Weakness plane controlled breakouts: examples and analyses from a deep borehole in a tilted anisotropic formation

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Summary

By far, borehole breakouts provide the most important simple indicator of crustal stress directions. The breakout azimuths are conceptually linked to stress orientations via near-borehole stress distribution calculations using Kirsch's equations (1898) for isotropic elastic rocks. Often, however, the elastic properties and strengths of both layered sedimentary and foliated metamorphic rocks are anisotropic. A rock's anisotropic strength can be further complicated by a single plane of weakness, the slip of which means that breakouts can occur at azimuths differing from those expected under the standard isotropic assumptions leading to erroneous stress azimuth interpretations. Here, we provide ultrasonic image log examples of foliation-controlled breakouts from a portion of a vertical wellbore drilled deep into the cratonic basement in NE Alberta. Over this interval (1650-2000m) the average breakout azimuth is N100°E: about 40° rotated from the general expected NE-SW compression. The breakout failure patterns appear as opposing crescent moon shapes. The azimuths of the peaks and troughs of these breakouts correlate with the orientation of the metamorphic foliations. We used a recently developed program **EASAfail** (Wang et al., 2021, 2022) to model the breakout failure pattern around the wellbore by taking the slippage failure into account. The model demonstrates that the observed breakout orientations at N100°E are consistent with the expected NE-SW compression when the textured anisotropic strength of foliation planes are included. This work demonstrated by a field example highlights that the existence of strength anisotropy can affect the overall failure pattern and that interpreting the breakout orientations at a face value under Kirsch-like assumptions can lead to errors. Therefore, weakness plane controlled breakouts should be taken into consideration when conducting in-situ stress analysis, especially in the undergoing laminated unconventional shale gas exploration and in the geothermal exploration of foliated metamorphic rocks.

Study Area

The 2363m-deep vertical wellbore locates in northeast Alberta, Canada, 30km west of Fort McMurray (56°45'N, 111°33'W). The wellbore was first drilled to 1649.0m in 1994 and was deepened to 2363.3m to test the novel hypothesis of deep hydrocarbon generation in the basement; the wellbore hereinafter is referred to as the Hunt well. The Hunt well is drilled through 541m in the Phanerozoic Western Canadian Sedimentary Basin (WCSB) and 1822m into the foliated meta-granites of the Taltson Magmatic Zone.

As a part of the geothermal activities associated with the Helmholtz-Alberta Initiative, temperatures were measured in the well in 2010 (Majorowicz et al., 2014). New high-resolution seismic and VSP data were collected in 2011 (Chan, 2013; Chan & Schmitt, 2015a) with corresponding studies on the age of the core (Walsh, 2013) and the rock anisotropy (Chan &

Schmitt, 2015b). The ultrasonic image logs described here were obtained in an extensive logging program in the well in later 2013.

Methods

Breakouts (BO) were firstly determined from the Ultrasonic Borehole Imager (Schlumberger UBI™) image and caliper logs. Pairs of failure zones separated by 180° with a smaller amplitude and longer travel time of the reflected echo compared to the original wellbore radius in UBI image logs and elongations of caliper logs in one arm are indicators for BOs. The ultrasonic images are of high quality showing distinctly the compositional related variations in the borehole wall acoustic reflectivity and allowing for interpretation of the foliation orientations over much of the borehole.

The state of stress was further inverted from the observed failure pattern and foliations using a recently developed program **EASAfail** (Wang et al., 2021, 2022) that accounts for variations in stress concentration near the borehole due to anisotropic elastic properties (Li et al., 2019) as well as anisotropic rock strengths.

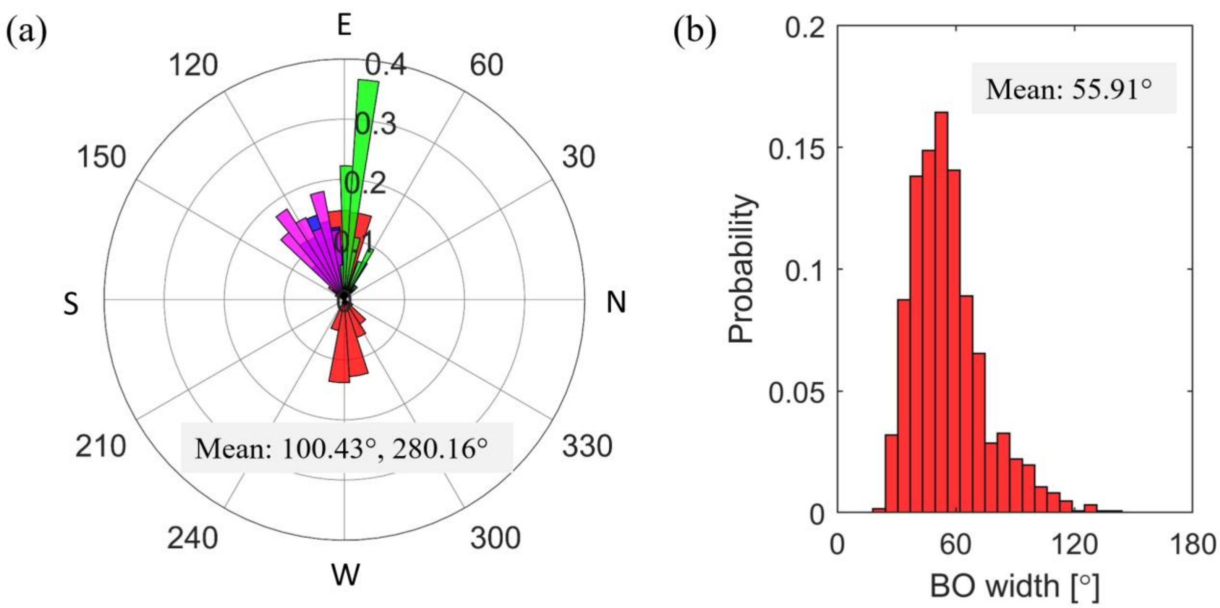

Figure 1 Statistics of breakout geometry at 1650-2000m. (a) Breakout orientations observed from UBI and caliper logs. Red, blue, magenta, and green bars represent the breakout orientation observed from UBI logs in 2013 and caliper logs in UBI PPC 2013, DSI PPC 2013 and Dipmeter 2011 respectively. (b) Breakout widths observed from UBI logs.

Results and Discussions

Here, we focus on only the interval from 1650-2000m depth characterized by uniform foliation and breakout orientations, and a more detailed discussion over the entire well is forthcoming.

Manual interpretation of the UBI images indicates that breakout azimuths at N100°E and breakout widths of 56° cover a total depth of 130m (Fig. 1). The breakout azimuths identified from caliper logs overlap with those determined manually from UBI logs, suggesting the good consistency between different tools. However, the breakout azimuth at N100°E observed here in the crystalline basement is not at all comparable to the breakout azimuth at N135°E commonly observed in the overlying sediment (Bell and Gough, 1979). Therefore, we refrained from interpreting the orientation of maximum horizontal stress $\boldsymbol{\sigma_{SH}}$ is N10°E based on the assumption of material isotropy before further analyses.

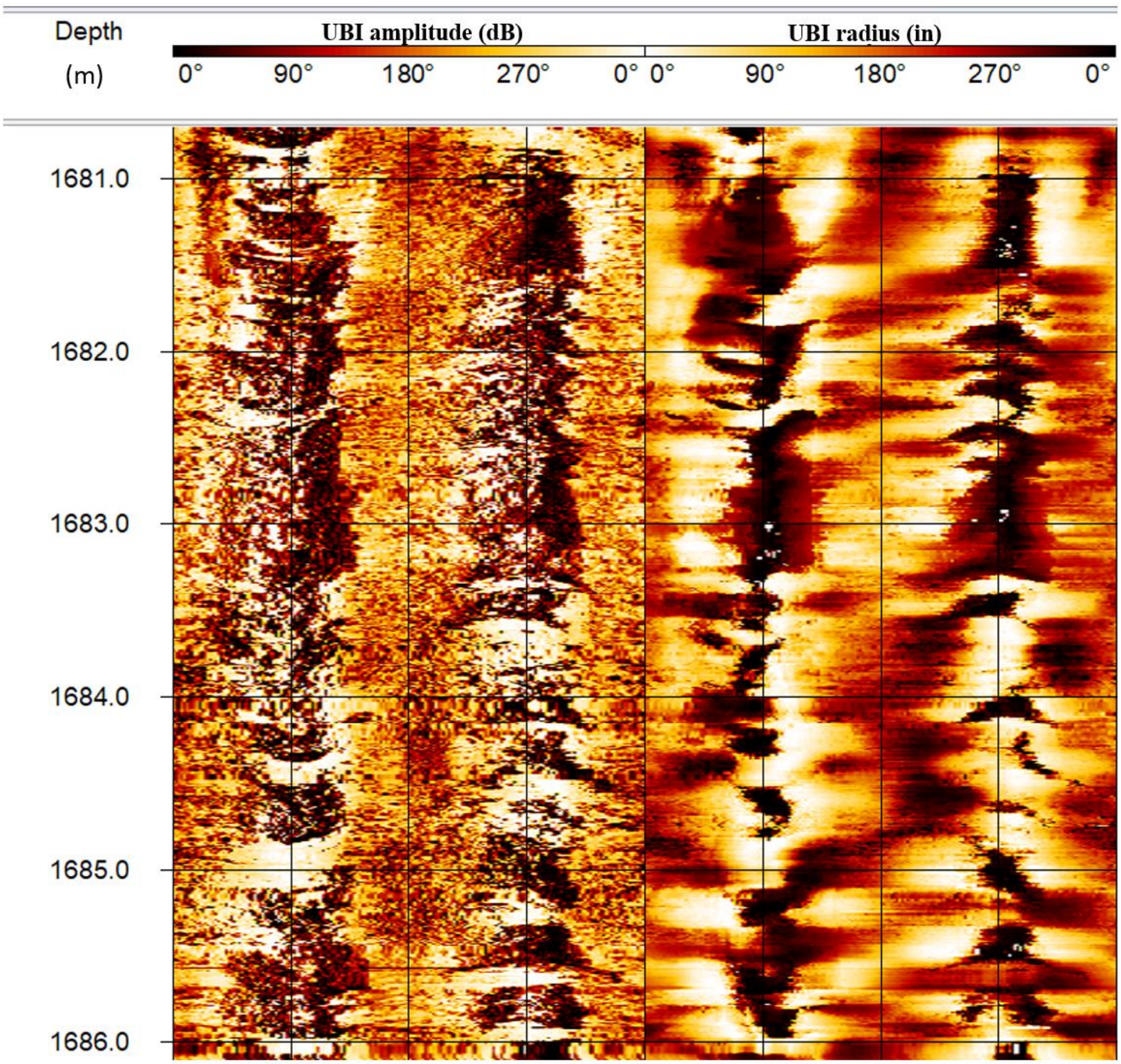

Figure 2 A portion of UBI image logs. Opposing crescent moon shapes are observed in breakouts.

A closer examination of breakouts in UBI logs shows that breakouts through this zone have the appearance of opposing crescent moon shapes (Fig. 2) suggesting that the potential slippage failure along the foliation planes might bias the breakout failure patterns. Moreover, foliations were discerned from UBI logs and have a mean dip direction of 97° and a mean dip angle of 50°, the dip direction of which is highly correlated to the observed breakout orientation (N100°E). To test whether failure along the foliation with a constant far-field stress direction similar to that in the sediment could explain the observed breakout patterns, the far-field stress information was inverted using the program proposed by Wang et al. (2021, 2022) to forward model the failure pattern with different combinations of input stress and strength parameters. An Andersonian stress state is assumed and the far-field maximum horizontal compressive stress azimuth $\boldsymbol{\alpha_{SH}}$ is set to N50°E, which is taken from the stress direction interpreted from drilling-induced fractures in 22 wells located ~100km southwest of the Hunt well (Morin, 2017).

Modeled results in Fig. 3 show that even though $\boldsymbol{\alpha_{SH}}$ is set to N50°E, the modeled breakout fails at N99°E, consistent with that has been observed in geophysical logs. Instead of failure in the intact rock matrix as commonly assumed in isotropic formations, rocks fail in the weakness plane of foliations, resulting in the breakout azimuth (N99°E) different from the input far-field minimum horizontal stress direction ($\boldsymbol{\alpha_{SH}}$ +90° = N140°E).

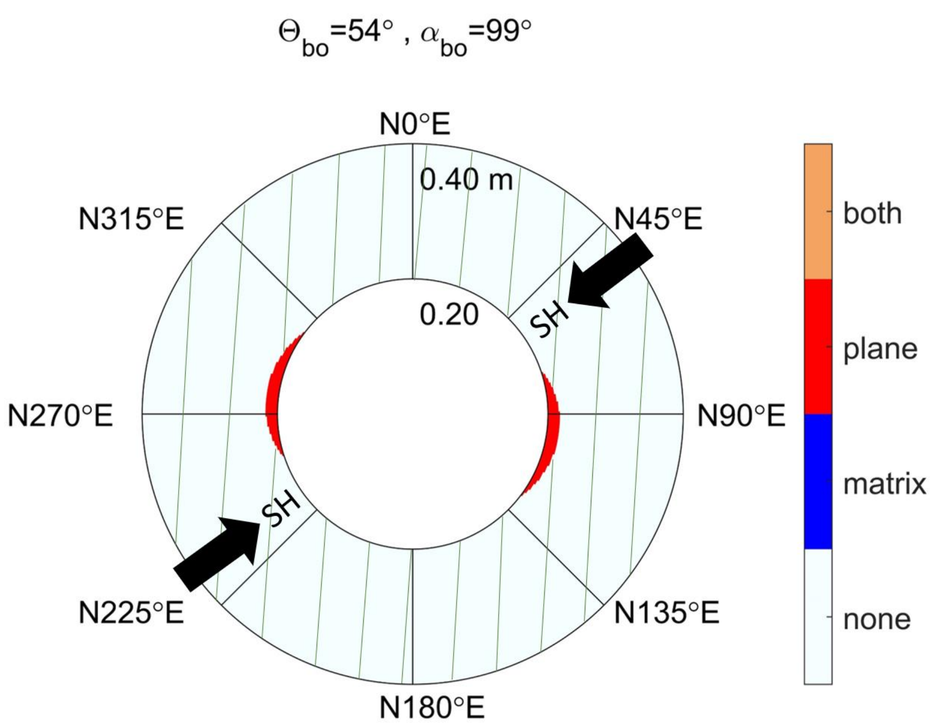

Figure 3 Modeled failure pattern. Parallel solid green lines represent the strike direction of the foliation planes. Light blue, dark blue, red, and orange areas represent no failure, failure only in the rock matrix, failure only in the weak plane and failure in both the rock matrix and the weak plane respectively. Two numbers at the top represent the breakout width $\boldsymbol{\Theta_{bo}}$ *and azimuth* $\boldsymbol{\alpha_{bo}}$ *respectively.*

Conclusions

The case study in Alberta suggested that the far-field minimum horizontal stress directions cannot be automatically equated to the observed breakout orientations when conducting stress analysis. Sedimentary layers, metamorphic foliations and aligned fracture sets could act as a plane of weakness with a slippage tendency. The slippage failure along the weakness plane biases the breakout that is normally assumed to occur due to the shear failure of the intact rock matrix. Cares must be taken when inferring stress information from drilling-induced failures due to the complexity of breakouts in anisotropic formations.

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