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Initial Field Testing in the Deep Subsurface for the Thermal Breakout Project for Measuring In Situ Stress

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ABSTRACT:

The current state-of-the-art technology for in situ stress measurements involves an integrated approach that combines borehole breakout observations, drilling-induced tensile fractures, and hydraulic fracturing tests (i.e., mini-fracs); however, this methodology has several limitations that often prevent successful in situ stress measurements. One major limitation is that breakouts do not appear in every borehole and are generally a natural occurrence that cannot easily be controlled. Because borehole breakouts are used to measure the maximum horizontal in situ stress magnitude, the absence of borehole breakouts presents a major data gap for in situ stress measurements. As a response to this data gap a new thermal breakout technology is being developed that will provide a method for thermally inducing borehole breakouts and obtaining consistent measurements of the maximum horizontal stress magnitude. This thermal breakout technology involves heating the borehole and increasing the thermoelastic compressive stress in the rock until a breakout develops, which is directly correlated to the maximum horizontal stress magnitude. An initial component of the thermal breakout project involves developing a prototype downhole tool and performing field testing in the deep subsurface. The primary objective of the initial tool development and field testing is to provide a physical proof of concept for the thermal breakout technology. Three thermal breakout field tests were performed at approximately 4850 feet deep in the Sanford Underground Research Facility. Each test was performed in a borehole that had been previously used for overcoring stress measurements. The third and final test successfully created two diametrically opposed breakouts after deploying the thermal breakout tool for approximately 3 hours of continuous heating. Post-analysis of the thermally induced breakouts confirmed that the thermal breakout orientation directly corresponds to the known in situ stress orientation and magnitude.

1. INTRODUCTION AND BACKGROUND

The measurement of the state of rock stress has been an area of active research for more than 60 years (Zoback, 2007). Hydraulic fracturing measures the state of stress by creating a tensile fracture that opens normal to the minimum horizontal stress direction. The fundamental analysis assumes that the fluid pressure required to open or close the fracture is a measure of the stress normal to the fracture, which is the minimum horizontal stress (also known as the shut-in pressure) (Raaen and Brudy, 2001; Edwards et al., 2002). Using the minimum horizontal stress and fracture reopening pressure provides a basis for approximating the maximum horizontal stress, provided that the stress concentration around the borehole and fracture can be assumed from linear-elastic theory. Oriented impression or borehole image logs determine the orientation of the fracture, which is the maximum horizontal stress direction.

Considerable confidence exists in using the shut-in pressure and fracture orientation to determine the minimum horizontal stress and maximum horizontal stress direction; however, recognition of fracture mechanics and pore pressure effects as well as a general uncertainty in fracture initiation processes have eroded the confidence in approximating the maximum horizontal stress magnitude based on hydraulic fracturing (Rutqvist et al., 2000).

Borehole imaging technologies and improvements in oriented caliper logging in the 1970s and 1980s greatly enhanced the recognition of borehole breakouts as indicators of in situ stress (Plumb and Hickman, 1985). Unlike hydraulic tensile fractures, borehole breakouts result from compressive fractures in the direction of the minimum horizontal stress rather than the maximum horizontal stress. These compressive borehole breakouts develop from the high stress concentrations created by the borehole, strength of the rock, and in situ stress field (Moos and Zoback, 1990; Peska and Zoback, 1995). By using a combination of hydraulic fracturing and breakout measurements, the minimum and maximum horizontal stress profiles as a function of depth can be estimated with reasonable accuracy (e.g., Molaghab et al. [2017]). Additional correlation between borehole breakouts and the in situ stress state has recently been extended by incorporating thermoporoelastic effects and artificial neural network analyses (Zhang et al., 2017; Zhang and Yin, 2019).

While breakouts are not uncommon, they do not appear in most wellbores. Breakouts are only observed when the magnitude of the maximum stress and its ratio to the minimum stress are sufficient to create stress concentrations that exceed the compressive strength of the rock. Other than drilling in regions prone to breakouts, a method does not currently exist for consistently creating breakouts where they do not naturally occur. The lack of borehole breakouts severely limits the potential areas where the traditional breakout technology of measuring the maximum horizontal stress can be applied; therefore, the current state-of-the-art technology for deep-borehole, in situ stress measurement needs to overcome this major limitation. The initial work described in this paper builds on existing, proven methods of in situ stress measurement by inducing limited breakouts that are created under definable thermoelastic conditions.

As part of a recent US Department of Energy- (DOE-) sponsored research project (Nopola and Vining, 2016; Nopola et al., 2017 and 2018), a downhole electric-resistance heater technology that could create a plug of melted backfill and rock to seal boreholes was developed. During development, this project also identified through numerical modeling and field-experiment confirmation that the heater technology would induce compressive and tensile fractures on laboratory-scale test blocks and in downhole tests at the Sanford Underground Research Facility (SURF) if the heat input was not properly regulated. Similar borehole heating experiments at the ONKALO Underground Rock Characterisation Facility in western Finland have loosely confirmed the correlation between thermally induced breakouts and the in situ stress state (Siren et al., 2015); however, the ONKALO experiments were conducted within a nearly isotropic in situ stress state, which generally presents challenges for accurately measuring the orientations and magnitudes of the in situ stresses.

By using this existing downhole heater technology, a 4-year, DOE-sponsored project to develop a new approach for measuring the maximum horizontal stress is in progress. This approach will induce breakouts by heating the rock and controlling the rock's thermoelastic expansion. To develop and refine this thermal breakout technology, the project research will occur in the following four phases:

- Phase 1: Analysis and modeling to provide a foundation for the subsequent testing and development phases
- Phase 2: Prototype thermal tool development and laboratory-scale testing in true triaxial and shaped-core testing machines
- Phase 3: Field testing at SURF in South Dakota
- Phase 4: Full-scale implementation in an actual deep borehole.

This paper presents select results from preliminary field testing. The purpose of presenting these initial results is to provide preliminary field validation for the theoretical foundation of the technology and guide the subsequent detailed numerical modeling, laboratory testing, and field testing that are still required to refine the calculations. In this paper, analytical modeling and preliminary field testing results are used to address the following primary research objectives:

- Investigate the fundamental thermal breakout mechanics compared to overcoring measurements
- Confirm if the expected temperature range that will be required to induce thermal breakouts from analytical calculations is reliable in the field.

The overall approach discussed in this paper involved several tasks, including the following:

- Develop the fundamental thermal breakout concept
- Review previously-measured in situ conditions at SURF
- Perform analytical modeling to estimate thermal and time requirements for the field experiments
- Conduct thermal breakout field experiments
- Evaluate and compare field measurements to the analytical model predictions.

The following sections discuss the approach and results for each task. The conclusions of the initial field testing and next steps of the breakout technology development process are also presented.

2. FUNDAMENTAL DEVELOPMENT

The theoretical development of the thermal breakout concept is based on analyses of the classic Kirsch (1898) solution, which is a set of equations that are commonly used to evaluate the three-dimensional (3D) stress state around a borehole that is drilled within an isotropic, linear-elastic medium. Figure 1 illustrates the horizontal in situ stress components, azimuth orientation, and breakout definition for a vertical borehole.

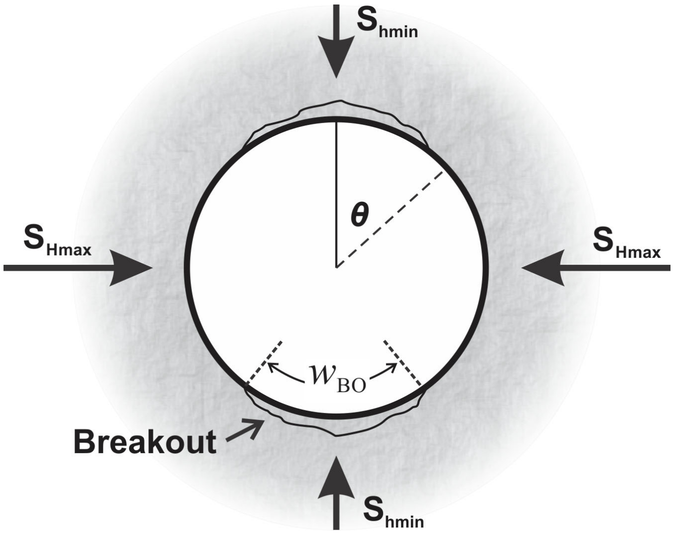

Fig. 1. In situ stress components and breakout orientation around a vertical borehole.

Based on Figure 1 and the Kirsch solution, the effective hoop stress acting on the borehole surface in the case of an applied temperature change is given by the following equation:

$$\sigma_{\theta\theta} = S_{\mathrm{hmin}} + S_{\mathrm{Hmax}} + 2\left(S_{\mathrm{Hmax}} - S_{\mathrm{hmin}}\right)\cos 2\theta - P_0 - P_m + \frac{\alpha_t E \Delta T}{1-\nu} \quad (1)$$

where:

$\sigma_{\theta\theta}$ = tangential stress (hoop stress) around the borehole

S_{Hmax} = maximum horizontal in situ stress

S_{hmin} = minimum horizontal in situ stress

θ = azimuth angle from S_{hmin} direction

P_0 = pore pressure

P_m = mud weight or internal borehole pressure

α_t, E, ν = rock properties that correspond to the coefficient of thermal expansion, Young's modulus, and Poisson's ratio, respectively

ΔT = change in borehole surface temperature.

For a borehole breakout to occur, the compressive stress on the borehole surface must exceed the rock's compressive strength. As evident in Eq. (1), an induced temperature increase on the borehole surface will lead to a corresponding increase in the hoop compressive stress, which provides a controllable means for initiating breakouts and is the basis for the thermal breakout technology that is currently in development. Thermoelastic effects on the hoop stress around boreholes have long been recognized as an important factor in calculating safe drilling mud windows (e.g., Gholilou et al. [2017]). The analysis that is presented in this paper uses a simple failure criterion for the initiation of borehole breakouts, which is given by:

$$\text{Breakout failure occurs when } \sigma_{\theta\theta} \geq \text{UCS} \quad (2)$$

where:

UCS = unconfined compressive strength of the rock.

Although more complex linear and nonlinear failure criteria (e.g., Mohr-Coulomb, Mogi-Coulomb, Hoek-Brown) can be used to evaluate breakout initiation, the criterion shown in Eq. (2) should provide a reasonable approach for this initial analytical modeling phase.

3. FIELD TESTING LOCATION AND OVERCORING RESULTS

Overcoring stress measurements were previously performed at the 4850 Level (i.e., approximately 1500 meters [m] below ground surface) of the former Homestake gold mine (Homestake) in Lead, South Dakota. During conversion of the mine to an underground laboratory, Golder Associates (Golder, 2010b) performed in situ stress overcoring measurements as part of the original planning of the Deep Underground Science and Engineering Laboratory (DUSEL) at Homestake, which was later renamed SURF. Several of the original 152-millimeter- (mm-) (6-inch-) diameter overcoring boreholes are still accessible, and their locations can be seen in the overview in Figure 2. Stress Measurement Site No. 3 was selected for the initial thermal breakout testing. The Site No. 3 borehole was drilled at an azimuth of 307 degrees from North and at an inclination of 24.2 degrees above horizontal with a depth of approximately 6.6 m (21.5 feet [ft]).

Site No. 3 was selected for several reasons. The geology in Site No. 3 consisted of rhyolite containing a relatively high quartz content. Quartz has a higher thermal expansion coefficient than most other minerals, which makes the rhyolite in Site No. 3 preferable to the amphibolite located in the other two boreholes. The previous overcoring stress measurements were also the most consistent at Site No. 3 compared to the other two boreholes. A summary of the overcoring stress measurements is provided in Table 1.

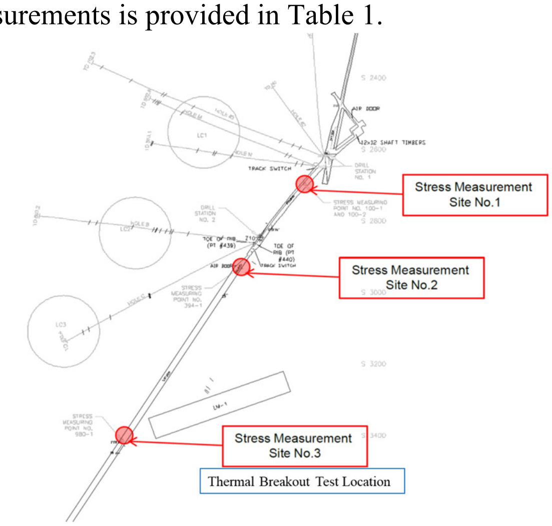

Fig. 2. Overview of overcoring locations at the SURF 4850 Level. Modified from Golder (2010b).

Table 1. Major and minor stresses for all of the overcoring tests at Site No. 3

Test	Major In Situ Stress			Minor In Situ Stress		
	Value (MPa)	Bearing (°)	Dip (°)	Value (MPa)	Bearing (°)	Dip (°)
SM-08	60.8	258	75	26.9	54	14
SM-09	59.5	175	75	30.7	40	11

Hydraulic fracturing stress measurements have also been performed on the 4850 Level of SURF for the kISMET project. These hydraulic fracturing tests were performed approximately 100 m away from Site No. 3. The kISMET tests indicated that the vertical, maximum horizontal, and minimum horizontal stresses were approximately 41.8, 34.0, and 21.7 MPa, respectively (Kneafsey et al., 2020).

A geotechnical characterization corehole (Borehole J) was also previously drilled at Site No. 3 on the opposite rib from the overcoring borehole. Post-analysis of Borehole J with an optical televiewer indicated that borehole breakouts had developed where amphibolite is in close contact with rhyolite dykes. As shown in Figure 3, the breakouts observed in the near-horizontal Borehole J are located at approximately the midpoints between the borehole crown and invert (Golder, 2010a). These breakout positions (and similar breakouts observed in several additional 4850 level boreholes) indicate that the vertical stress is likely the maximum stress within the vicinity of Site No. 3, which is consistent with both the overcoring stress measurements and the kISMET hydraulic fracturing tests.

4. INITIAL ANALYTICAL MODELING AND PARAMETERS

Initial analytical modeling was performed to estimate the thermal and time requirements for the planned field experiments. The initial analytical modeling incorporated the previous overcoring stress measurements and rhyolite properties that were obtained from Site No. 3. Eq. (1) provided the foundation for the initial analytical modeling.

The transient response of the temperature field to the thermal tool must be evaluated to obtain the borehole surface temperature change (ΔT) in Eq. (1). The transient temperature field was approximated by Fourier's 1D cylindrical heat equation:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)=\frac{c_p}{k\rho}\frac{\partial T}{\partial t} \quad (3)$$

r = radius

T = temperature as a function of radius and time, $T(r,t)$

c_p = specific heat capacity at constant pressure

k = thermal conductivity

ρ = density.

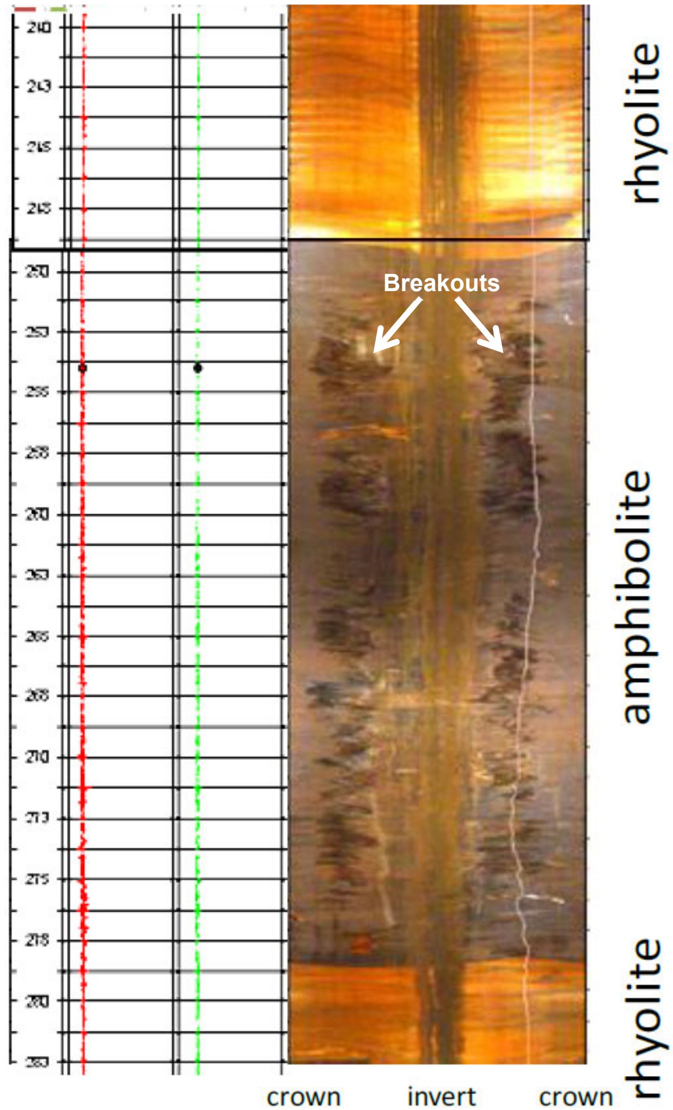

Fig. 3. Breakouts observed in Borehole J from 240–283 feet (73–86 m) with depth markings corresponding to 1.25 feet (0.38 m).

Eq. (3) was solved with the following initial and boundary conditions:

$$T(r,0)=T_0 \quad (4)$$

$$-k\frac{\partial T}{\partial r}(R_i,t)=q_0 \quad (5)$$

$$T(R_0,t)=T_0 \quad (6)$$

where:

T_0 = in situ temperature

R_i = borehole radius

R_0 = far field radius, such that $R_0 \gg R_1$

q_0 = heat flux provided by the borehole thermal tool.

To estimate the changes in temperature and hoop stress on the borehole surface, several physical parameters must be defined, as shown in Eqs. (1) and (3). These parameters include in situ stresses, pressures, material properties, and thermal conditions. The in situ stresses and temperature were obtained from the previous overcoring stress measurements at Site No. 3. Field testing will be performed in a dry borehole with primarily dry rock; therefore, the internal borehole pressure and pore pressure were set to zero. Rhyolite material properties were obtained from previous laboratory testing on rhyolite specimens obtained from the Site No. 3 borehole (Melegard et al., 2010) and other rhyolite specimens from SURF (Osnes et al., 2015). Table 2 lists the model and material parameters that were used in the initial analytical modeling.

Table 2. Model parameters

Parameter	Average Value	Unit
S_{hmin}	28.8	MPa
S_{Hmax}	60.2	MPa
P_o	0	MPa
P_m	0	MPa
R_i	76	mm
α_t	7.9E-6	1/K
E	50	GPa
ν	0.20	—
UCS_max	223	MPa
UCS_avg	111	MPa
UCS_std_dev	55	MPa
UCS_min	28	MPa
k	2.5	W/m-K
c_p	1000	J/kg-K
ρ	2.55	g/cm^3
T_0	26	°C

Based on the parameters that are listed in Table 2, Eqs. (1) and (3) were solved with a zero heat flux (i.e., no heating) and also a constant heat flux that corresponds to applying 1000 watts (W) of heat (i.e., a heat flux [q_0] equal to 6800 W per square meter [W/m^2]) to the borehole wall. Figure 4 shows the predicted borehole wall temperature as a function of heating time. As shown in Figure 4, the borehole wall is expected to reach a temperature of approximately 220 degrees Celsius (°C) after 2.5 hours of constant heating, which corresponds to a temperature change of approximately 194°C.

The predicted temperature response was then used to estimate the change in borehole wall hoop stress, as defined in Eq. (1). Figure 5 shows the predicted borehole wall hoop stress before heating (blue line) and after 2.5 hours of constant heating at 1000 W (red line). Figure 5 also shows the range of rhyolite unconfined compressive strength (UCS) values (horizontal black lines). The heating-induced thermal stress is predicted to significantly increase the hoop stress on the borehole wall. When the predicted hoop stress in Figure 5 exceeds the UCS, a borehole breakout is expected to develop. As shown, the predicted increase in hoop stress after 2.5 hours of heating is anticipated to produce a borehole breakout even when considering the maximum UCS that was measured from laboratory testing; therefore, the initial analytical modeling of a 1000-W thermal tool was expected to achieve breakout conditions in the field tests at SURF.

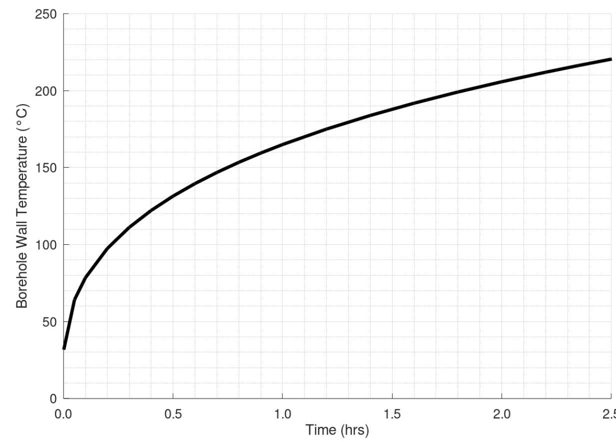

Fig. 4. Predicted transient borehole temperature with a constant heat application of 1000 watts.

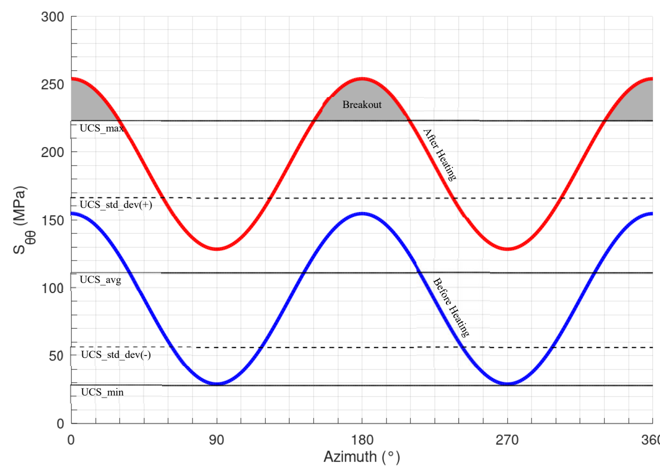

Fig. 5. Predicted hoop stress before heating (blue line) and after 2.5 hours of constant heating at 1000 watts (red line). Black horizontal lines indicate the range of rhyolite UCS values.

5. FIELD TESTING APPROACH AND RESULTS

In parallel with efforts investigating the design and construction requirements of the thermal breakout tool (which are not the focus of the current paper), preliminary field tests were initiated to perform early field validation of the modeling and preliminary tool design concepts. The team met with SURF staff to develop plans for the initial field-testing activities. The aforementioned boreholes that are owned by SURF were identified and the approval process for using these holes was initiated and obtained. During the borehole selection process, the existing boreholes were investigated and scoped with a camera. Figure 6 shows the interior of the borehole with relatively smooth walls and uniform rhyolite geology. The approximate location of the heater is also indicated in Figure 6. Several site visits were performed to prepare the test areas and ensure that adequate space and infrastructure (i.e., specifically regarding electric power requirements) were accessible. The buildout of the prototype heater was initiated in the laboratory based on the geometry of the borehole and anticipated power requirements predicted by preliminary modeling.

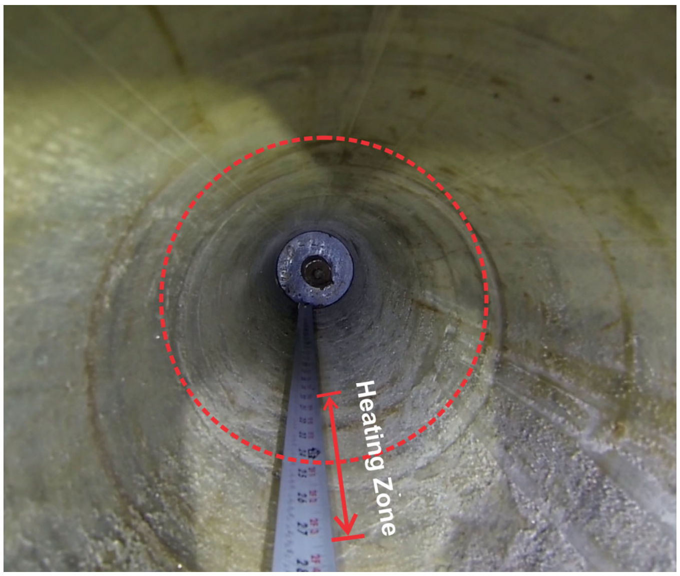

Fig. 6. Site No. 3 overcoring borehole at SURF before thermal breakout testing.

Figure 7 shows a rendering of the prototype tool and thermocouple sensor locations. Although the prototype design dimensions vary slightly in different tests, Figure 7 provides a reasonable representation. Skids were designed at both ends of the tool to center the heating element in the borehole but were omitted from the central heating section to provide uniform heating entirely around borehole. Thermocouples were installed in the center of the heating element, inside the steel housing of the canister, and at the borehole walls. The thermocouples at the borehole walls were placed through the skids and the protective thermocouple casing was bent slightly so that the connection was in contact with the borehole wall, with the objective of measuring the borehole wall temperature.

Three initial field tests were performed at SURF in a borehole located approximately 4850 feet (1500 m) underground to evaluate the functionality of the prototype tool. All of the test durations were between 2 and 4 hours. The following list summarizes each test:

Field Test 1: The first prototype heater tool was constructed using an aluminum housing and contained a 38-mm- (1.5-inch-) diameter heating element with a power rating of approximately 1300 W, which was expected to be sufficient based on the initial analytical modeling discussed in Section 4. Despite reaching heater temperatures exceeding 1000°C, borehole wall temperatures of only approximately 160°C were achieved (with the in situ temperatures of approximately 26°C) and no breakout occurred. Although Field Test 1 was unsuccessful in creating breakouts, three important lessons were learned:

- Aluminum should not be selected as a housing material because of its low emissivity (i.e., inefficient radiation heat transfer)
- The requested power supply was insufficient and lead to severe voltage drop
- Thermocouple grounding issues may have caused inaccurate temperature measurements.

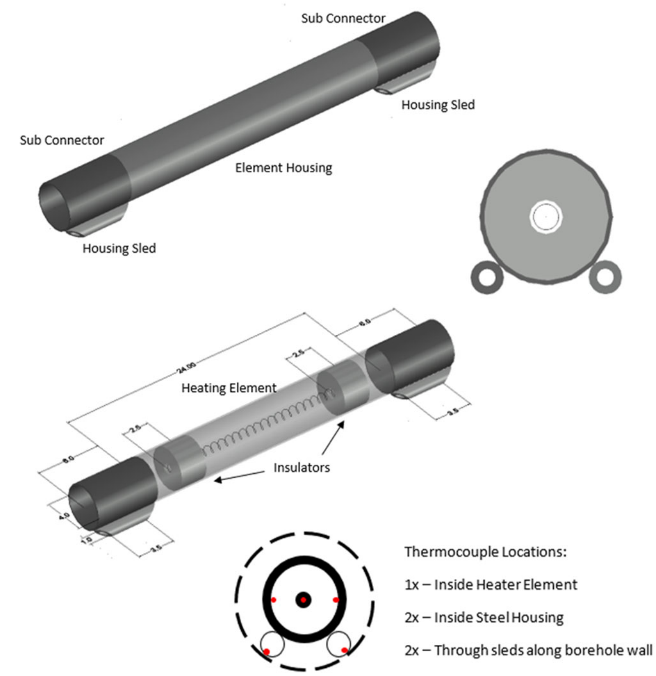

Fig. 7. Prototype tool for the initial field tests. Dimensions in inches.

Field Test 2: The Field Test 2 prototype heater was modified to include a steel housing while retaining the 1300 W heating element used in Field Test 1. SURF supplied an on-site generator to provide a more reliable power supply. During the test, the central thermocouple is believed to have slipped out of the center of the heating element and backward into the insulator as maximum temperatures of only 610°C were recorded in the heating element thermocouple. However, borehole wall temperatures of up to 310°C were recorded but again, no breakout occurred. The test results suggested that the initial simplified analytical approach to calculating the required temperature increase may be inadequate for understanding the complexity of the thermal breakout system. In concert with additional, more detailed analytical and numerical modeling, a more robust heater design was initiated to achieve greater temperatures.

Field Test 3: The Field Test 3 prototype heater was modified to include a larger, 63.5-mm- (2.5-inch-) diameter heating element that is rated for 3500 W. Figure 8 shows the measured temperatures during Field Test 3. An initial system test was performed for approximately 1 hour followed by an approximately 15-minute cooldown. After approximately 2.5 hours of full-power testing of the heater in the borehole, the test personnel noted audible indications of rock fracturing, as well as a sudden increase in the measured temperatures. During this period, the heating element temperatures again exceeded 1000°C but the borehole wall temperatures were able to reach between approximately 400 and 500°C.

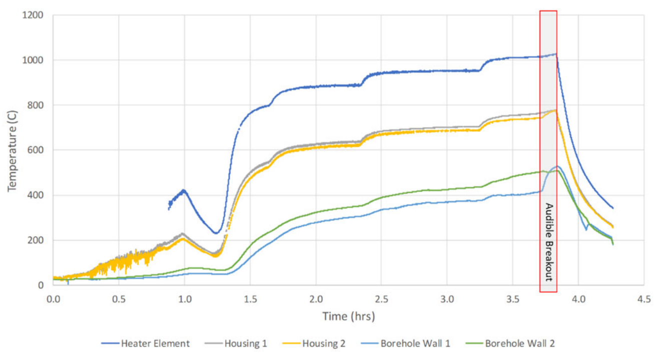

Fig. 8. Measured temperatures from Field Test 3.

After the audible rock fracturing and temperature spike, as noted in Figure 8, the test was immediately terminated. After a sufficient cooling period, a borehole scope was inserted into the borehole to investigate the outcome. Figure 9 shows that diametrically opposed breakouts were observed (outlined by the red dotted lines). Another minor fracture developed at an approximately 90 degree offset from the two major breakouts (outlined by the yellow line in Figure 9).

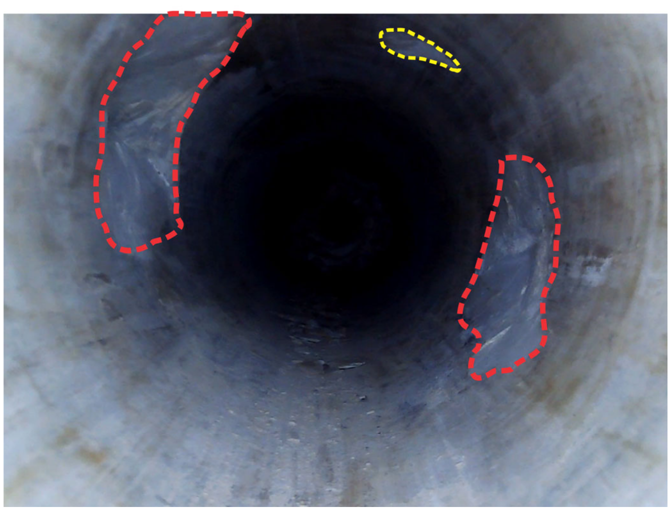

Fig. 9. Thermally induced breakouts from Field Test 3.

After field testing was completed, a 3D AutoCAD model was created containing the drift and borehole geometry, as well as a visual representation of the stress measurements recorded from overcoring. An example of the model is shown in Figure 10. In Figure 10, the stress directions are scaled relative to their respective magnitudes with red representing the major principal stress, green representing the intermediate stress, and blue representing the minor principal stress. The dashed versus solid lines represent the two overcoring stress measurements from the borehole.

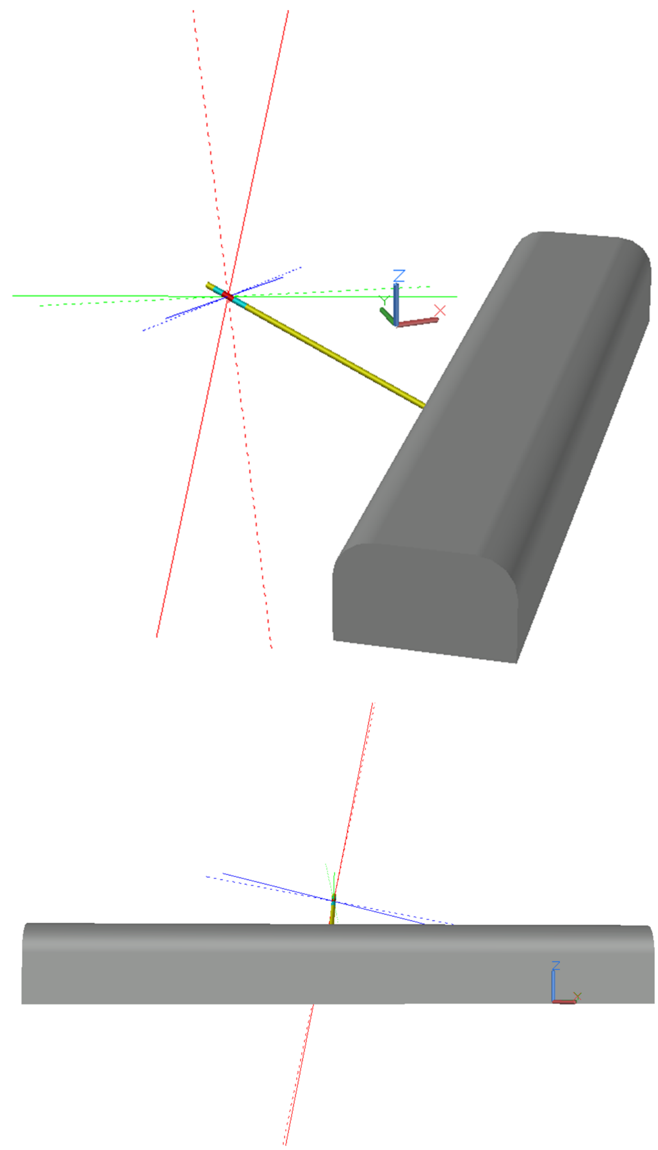

Fig. 10. Isometric and side views of the three-dimensional model of the Site No. 3 location with overcoring stress measurements represented by red, green, and blue lines for major, intermediate, and minor principal stresses, respectively. Solid lines correspond to the SM-08 overcoring results while dashed lines correspond to the SM-09 overcoring results.

The 3D model and relative stress directions were translated on top of the borescope images to obtain the relationship between the principal stress directions and observed breakouts. This relationship is presented in Figure 11, which shows that the thermally induced breakout orientation is consistent with the in situ stress magnitudes and directions that were measured from the previous overcoring tests in this borehole, specifically that the breakouts occurred roughly parallel to the minimum principal stress and perpendicular to the maximum principal stress, as would be expected. The smaller fracture outlined by yellow lines in Figure 9 is approximately parallel to the major principal stress. This smaller fracture also appears to indicate the stress along the borehole direction (i.e., roughly the intermediate stress) but requires further analysis to understand the propensity of this type of fracture to occur, as well as its underlying mechanics.

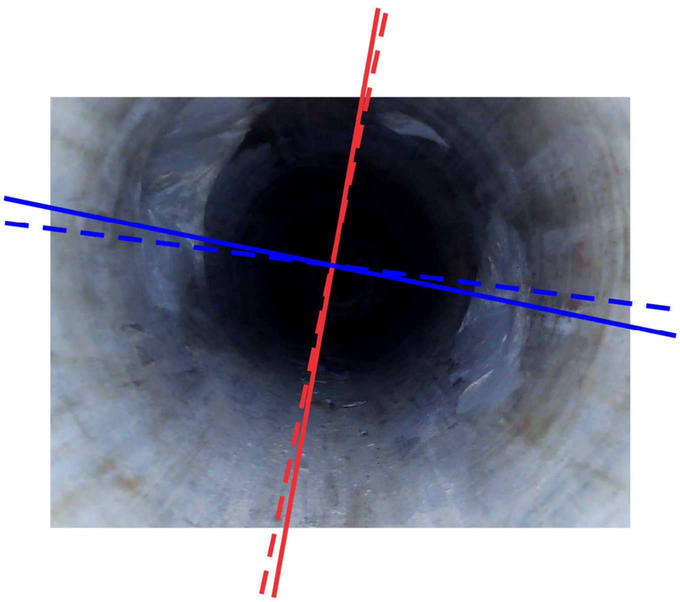

Fig. 11. Relationship between the thermally induced breakout and major (red) and minor (blue) principal stresses

6. POSTTEST ANALYTICAL MODELING AND ANALYSIS

The analytical model discussed in Section 4 was used to analyze the outcome of Field Test 3 and compare the predicted behavior to the measured behavior. Based on a measured electrical input of approximately 3250 W to the thermal tool in Field Test 3, the transient thermal modeling was repeated to compare the measured and predicted borehole wall temperatures; however, although the thermal tool controller provided an electrical output of 3250 W, some inefficiencies in the electrical transmission, resistive heating, and thermal transfer to the borehole wall are expected. The thermal tool efficiency was therefore used as a fitting parameter when comparing the analytical thermal model to the measured borehole wall temperatures. The resultant thermal efficiency was estimated to be approximately 66 percent with an actual heat output of 2150 W. Figure 12 compares the predicted transient borehole wall temperatures to the measured borehole wall temperatures based on the assumed efficiency and applied heating watts. The figure shows that the predicted transient borehole wall temperatures are in satisfactory agreement with the measured borehole wall temperatures. The assumed thermal efficiency of 66 percent appears to be reasonable based on Figure 12.

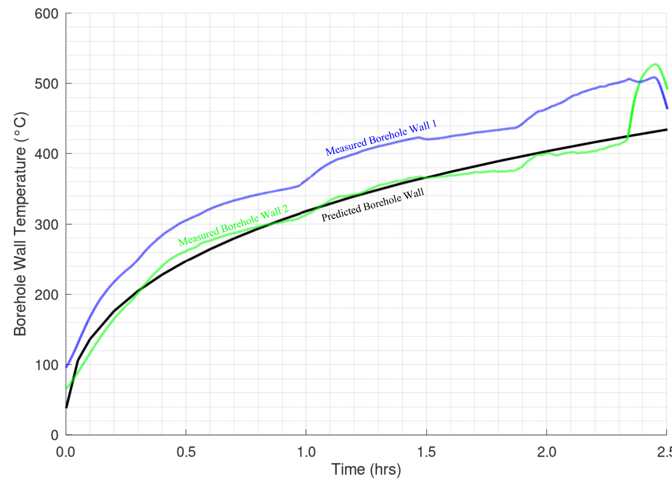

Fig. 12. Comparison between the measured borehole wall temperatures (blue and green lines) and predicted borehole wall temperatures (black line).

The predicted transient borehole wall temperatures were used to estimate the hoop stress evolution during Field Test 3. Figure 13 shows hoop stress contours as a function of azimuth and heating time. The heat-induced thermal stress is predicted to increase the maximum hoop stress from approximately 160 MPa to nearly 370 MPa at the end of the test.

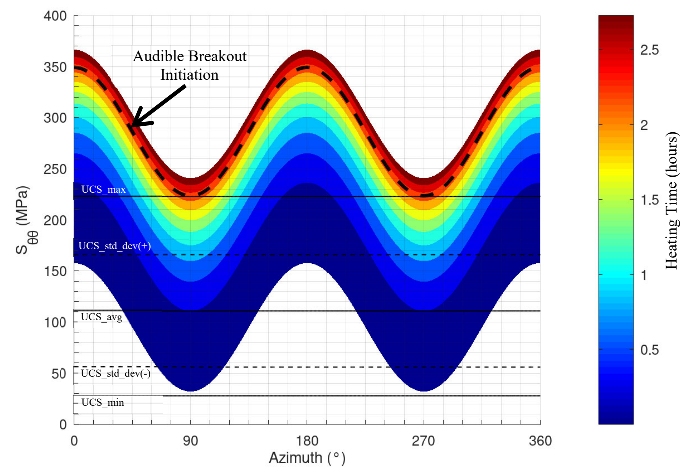

Fig. 13. Contour plot of the predicted transient hoop stress evolution during Field Test 3. Black horizontal lines indicate the range of rhyolite UCS values.

At the time that audible breakout indications were noted in Field Test 3, the predicted hoop stress (the thick, dashed, black line in Figure 13) exceeds the maximum measured rhyolite UCS for all of the azimuth angles. One would therefore expect that significant borehole damage would have been observed (i.e., the entire borehole circumference was predicted to exceed the UCS); however, post-analysis of Field Test 3 only indicated limited borehole breakouts. Several factors may contribute to this discrepancy, but a probable explanation involves using the UCS as a criterion for the onset of borehole breakouts, which may be an inaccurate means of predicting failure.

Previous statistical thermal breakout modeling (Voegeli et al. [in press]) suggests that the accuracy of breakouts as indicators of the in situ stress magnitude is most sensitive to the rock strength. In addition to the sensitivity to the rock strength, laboratory thermal breakout testing that is being performed in Phase 2 of this project has suggested that breakouts develop at hoop stresses that greatly exceed the measured UCS (Trzeciak et al., 2020). Several authors have also presented findings that suggest an apparent critical breakout hoop stress (i.e., borehole compressive strength [BCS]) that is noticeably greater than that predicted by classic rock-strength failure criteria (Cuss et al., 2003; Meier et al., 2013). This behavior appears to result from the combined grain size, porosity, and relative borehole diameter. Experimental results suggest that the BCS can be approximately 1.5 to 2.0 times the UCS at typical borehole scales. This relationship between the BCS and UCS may explain the greater-than-expected hoop stress required to create breakouts in Field Test 3 and will be evaluated in greater detail as the project progresses.

7. SUMMARY AND CONCLUSIONS

The current state-of-the-art technology for in situ stress measurements involves an integrated approach that combines borehole breakout observations, drilling-induced tensile fractures, and hydraulic fracturing tests. This methodology has achieved wide application but has several limitations that often prevent successful in situ stress measurements. One major limitation is that breakouts do not appear in every borehole and are generally only a natural occurrence that cannot easily be controlled. Because borehole breakouts are used to directly measure S_{Hmax}, the absence of borehole breakouts presents a major data gap for in situ stress measurements. In response to this data gap, a new thermal breakout technology is currently in development that will provide a method for thermally inducing borehole breakouts and allow for consistently measuring the S_{Hmax}.

This paper summarizes preliminary observations between the initial analytical modeling evaluation of the thermal breakout process and field-testing results recorded in a deep underground environment where existing stress state information was available. The overall outcome of the initial field tests provided valuable lessons for advancing the initial tool design, and the success of Field Test 3 demonstrated an important proof of concept for the thermal breakout stress measurement technology that will provide confidence in the project as it progresses. Specifically, the results of the preliminary field test results showed that thermally induced breakouts can be created with modest power requirements and within a moderate time frame in an open borehole in the deep subsurface. Comparisons with previous overcoring measurements from the same borehole (and hydraulic fracturing measurements and natural breakouts in nearby boreholes) indicate that the thermal breakout technique can predict the approximate principal stress directions. Measurements and results from the field tests are being used to refine subsequent analytical and numerical predictions so that calculations of the stress magnitudes will become more accurate. One future focus will be determining if the UCS is a reliable parameter for predicting rock strength around boreholes, which will be further evaluated in the laboratory testing program.

Although refinements will continue, the combined results of the study presented in this paper suggest that the thermal breakout technology is feasible with relatively modest temperature requirements. All of the required data for analyzing thermal breakouts can be obtained from conventional methods (e.g., wireline logging); therefore, the thermal breakout concept has a strong technical foundation that can be refined and deployed in real-world applications.

The study presented in this paper is only an initial phase of the research and development project. As this 4-year project advances, more detailed and complex analyses, testing, and validations will be performed to further refine the thermal breakout technology.

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