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Development of Thermal Breakout Technology for Determining the Maximum Horizontal In Situ Stress

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Introduction and Background

Hydraulic fracturing measures the state of stress by creating a tensile fracture that opens normal to the minimum horizontal stress direction. The analysis assumes that the fluid pressure that is 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). Using the minimum horizontal stress and the fracture initiation pressure (i.e., breakdown pressure) provides a basis for approximating the maximum horizontal stress, provided that the rock's effective tensile and the stress concentration around the borehole are known or can be assumed from elastic theory. Oriented impression or borehole image logs determine the orientation of the fracture, which is the maximum horizontal stress direction.

While there is considerable confidence in using the shut-in pressure and fracture orientation to determine the minimum horizontal stress and maximum horizontal stress direction, recognition of fracture mechanics effect, pore pressure effects, and a general uncertainty in fracture initiation processes have together 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. Unlike hydraulic tensile fractures, borehole breakouts form from compressive fractures in the direction of the minimum rather than the maximum horizontal stress. These compressive borehole breakouts develop as a combined result of the high stress concentrations created by the borehole, the strength of the rock, and the in situ stress field.

The work of Mark Zoback and his colleagues at Stanford University, including Colleen Barton and Daniel Moos, helped to develop an integrated stress-measurement approach that incorporates breakouts and hydraulic fractures that the drilling fluids can induce. Unlike classic hydraulic fracturing and breakout approaches, the Stanford-integrated approach considers the full three-dimensional stress field and requires that the borehole be in principal stress directions. This methodology recognizes that some orientations of boreholes will be more or less susceptible to breakouts and drilling-induced fractures; thus, the absence of these features in some orientations is as important as the presence of these features. Zoback [2007] provides an excellent overview of the integrated approach using breakouts and drilling-induced fractures, which has become a standard method in petroleum reservoir geomechanics.

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 the simple act of 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 advance to overcome this major limitation. In response, RESPEC is in the process of developing a new technology that builds on existing, proven methods of in situ stress measurement by inducing limited manmade breakouts that are created under definable thermoelastic conditions.

As part of a recent Department of Energy- (DOE-) sponsored research project [Nopola and Vining, 2016; Nopola et al., 2017; Nopola et al., 2018], RESPEC developed downhole electric-resistance heater technology to create a seal of melted backfill and rock in support of nuclear waste disposal. During development, this project also identified, through numerical modeling and confirmed with field experiments, that the heater would induce compressive and tensile failure on laboratory-scale test blocks as well as in downhole tests at the Sanford Underground Research Facility (SURF, located in the former underground Homestake mine in Lead, SD) if not properly regulated.

The rock melt experiments were able to reach temperatures of 1,200 degrees Celsius (°C) in downhole tests at SURF, which is much greater than what will be required for thermal fracturing (nearly by an order of magnitude). The rock melt project evaluated several types of off-the-shelf materials that could be used to maintain cost competitiveness. Using a low-resistance heater with relatively high voltage and low amperage reduced the cable diameter, which is an important consideration for both cost and buoyancy (if wireline technology will be used). The much lower temperatures required for inducing breakouts compared to melting rock eliminate some of the engineering challenges of the rock melt sealing system. Therefore, the technology readiness level of the thermal breakout concept has already been demonstrated but still needs to be quantified and validated.

The DOE recently sponsored the RESPEC team to develop, validate, and field test an approach to measure the most compressive stress in the deep subsurface that induces breakouts by heating the rock and achieving breakouts through the rock's thermoelastic expansion. The key components that support this technology already exist: (1) breakouts can be used to measure maximum compressive stresses, (2) the impact of thermal-mechanical response in the deep subsurface is widely recognized, and (3) the basic technology for downhole-resistive heaters is established. The final objective of this 4-year DOE-sponsored research project is to develop a downhole thermal tool that will raise the local temperature of the rock to create compressive breakouts, which provides a means for consistently measuring the maximum horizontal stress. The tool will include acoustic-emission sensors to determine the onset of breakout behavior and locate the source of emissions around the hole.

Theory and Approach

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

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

where:

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

S_{Hmax} = most-compressive in situ horizontal stress

S_{hmin} = least-compressive in situ horizontal 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.

The value of S_{hmin} can be determined using standard hydraulic fracturing tests or drilling-induced fractures. The mud weight can be calculated based on density or measured using downhole transducers. If allowed time to equilibrate, the pore pressure in the immediate borehole surface is equal to the mud weight. Additional measurements required are the elastic properties of the rock and the thermal expansion coefficient. All of these additional properties can be measured in the laboratory. Additionally, correlations to elastic properties from downhole sonic logs are also widely used [Jaeger and Cook, 1979], and weighted averages of thermal expansion based on the quartz content (which has a higher thermal expansion coefficient relative to other minerals) are generally accurate [Robertson, 1988]. Based on these parameters, the equation above indicates that an induced thermoelastic expansion will cause a proportional increase in the hoop stress, which could potentially exceed the rock's strength and result in the formation of a compressive borehole breakout.

As a basic example, Figure 1b shows the calculated hoop stress on the borehole surface for dry conditions, typical rock properties, and an in situ stress state where S_{Hmin} = 20 MPa and S_{Hmax} = 40 MPa. This in situ stress state is similar to the Collab/kISMET field site at the SURF facility, where borehole breakouts are not currently present. Calculations using analytical solutions show that a 75°C temperature increase will produce a borehole breakout with a width of approximately 60 degrees when using an average UCS of 120 MPa. This simple analytical solution provides a feasibility proof-of-concept for inducing thermal breakouts. Additionally, if the maximum horizontal stress is assumed to be unknown but a measurement of the breakout width is obtained (w_{BO}), the equation above can be easily rearranged to back-calculate the maximum horizontal stress based on the same input parameters. This maximum horizontal stress calculation based on the thermally induced breakout width is the foundation of the thermal breakout technology. More detailed analysis and testing are currently in progress for the DOE-sponsored research project to account for many of the real-world complexities.

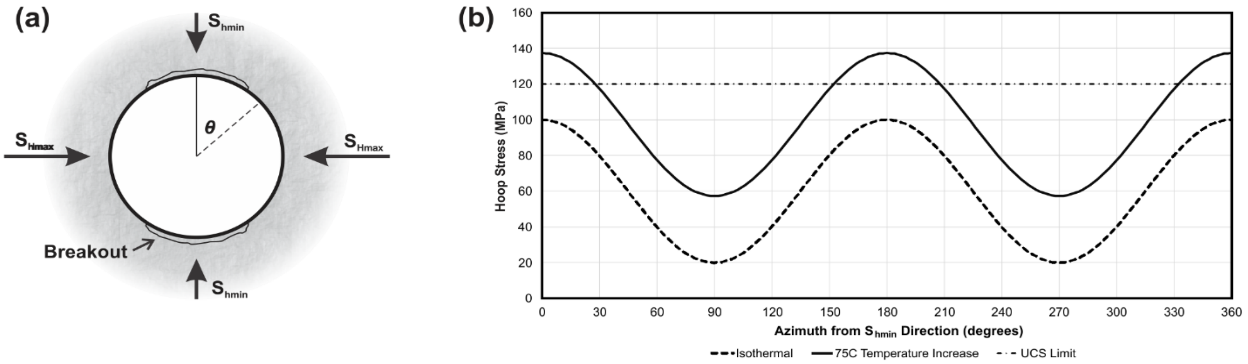

Figure 1. (a) In situ stress components and breakout. (b) Calculated hoop stress for SURF initial conditions and with a 75°C temperature increase.

This thermal breakout technology will be developed and proven based on a combination of numerical modeling, laboratory testing, and small- and full-scale field testing. As a final outcome, we expect to provide industry with a proven tool that will advance our ability to measure and understand the in situ stress state underground.

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