Borehole breakout analysis from four-arm caliper logs

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Introduction

Borehole breakouts are an important indicator of horizontal stress orientation, particularly in aseismic regions and at intermediate depths (<5 km). Approximately 19% of the stress orientation indicators in the World Stress Map (WSM) database have been determined from borehole breakouts. Here we present the procedures for interpreting borehole breakouts from four-arm caliper log data and for WSM quality ranking of stress orientations deduced from borehole breakouts.

Borehole Breakouts

Borehole breakouts are stress-induced enlargements of the wellbore cross-section (Bell and Gough, 1979). When a borehole is drilled the material removed from the subsurface is no longer supporting the surrounding rock. As a result, the stresses become concentrated in the surrounding rock (i.e. the wellbore wall). Borehole breakout occurs when the stresses around the borehole exceed that required to cause compressive failure of the borehole wall (Zoback et al., 1985; Bell, 1990). The enlargement of the wellbore is caused by the development of intersecting conjugate shear planes, that cause pieces of the borehole wall to spall off (Figure 1).
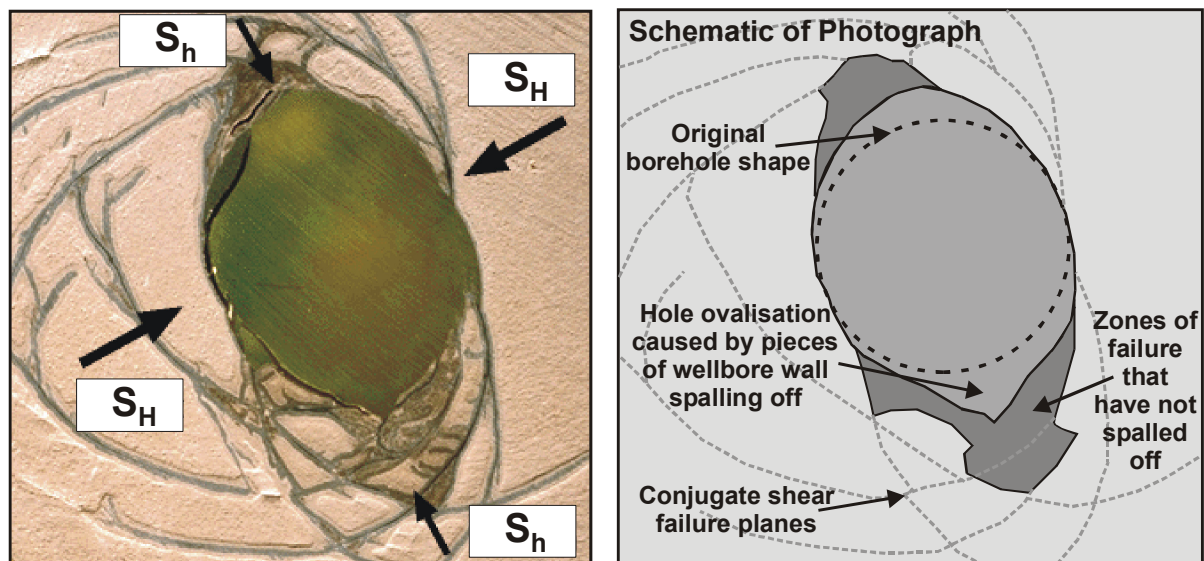

Figure 1: Results of a hollow cylinder lab test simulating borehole breakout (performed by the CSIRO Division of Geomechanics). Intersection of conjugate shear failure planes results in enlargement of the cross-sectional shape of the wellbore. S_H and S_h refer to the orientations of maximum and minimum horizontal stress respectively.

Around a vertical borehole stress concentration is greatest in the direction of the minimum horizontal stress S_h. Hence, the long axes of borehole breakouts are oriented approximately perpendicular to the maximum horizontal stress orientation S_H (Plumb and Hickman, 1985).

Four-Arm Caliper Tools

Four-arm caliper tools (such as Schlumberger's HDT, SHDT and OBDT) are commonly run in the hydrocarbon industry to obtain information about the formation (primarily strike and dip of bedding) and to estimate the volume of cement required for casing. However, unprocessed oriented four-arm caliper logs can also be used to interpret borehole breakouts. The logs needed for interpretation are (nomenclature given on Figure 2):

- Azimuth of pad 1 (P1AZ) relative to magnetic north;

- diameter of the borehole in two orthogonal directions ('Caliper 1' (C1) between pad 1 and 3 and 'Caliper 2' (C2) between pad 2 and 4);

- borehole deviation (DEVI) from vertical;

- azimuth of borehole drift (HAZI), and;

- bearing of pad 1 relative to the high side of the hole (RB).

Depth, C1, C2 and DEVI must be available to interpret breakouts. However, only two of P1AZ, RB and HAZI are necessary as the missing log can be calculated using following equation:

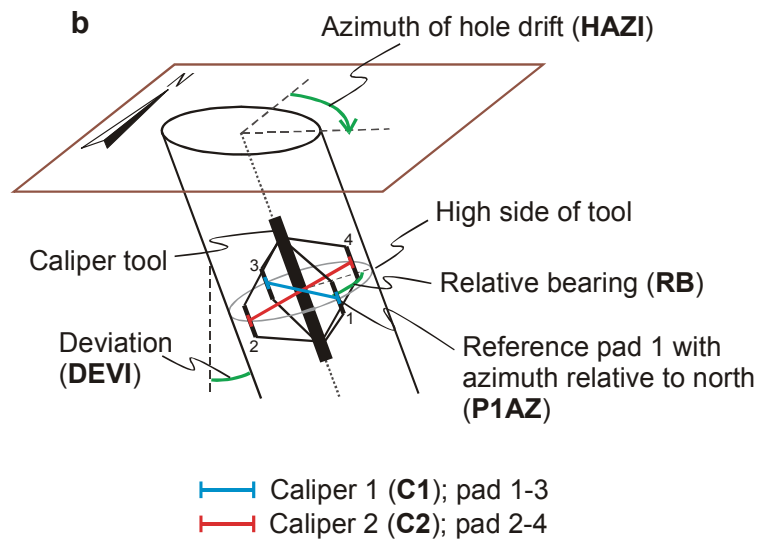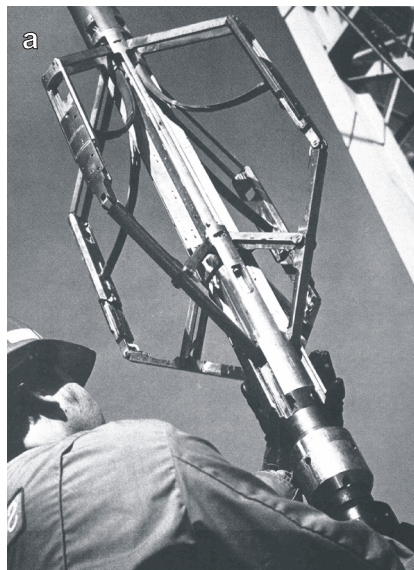$$P1AZ = HAZI + atan\frac{\tan RB}{\cos DEVI}$$

Figure 2: a) The Schlumberger High-resolution Dipmeter Tool (HDT; from Plumb and Hickman, 1985). Note the four orthogonal caliper arms. b) Geometry of the four-arm caliper tool in the borehole and data used for interpreting borehole breakouts.

Interpreting Breakouts from Four-Arm Caliper Data

The four-arm caliper tool will rotate as it is pulled up the borehole due to cable torque. However, the tool stops rotating in zones of borehole enlargement if one caliper pair becomes 'stuck' in the enlargement direction (Plumb and Hickman, 1985; Figures 3b and 4). The combined use of the six logs listed above enables the interpreter to distinguish zones of stress-induced breakouts from other borehole enlargements such as washouts and key seats (Figure 3 and 4). To identify zones of breakout and the orientation of the enlargement we suggest the criteria in Table 1 (based on Plumb and Hickman, 1985; Bell, 1990; Zajak and Stock, 1997):

Table 1: Criteria for interpreting borehole breakouts from four-arm caliper data.

1. Tool rotation must cease in the zone of enlargement.

2. There must be clear tool rotation into and out of the enlargement zone.

3. The smaller caliper reading is close to bit size. Top and bottom of the breakout should be well marked.

4. Caliper difference has to exceed bit size by 10 %.

5. The enlargement orientation should not coincide with the high side of the borehole in wells deviated by more than 5°.

6. The length of the enlargement zone must be greater than 1 m.

Breakout orientations can rotate in inclined boreholes and may not always directly yield the horizontal stress orientations (Mastin, 1988; Peska and Zoback, 1995). Hence, the maximum horizontal stress orientation can only be reliably estimated from breakouts in approximately vertical boreholes (less then 10° deviation from vertical). All orientations measured from four-arm caliper tools need to be corrected for the local magnetic declination at the time of measurement.
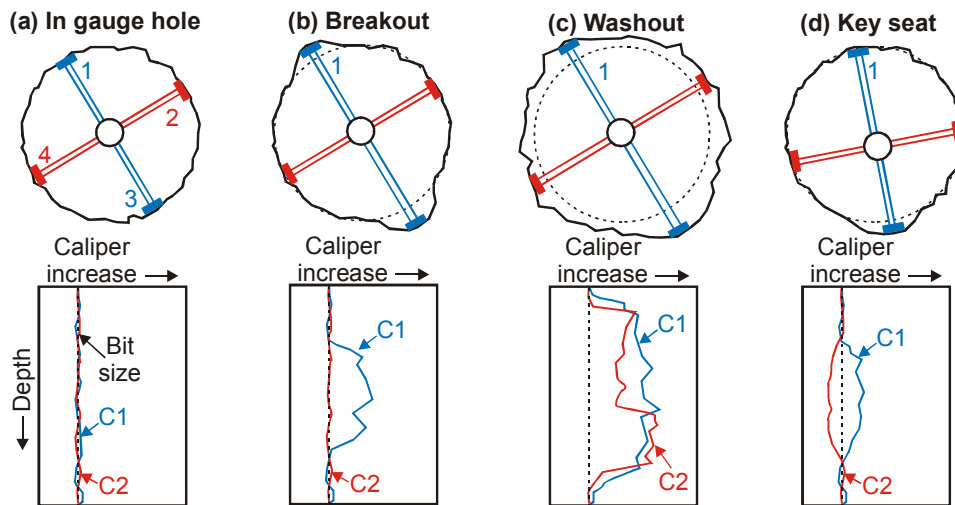

Figure 3: Common types of enlarged borehole and their caliper log response (after Plumb and Hickman, 1985).
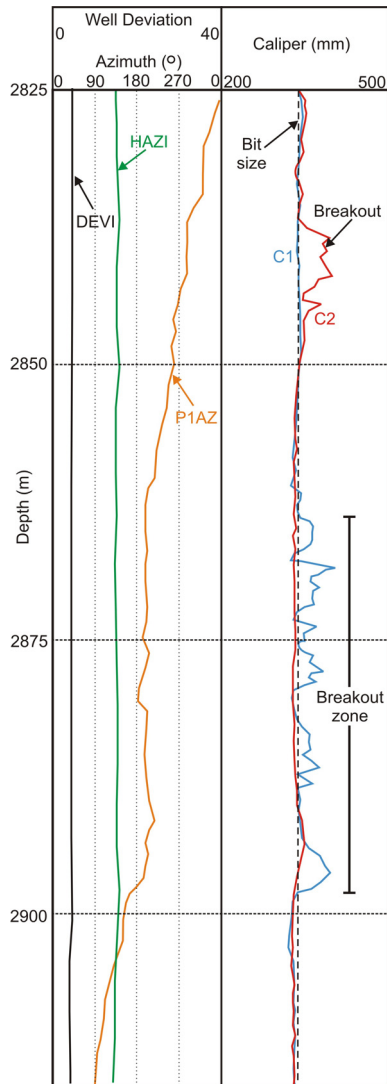
Figure 4: Four-arm caliper log plot displaying borehole breakouts. Caliper one (C1) locks into breakout zone from 2895-2860 m (P1AZ ≈ 200°), the tool then rotates 90° and Caliper two (C2) locks into another breakout from 2845-2835 m (P1AZ ≈ 290°). Both breakout zones are oriented approximately 020° and suggest a S_{Hmax} direction of 110°. The borehole is deviated 4° (DEVI) towards 140° (HAZI).

Determining the Average Maximum Horizontal Stress Orientation: Circular Statistics

Breakout orientations are bimodal data. Data between 180° and 360° are equivalent to those between 0° and 180° (S_H varies between 0° and 180°). According to Mardia (1972) the mean breakout azimuth θ_m (i.e. S_h) of a population of n picked breakout directions θ_i is derived by first transforming the angles to the 0-360° interval.

$$\theta_i^* = 2\,\theta_i$$

Then, the direction cosine and sine have to be added and averaged either by the number of measurements (for number weighted mean) or by the total breakout length L (length weighted mean).

<table>
<tr><td align="center">number weighted:</td><td align="center">length weighted:</td></tr>
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$$C = \frac{1}{n}\sum_{i=1}^{n} \cos\theta_i^* \qquad\qquad L = \sum_{i=1}^{n} l_i$$

$$S = \frac{1}{n}\sum_{i=1}^{n} \sin\theta_i^* \qquad\qquad C = \frac{1}{L}\sum_{i=1}^{n} l_i \cos\theta_i^*$$

$$S = \frac{1}{L}\sum_{i=1}^{n} l_i \sin\theta_i^*$$

where l_i is the length of breakout i with orientation θ_i^*.

The mean azimuth results from: $\qquad\qquad \theta_m = \frac{1}{2}\arctan(S/C)$

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(Make sure that the angles are converted from rad into deg!)

The standard deviation s_o is derived as

$$s_o = 360/2\pi \, (-1/2 \; \log_e R)^{1/2} \qquad \text{with} \qquad R = (C^2 + S^2)^{1/2}.$$

World Stress Map Quality Ranking

All data in the WSM database are quality ranked to facilitate comparison between different indicators of stress orientation (e.g. focal mechanism solutions, drilling-induced tensile fractures, overcoring). The quality ranking criteria for stress orientations determined from breakouts interpreted from four-arm caliper logs is presented in Table 2.

Table 2: World Stress Map quality ranking criteria for breakouts (s.d. = standard deviation) (Sperner et al., 2003).

A-Quality	B-Quality	C-Quality	D-Quality	E-Quality
Wells that have ten or more distinct breakout zones with a combined length > 300 m; and with s.d. ≤ 12°	Wells that have at least six distinct breakout zones with a combined length > 100 m; and with s.d. ≤ 20°	Wells that have at least four distinct breakouts zones with a combined length > 30 m; and with s.d. ≤ 25°	Wells that have less than four breakouts zones or a combined length < 30 m or with s.d. > 25°	Wells with no reliable breakouts detected or with extreme scatter of breakout orientations (s.d. > 40°)

References

Bell, J.S. (1990): Investigating stress regimes in sedimentary basins using information from oil industry wireline logs and drilling records. - In: Hurst, A., M. Lovell and A. Morton (eds.): Geological applications of wireline logs, Geol. Soc. Lond. Spec. Publ., 48, 305-325.

Bell, J.S. and D.I. Gough (1979): Northeast-southwest compressive stress in Alberta: evidence from oil wells. - Earth Planet. Sci. Lett., 45, 475-482.

Mardia, K.V. (1972): Statistics of directional data: probability and mathematical statistics. - 357 pp., London (Academic Press).

Mastin, L. (1988): Effect of borehole deviation on breakout orientations. - J. Geophys. Res., 93, 9187-9195.

Peska, P. and M. D. Zoback (1995): Compressive and tensile failure of inclined well bores and determination of in situ and rock strength. - J. Geophys. Res., 100, 12791-12811.

Plumb, R.A. and S.H. Hickman (1985): Stress-induced borehole enlargement: a comparison between the four-arm dipmeter and the borehole televiewer in the Auburn geothermal well. - J. Geophys. Res., 90, 5513-5521.

Sperner, B., B. Müller, O. Heidbach, D. Delvaux, J. Reinecker and K. Fuchs (2003): Tectonic Stress in the Earth's Crust: Advances in the World Stress Map Project. - In: Nieuwland D. (ed.): New Insights into Structural Interpretation and Modelling, Geol. Soc. Lond. Spec. Publ., 212, 101-116.

Zajac, B.J. and J.M. Stock (1992): Using Borehole Breakouts to Constrain the Complete Stress Tensor: Results from the Sijan Deep Drilling Project and Offshore Santa Maria Basin California. - J. Geophys. Res., 102, 10083-10100.

Zoback, M.D., D. Moos, L.G. Mastin and R.N. Anderson (1985): Well bore breakouts and in situ stress. - J. Geophys. Res., 90, 5523-5530.