rock, the resulting breakout causes perturbations in the stresses around the borehole in the near vicinity. As those stresses are redistributed around the breakouts over the course of the year, the breakouts widen. The fact that no new breakout zones have formed suggests that the brittle creeping is not likely to initiate breakouts and that an initial perturbation during drilling (i.e., a breakout) is required to observe such a phenomenon. However, those observations are only speculative and measurements of in situ S_{Hmin} as well as laboratory UCS and creep tests are necessary to test the brittle creep hypothesis and to quantify the influence of breakout growth on S_{Hmax} magnitude estimation.

6.4. Scarcity of Breakouts and DITFs in Crystalline and Metamorphic Rocks

The infrequency of breakouts is commonly observed in metamorphic and crystalline rocks, especially at shallow depths. Ask *et al.* [2014] observe a limited number of breakouts in granites and gneisses in northern Norway in acoustic televiewer logs above 0.8 km depth, in the passive margin tectonic setting. In the Sulu-Dabie high-pressure ultrahigh-pressure metamorphic belt near Lianyungang, China, breakouts in deep scientific drilling do not occur above 1.2 km in the eclogite, amphibolite, ultramafic rocks, and gneisses of the subduction-collision [Cui *et al.*, 2009]. In the deep Cajon Pass borehole, situated in crystalline and meta-crystalline rocks near the San Andreas strike-slip fault, breakouts were observed deeper than 1.7 km [Shamir and Zoback, 1992]. Lund and Zoback [1999] also report breakouts being infrequent above 1 km and 2 km in the granite penetrating Gravberg-1 and Stenberg-1 wells, respectively, where the midcontinental tectonic setting is also the location of a fossilized impact crater. Brudy *et al.* [1993] show that breakouts in the main KTB borehole have a consistent breakout trend from 1.0 to 6.0 km depth. Below 3.0 km imaging of breakouts with acoustic televiewer and microresistivity tools imaged high-quality breakouts extending ~10 m along the borehole axis [e.g., Brudy *et al.*, 1997]. These observations show that the lack of breakouts in the shallow sections is not limited to a particular tectonic setting. The common factor between all borehole presented is that they penetrate crystalline or metamorphic rocks, which are generally elastically stiff and have high mechanical strength.

The paucity of stress-induced breakouts or DITFs in COSC-1 is likely due to the high rock strength of the lithologies encountered throughout the borehole. Breakouts form regardless of dominant rock type in mafic, felsic, and mica-rich units; however, there are no occurrences in the deepest mylonite-rich zone at the base of the well (Figure 4a). Felsic, calc-silicate, and amphibolite gneisses have high elasticity, as shown by the dynamic moduli (Table 5 and Figure 6). Chang *et al.* [2006] show that sedimentary rocks with high Young's modulus or high velocities are also associated with high unconfined compressive strength (UCS). Assuming the relation that higher Young's modulus invokes a higher UCS is valid for metamorphic rocks, high rock strength in all the rock types measured in COSC-1 would hinder breakout and DITF formation. This would be especially important in the uppermost 600 m of the well where stress magnitudes would be lower and breakouts do

not form. Assuming Mohr-Coulomb failure criteria, the cohesive or unconfined compressive strength of the rock required to avoid compressive failure must increase as differential “far-field” horizontal stresses increase [Zoback *et al.*, 1985]. Zoback [2007] compiled examples of principal stress magnitude with depth for various faulting regimes (normal, strike-slip, and reverse) that show that higher differential “far-field” horizontal stresses occur with depth. The lack of breakout in the uppermost part of boreholes in strong rock types (e.g., metamorphic and crystalline rocks) promotes the notion that the high rock strength hinders breakout formation until the required higher differential “far field” horizontal stresses are reached at depth. The limited development of DITFs is also coupled to the low temperature difference between the borehole drilling fluid and the formation temperature that results in low thermal stresses [Brudy and Zoback, 1999]. With no direct measurements of stress magnitudes or stress anisotropy in the borehole, we infer a likely in situ stress scenario based on seismicity. The COSC-1 borehole is situated in a zone of low seismic activity (Figure 2b), but the presence of earthquakes signifies in situ stress anisotropy. Therefore, it is plausible that in the COSC-1 area the in situ stress anisotropy is low, which, combined with the high rock strength, contributes to the lack of stress indicators in the borehole.

6.5. Structural Observations From Image Logs

Sheath folds and recumbent folds are visible in the acoustic televiwer logs and rolled core scans throughout the borehole. An example (Figures 7a–7c) from a section in the middle of the borehole (1671 to 1677 m) shows high acoustic amplitude amphibolite layers folded with lower acoustic amplitude gneiss layers in the acoustic televiwer logs, as well as green amphibolite layers and grey gneiss layers in the rolled core scans. Differences between hole diameter and core diameter give rise to the discrepancy between image log and core scan circumference. A zoom of the sheath fold (eyefold) is displayed in Figure 7b, while typical recumbent fold structures are shown in Figure 7c. Boudinage or pinch and swell structures in the rolled core scan are shown in Figure 7d. The foliation dip azimuth above ~500 m is primarily to the SW (Figures 4c and 4h). Below ~500 m the foliation dip direction is concentrated to the NE; however, variability in foliation orientation occurs from 500 to 2500 m (Figure 4c). The fluctuations in dip azimuth from 500 to 2500 m are attributed to the tight recumbent folding (developing into sheath folds) and boudinage in the Seve Nappe Complex, which is also observed at outcrops in the central Jämtland region [Hedin *et al.*, 2016]. Sheath folds and recumbent folds typically form during simple shear and are characteristic of strongly deformed shear zones. The recumbent fold and boudinage structures observed in core scans, borehole imaging, and outcrops reiterate their role as the source for the fluctuating foliation measured in the borehole and observed in seismic profiles [e.g., Hedin *et al.*, 2016, Figure 1c]. In addition, the foliation in the seismic profile along the borehole trend (Figure 1c) shows shallow westward dipping foliation until ~600 to 700 m depth and then becomes apparently eastward dipping in the deepest borehole section, which is corroborated by the foliation orientation observed in the image logs (Figures 4c and 4h).

Orientation and dip of fractures along the depth of the logged section are depicted in Figures 4e, 4f, 4i, and 4j. Typically, the fractures dip steeply ($>70^\circ$). The range of fracture orientation is broader above ~800 m. Stephansson *et al.* [1991] remark that near-surface stress is scattered in the uppermost 400 m in Fennoscandia, which is corroborated by the observed near-surface fracture orientations in COSC-1. Surface effects such as local topographic loading could be influencing near-surface stresses in a way that would perturb local magnitudes and orientations, giving rise to the disoriented fractures above 800 m [Hergert *et al.*, 2015]. Glacial loading and unloading could be an additional source for the disoriented fracture pattern in the uppermost 800 m. Below 800 m the orientation of the fractures is more uniform with a tighter distribution primarily oriented with a strike NW-SE. Below 2200 m natural fractures are rarely observed, which can be attributed to the change in lithology into the mylonite and meta-sedimentary sections, which begins the transition into the underlying Särö Nappe. The more coherent fracture orientation below 800 m could be indicating a more stable stress regime at depth. Breakouts and, to lesser certainty, DITFs show that S_{Hmax} is oriented in a similar NW-SE direction (Figures 4b and 4g). Breakouts and DITFs also begin to form around 600 m, which correlates to the same region where the change in fracture orientation occurs. Assuming that these fractures formed by fracture and jointing processes near the surface, they should have formed under extensional or hybrid shear conditions. The core reveals that many of the natural fractures are mineralized. There is clear evidence that the orientation of most of the fractures is aligned with today's observed S_{Hmax} direction. We infer that these fractures

Figure 7. Common structures observed in acoustic borehole televiewer logs and core. (a) Acoustic televiewer amplitude log showing sheath folds and isoclinal recumbent folds in marked areas. (b) The sheath fold (eyefold) in an enlarged acoustic televiewer image. The corresponding rolled core scan highlights the outline of the sheath fold on the top half of the image, with steeply dipping foliation (high amplitude sinusoids) and at the base shallow dipping foliation. (c) Isoclinal recumbent folds in an enlarged acoustic televiewer image. The corresponding rolled core scan highlights the outline of the isoclinal fold on the top half and bottom half of the image, which are both bounded between shallow dipping foliation (low-amplitude sinusoids). (d) Undulating layering due to boudinage structure in rolled core scan, where the pinch and swell structure is bounded between shallow dipping foliation (low amplitude foliation). A matching televiewer image could not be identified. For Figures 7b–7d the core scan or image log is wrapped to form a cylinder for a three-dimensional visualization. For Figures 7b and 7c the image log circumference is 0.24 m and the core scan is 0.15 m due to differences in hole diameter and core diameter. Here an NQ3 drill bit is used (0.076 m hole diameter and 0.045 m core diameter). For Figure 7d the rolled core scan diameter is 0.20 m for the HQ3 drill bit (core diameter 0.061 m).

formed under similar in situ stress conditions as those observed in the borehole due to their alignment with the S_{Hmax} direction. Absence of differently oriented natural fractures indicates the longevity of the current day stress field, which may be related at least to the opening of the Atlantic Ocean and onset of the Mid-Atlantic spreading center. Dating of these fractures could provide understanding of the temporal evolution of the stress field in central Sweden.

7. Conclusions

A new stress orientation measurement has been established in an aseismic area of the Baltic Shield where only a few boreholes already existed. Borehole breakouts, DITFs, and natural structures are analyzed from 100 to 2485 m in ultrasonic acoustic televiewer logs that were run in the COSC-1 borehole in two campaigns during drilling pauses and 15 months after drilling concluded. Overall, stress-induced failures are infrequent in COSC-1. Breakouts occur in 13 distinct zones with a total length of 22 m and an S_{Hmax} orientation of $127^\circ \pm 12^\circ$. DITFs are even more infrequent, occurring as a single couplet. The S_{Hmax} orientation in COSC-1 closely matches the orientations in the Gravberg-1 and Stenberg-1 deep wellbores and fits into the regional trend across Scandinavia. This orientation is compatible with many tectonic drivers of stresses (i.e., ridge push, mantle-driven stresses, and topographic loading of the Caledonian mountain range).

A unique observation from the comparison of the two logging campaigns shows that some breakouts have grown both along and radially around the borehole wall. Such radial breakout growth around the borehole has implications for estimation of intermediate principal stress magnitudes. High rock strength, coupled with the perceived weak in situ stress anisotropy, contributes to the lack of stress-induced borehole deformation. Given the occurrence of breakouts and breakout growth in various lithologies, stress-induced deformations do not appear to be correlated to rock type. Natural fractures, especially those below 800 m, are aligned with the S_{Hmax} orientation derived from breakout and DITF analysis, indicating that the stress during formation of these fractures is aligned with the present-day stress field. Fluctuations in foliation orientation are due to recumbent folding and boudinage of layering in the Seve Nappe Complex.

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