Borehole Breakout Method for Stress Determination – Theory and Practice –

K. Fuchs
B. Clauss

BOREHOLE BREAKOUT METHOD FOR STRESS DETERMINATION - THEORY AND PRACTICE -

K. FUCHS and B. CLAUß, Karlsruhe

Theory and application of borehole breakout analysis to determine the maximum horizontal principal stress direction

COX (1970) and BABCOCK (1978) were the first to investigate borehole breakouts in deep drillings. They observed that zones of elongated cross section, over a great depth interval of a drilling, show a constant preferential elongation direction which is independent from the stratigraphy. While BABCOCK (1978) interpreted this as a result of the interaction of the drillbit with pre-existing joints, BELL & GOUGH (1979) concluded that these borehole cross section elongations are breakouts of the borehole wall. These are caused by stress concentration around the hole in a regional stress field with horizontal principal stresses of different magnitudes. The orientation of the long axes of the breakout elongation is perpendicular to the maximum horizontal stress and gives the possibility for determining the orientation of the principal stresses. BLÜMLING ET AL. (1983), ZOBACK ET AL. (1985) and PLUMB & HICKMAN (1985) improved the data processing and the criteria for the determination of borehole breakouts. ZOBACK ET AL. (1985) as well as SCHNEIDER (1985) calculated theoretically the breakout development. The hypothesis of BELL & GOUGH was confirmed by surveying and interpreting breakouts in crystalline and sediment drillings in various regions. A comparison of stress directions derived by earthquake fault plane solution and by Hydraulic Fracturing with those determined by breakout analysis also verified the method.

Prof.Dr.rer.nat. K.FUCHS and Dipl.-Geophys. B.CLAUß
Geophysical Institute, University of Karlsruhe, D-7500 Karlsruhe 21

1. Theory of breakouts caused by stress

To derive the analytical solution of the stress distribution around a borehole, the following assumptions are made: The hole is drilled in homogeneous rock with an anisotropic stress field parallel to one of the principal stress directions. This is the case for nearly vertical wells in less active tectonic regimes where one of the principal stresses is assumed to be vertical. The surface of the borehole wall created by drilling leads to a stress concentration, which can be described by the KIRSCH-equations. These were derived by KIRSCH (1898) for the case of a circular well in an infinite homogeneous plate with the stresses S_H and S_h as major and minor stresses at infinity (see fig. 1). A description of this derivation is found in SCHNEIDER (1985) and TIMOSHENKO and GOODIER (1951).

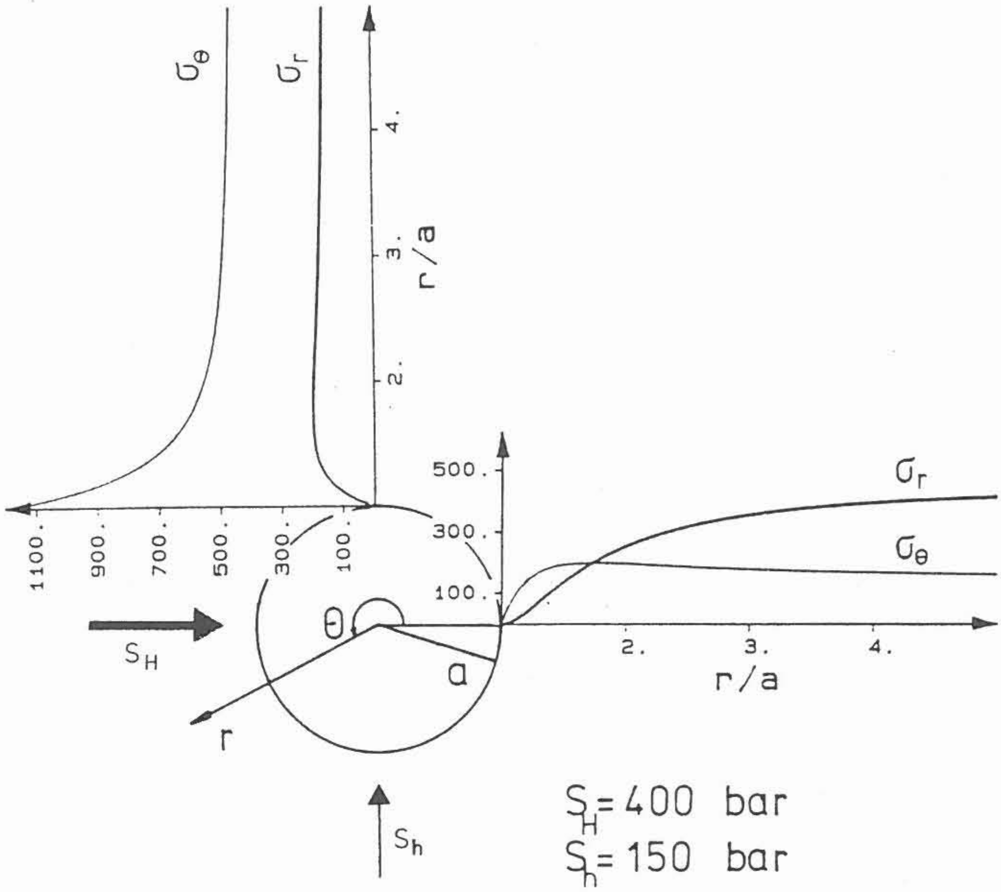

Fig. 1: The radial and tangential stresses for the angles θ = 0° and θ = 90° (after MASTIN, 1984), calculated with the KIRSCH-equations for a borehole under compression.

KIRSCH-equations:

Radial Stress

$$\sigma_r = \frac{S_H + S_h}{2} \left(1 - \frac{a^2}{r^2}\right) + \frac{S_H - S_h}{2} \left(1 + 3\frac{a^4}{r^4} - 4\frac{a^2}{r^2}\right) \cos 2\theta$$

Tangential Stress

$$\sigma_\theta = \frac{S_H + S_h}{2} \left(1 + \frac{a^2}{r^2}\right) - \frac{S_H - S_h}{2} \left(1 + 3\frac{a^4}{r^4}\right) \cos 2\theta$$

Shear Stress

$$\tau_{r\theta} = -\frac{S_H - S_h}{2} \left(1 - 3\frac{a^4}{r^4} + 2\frac{a^2}{r^2}\right) \sin 2\theta$$

If there is no stress at the wall of the hole r = a, the boundary conditions are $\sigma_r = \tau_{r\theta} = 0$, and we get

$$\sigma_\theta = (S_H + S_h) - 2(S_H - S_h)\cos(2\theta)$$

where $\sigma_\theta = 3S_h - S_H$ for $\theta = 0°$ and $\theta = 180°$, and $\sigma_\theta = 3S_H - S_h$ for $\theta = 90°$ and $\theta = 270°$.

In case of compression ($S_H > S_h \geq 0$; here compressional stresses are taken as positive) a maximum stress concentration at the borehole wall under the angles 90° and 270° is noted. Calculating the course of the stresses as a function of r/a and the ratio S_H/S_h we see that the stresses increase or decrease respectively to the values at a great distance to the borehole in less than 3 borehole radii (Fig. 1).

GOUGH & BELL (1981) applied a MOHR-COULOMB failure criterion together with the calculation of the stresses from the KIRSCH-equations. They determined those areas where the stresses exceeded the shearing strength of the rocks. The shear plains are constructed by use of the MOHR-COULOMB failure criterion at an angle of 22.5° in the direction of S_H. An elongation of no more than 8% is possible, as only those shear plains that start or end at the wall of the borehole wall lead to breakouts. If the sheared material breaks out of the borehole wall, borehole breakouts parallel to the direction of S_h are generated. Under an assumption of conjugate shear failures a dog ear shape is formed (see 2a). However, this hypothesis is deficient, because the fracturing of the material causes a new free surface to develop, inducing a change in stress concentration which will lead to further failure, a.s.o.

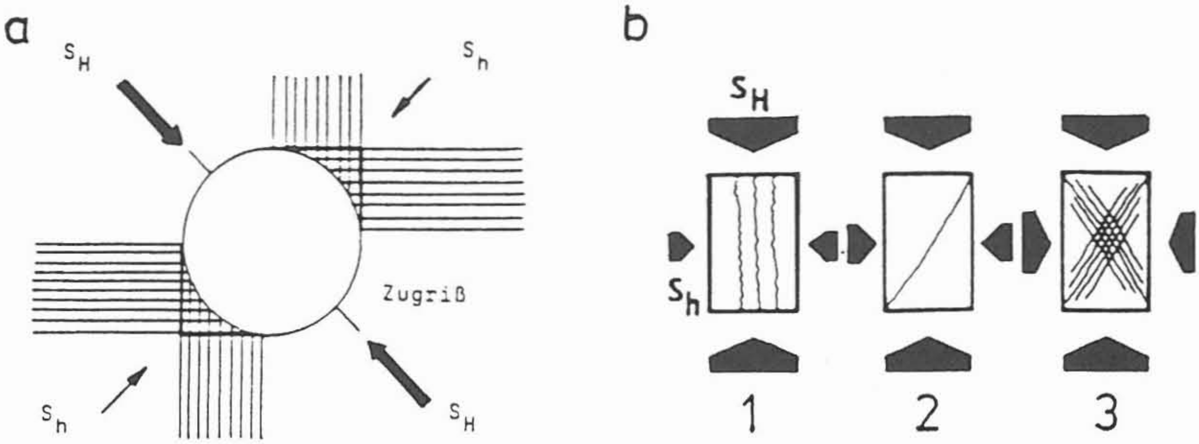

Fig. 2 a) Plot of the conjugated shear failure planes and tensile crack direction. The dark-edged parts of the drilling break off and elongate the borehole parallel to S_h. This results in a dog ear shape of the breakout (after GOUGH & BELL).

b) The behaviour of the fracturing of the rocks at different confining pressures determined by triaxial laboratory studies. It is shown that at a low confining pressure fractures occur parallel to S_H (BECKER ET AL., 1984).

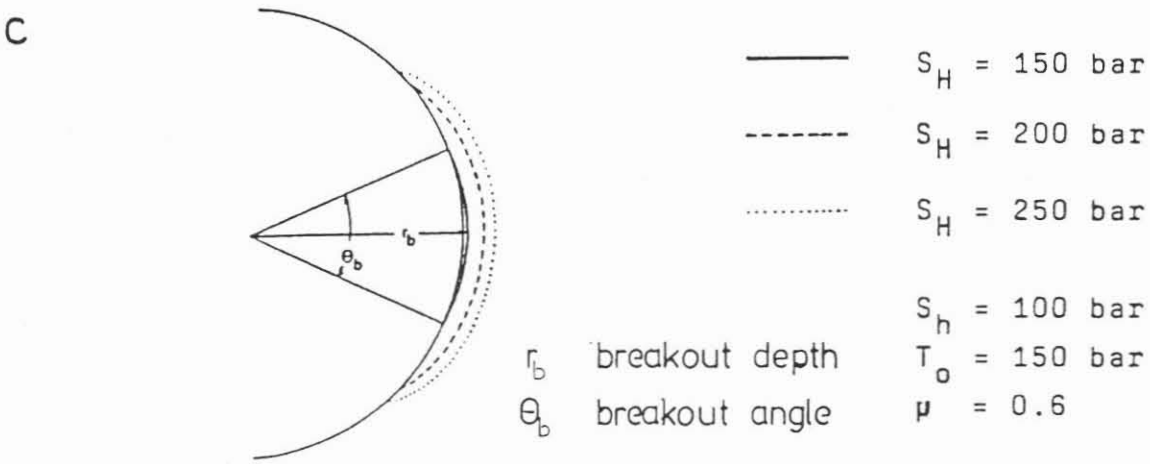

Fig. 2 c) Envelope of the region, where in assumption of the COULOMB-NAVIER criterion for the shear failure the shearing strength is exceeded. The envelopes are presented as a function of $S_H : S_h$ (after MASTIN, 1984).

According to the value of the confining pressure in rocks different types of fracture occur, as was shown in laboratory experiments (LEON & WILHELM, 1910; GRIGGS & HANDIN; 1960). Whereas at a low confining pressure fractures parallel to the direction of S_H are observed, at higher confining pressure conjugated shear fractures develop (Fig. 2b).

ZOBACK (1982) and BLÜMLING (1986) calculated the geometry of the breakouts using the COULOMB-NAVIER fracture criterion and the stress distribution in the rocks around the borehole according to KIRSCH. The envelope of the zones where failure occurs leads to breakout geometries (Fig. 2c and 3) which are more like those observed. In contrast to the more general name "borehole elongation" only those elongations that show two fracture zones facing each other are called "breakouts" and are caused by stress concentration whereas other borehole elongations can be produced by other phenomena as natural hydraulic fractures or mechanical wear by drilling or drill fluids.

ZOBACK (1985), MASTIN (1984) and BLÜMLING (1983), as well as SCHNEIDER (1985) who used the Finite-Element-Method, investigated the possibility of determining the stress magnitude by analysis of the breakout geometry. Laboratory experiments by HAIMSON & HERRICK (1985) show that breakout depth and width are related to the state of stress. Measuring breakout depth r_b and breakout angle θ (Fig. 2) from laboratory tests allowed an estimate of the stress magnitudes even for large values of r_b and θ_b.

At in situ breakout measurements, however, a comparison of stress magnitudes calculated from breakout geometry with those determined by Hydraulic Fracturing tests shows a correspondence only for small breakout depths.

2. Data acquisition and data processing

Elongations of the borehole wall can be measured by optical (borehole camera), mechanical (orientated four-arm-caliper tool) and acoustic (seismo-acoustic televiewer) methods.

2.1. Measurement with four-arm-caliper

The four-arm-caliper tool as a part of the dipmeter tool is a standard logging tool. The dipmeter determines the strike and dip of bedding planes by registration of formation resistivity on four orthogonal pads. Those pads are hydraulically extended to the borehole wall and therefore monitor the hole geometry as the tool is drawn up the borehole. Those geometry measurements allow an estimate of the cementation volume which is important for the casing (Fig. 3). The distance between the opposite pads is recorded. The distance between pad 1 and 2 is called caliper 1-3 and between pad 2 and 4 caliper 2-4. In addition, the deviation of the well from the vertical and the strike of the projection of the drilling at the surface (Hole Azimuth) are determined for every depth.

To orient the pads the angle (Relative Bearing) between pad 1 and the direction from the middle of the tool to the "High Side of Tool" is measured in a plane perpendicular to the hole axis (Fig. 3b). For wells with a small deviation the angle between pad 1 (P1AZ) and north is derived from the sum of Hole Azimuth (HAZ) and Relative Bearing (RB):

$$P1AZ = HAZ + RB$$

For stronger deviations the angles RB and HAZ are measured in two different planes. The angle between the two planes is given by the deviation of the borehole. To determine the orientation of pad 1 the following equation is needed:

$$P1AZ = HAZ + ARCTAN \left(\frac{TAN\ (RB)}{COS\ (DEVI)} \right)$$

Four-arm-caliper measurements are carried out by drawing up the tool (as it is done with most tools). As the tool is drawn up it is rotating clockwise because of the tension of the cable at which the tool is hanging and because of the amount of twisting of the cable. The borehole shape is recorded over the depth interval in which the tool rotates 90°. The nearer to the surface the slower the rotation the decreasing cable torque (PODROUZEK & BELL, 1985) and the larger the depth interval for a 90°-rotation.

The measured caliper 1-3, caliper 2-4, RB, HAZ and Deviation are either presented in so-called logs or on magnetic tapes (Fig. 3).

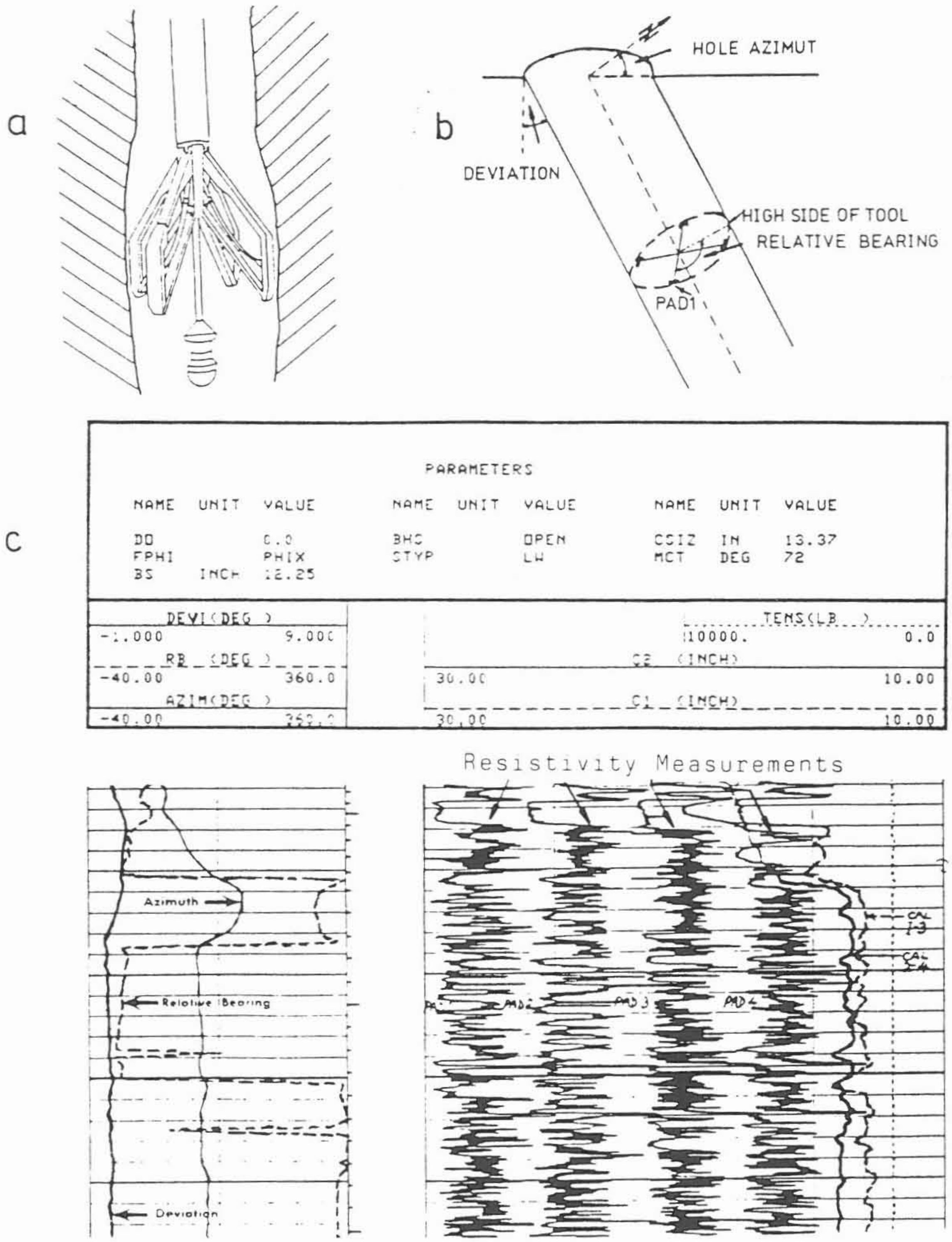

Fig. 3: a) four-arm-caliper tool

b) illustration of the orientation of the pads

c) recording of the calipers C1 and C2 and the angles of orientation Hole Azimuth, Relative Bearing and Deviation as a log.

2.2. Criteria for the determination of the borehole breakouts

The tool geometry forces certain restrictions upon the breakout size. The pads have a length of 30 to 60 cm and a width of about 6 cm. Therefore, breakouts that do not exceed these values cannot be recorded. PLUMB & HICKMAN (1985) set up the following issues to determine breakouts.

- The tool is rotating beyond and below a borehole breakout.
- The rotation stops over the breakout zone. The required breakout depth is about 0.6 cm which means a diameter difference of 12 mm.
- The borehole elongation is clearly seen in the log. In contrast to the so-called washouts (Fig. 4) only one pair of pads show a relatively sharp ascent and descent of the borehole diameter.
- The smaller borehole diameter is nearly equal to the bit size. If both caliper values are higher than the bit size, the shorter pad distance must show a smaller variation of the borehole diameter.
- The elongation direction should not correspond to the Hole Azimuth for a longer time if the drilling deviates from the vertical.

Using the above criteria some further explanation is needed for data interpretation:

At very shallow breakouts the tool rotation is only slowing down and it does not stop. This results in a great inaccuracy of the determination of the direction, especially in zones where the tool is rotating very slowly. Besides, the tool rotation might stop during a borehole elongation which might not necessarily be a breakout. Therefore this criterion alone is not decisive for finding borehole breakouts. The breakouts may be camouflaged by elongations all around the borehole wall, the so-called washouts. Instead of a sudden rise of the caliper only a gradual increase can be distinguished, which is typical for washouts (Fig. 4).

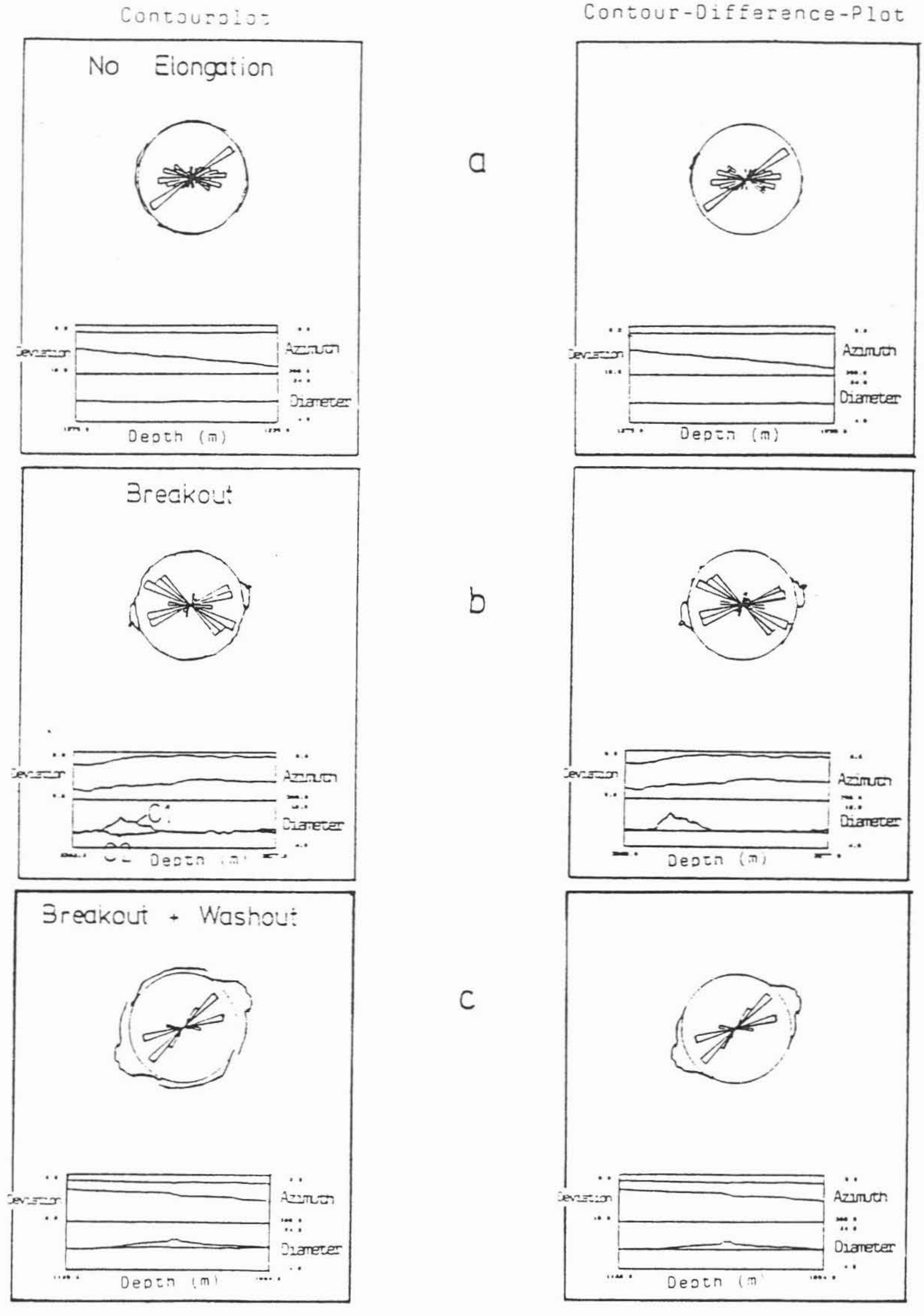

Fig. 4: Examples for different kinds of borehole elongations. Left hand side are shown the borehole outline (contour), right hand side the presentation of the caliper differences. For detailed explanations see above.

These washouts are effected by mechanical strain of the rocks during the drilling or by interference with the drill fluid. They do not show a preferred orientation over large intervals in the well (COX, 1983).

According to BABCOCK (1978) and BLÜMLING (1986), at non vertical drillings borehole elongation can be induced by the weight effects of the drilling bars. Therefore, elongations showing a preferred orientation towards the drilling (Hole Azimuth) are not considered as breakouts.

Fig. 4 shows a few combinations of measured caliper data and their interpretation.

2.3. Determination of borehole breakouts using data processing

First of all the data curves which are drawn on logs are digitized to enable an objective determination of the breakouts and their directions. Then, a so-called contour plot is produced, where the half of the measured caliper value is projected onto a plane in the corresponding and facing azimuths. Stacking the data over depth intervals of about 100 m gives an impression of the mean borehole contour in this interval (Fig. 4). In this case borehole breakouts might be covered by the caliper diameters that are produced by washouts of the borehole wall.

Therefore the difference plot was suggested by BLÜMLING (1986) to eliminate the influence of washout effects in the plots. In this case the difference of the caliper diameter (C1-3, C2-4) is computed and only the value of this difference is plotted in a polar coordinate diagram (Fig. 4).

Using this procedure borehole breakouts are desribed more clearly, when the actual contour plot is not able to display the breakout in an evident way because of the rotation velocity and the digitizing rate of the tool (Fig. 5).

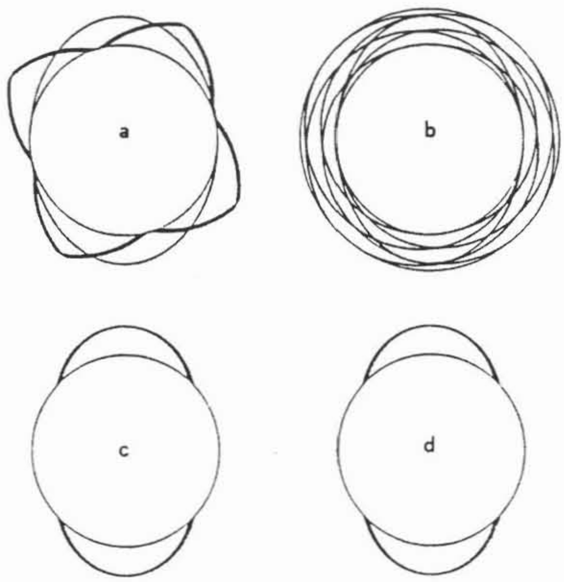

Fig. 5: Simulation of a caliper plot assuming a circular borehole superimposed by an elliptical elongation. Various contour plots for the same breakout geometry are maintained by different rotation velocities and digitizing rates (a and b). In contrast the caliper difference plots (c and d) show the direction of the borehole elongation in each case.

Additionally BLÜMLING (BECKER ET AL., 1984) suggested a weighted statistical interpretation, which is very useful in cristalline drilling with small breakout depths. The azimuthal scattering of the pad position is weighted with the caliper differences. This is presented as a rose diagram of the contour and the contour difference plot respectively. However, the interpretation of the rose diagrams alone might lead to systematical mistakes in determining the stress direction. This is caused by the stopping of the tool rotation that does not occur at the middle of the breakout, but at the edge where the pad begins to leave the borehole breakout. Depending on how distinctive this behaviour is (Fig. 6), the rose diagram will show its maximum in direction of the breakout edge. Assuming S_H is perpendicular to the maximum of the diagram and the tool rotation is clockwise, principal stress directions are determined that are systematically too high. Therefore, for an interpretation it is necessary where use is made of every available criterion.

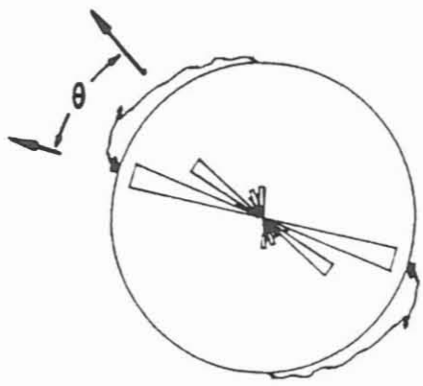

Fig. 6: Example for a possible wrong interpretation of the breakouts. The angle of the maximum of the direction statistic is smaller than the true breakout direction. (Here the tool rotated anti-clockwise)

Using digital data processing zones, where at high deviation of the well elongations point in direction of the well azimuth can be found and eliminated. Normally, in the interpretation those values that show a deviation of over 1° and RB 10°, are neglected to restrain the mechanical effects of the drilling bars.

2.4. Abnormal breakout directions

In the compressive case ($S_H > S_h \geq 0$) breakouts of the borehole wall occur parallel to the direction of S_h. As interpretations of borehole breakouts in North America (PLUMB & HICKMAN, 1985) showed, the breakout direction within a well is not necessarily consistent and in zones near the surface the direction might be perpendicular to those in deeper zones. Hence the question is, if this is caused by a rotation of the stress field or if there are explanations for the abnormal breakout direction under a consistent orientation of the stress field.

Above all, variations of the breakout direction result from the KIRSCH-equation considering the influence formation fluid pressure and the drilling mud pressure. So the following equation for tangential stress at the borehole wall ($r = a$) is maintained:

$$\sigma_\theta \Big|_{r=a} = S_H + S_h - 2(S_H - S_h) \cos 2\theta - \quad P$$

whereas P is the difference between the drilling mud pressure and the formation fluid pressure. The higher the formation fluid pressure, the higher P. Caused by this the tangential stress transgresses the tensile strength of the rocks and induces tensile fraction parallel to S_H. But this can also happen in the compressive case ($P = 0$, $3\ S_h > S_H$). Taking advantage of the influence of the formation fluid pressure Hydro-Fracturing-experiments are carried out.

Micro fractures or anisotropic elastic characteristics of the rocks might be another reason for abnormal breakout directions. Generally they are called anisotropy of material. According to BLÜMLING (1986) a material anisotropy in form of micro fractures changes the breakout shape in that way that more fractured zones, dependent on the angle between S_H and the micro fractures, occur. The interpretation of the breakouts is impeded by this, and determining the principle stress direction it can lead to mistakes of 40°.

The breakout geometry depends on:

- the ratio of the YOUNG's moduli, that are orthogonal to each other and show different values according to its direction
- the angle between the elasticity anisotropy direction and the direction of the main principle stress direction (see Fig. 7).

This leads to the following observations:

- At the borehole wall the minimum value of the stress decreases with increasing anisotropy of elasticity. The result might be tensile stress parallel to S_H, that evoke breakouts caused by less tensile strength of the rock. Here these tensile stress breakouts can cover larger zones than the areas fractured by compression (breakouts) that are perpendicular to the maximum horizontal principal stress direction. The position of the minima varies by changing the angle of anisotropy and the stress distribution will be asymmetrical.

- Else, sidemaxima appear beside the maximum values of stress. But they only change the breakout direction that is definitly connected to very high material anisotropy.

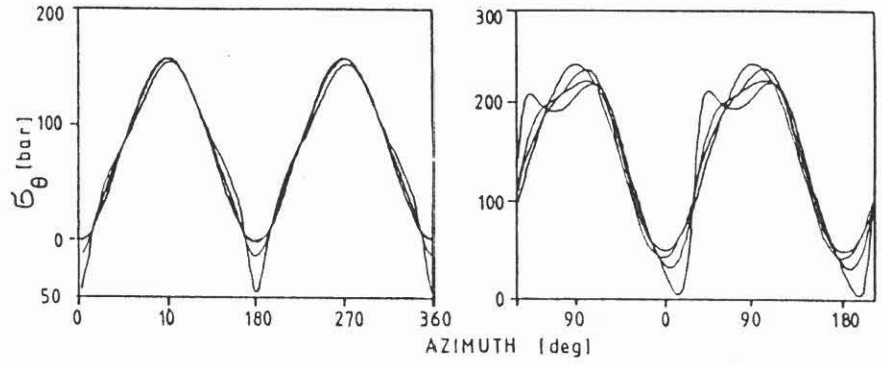

Fig. 7: stress distribution at the borehole wall deperding on the anisotropy of material.
a) Variation of E_x/E_y, whereas S_H parallel to E_x and S_h parallel to E_y.
b) like a) but according to an angle of 30° between S_H and E_x.

The behaviour is supported by a high ratio of S_H and S_h that, according to MCGARR & GAY (1978), can be 2:1 or 4:1 in lesser depth. This would explain the abnormal breakout directions near the surface.

To distinguish between discrete zones, where tensile fractures occured, and the zones of normal borehole breakouts, PLUMB & HICKMAN (1985) suggested an interpretation of conductivity that is also measured by four-arm-caliper tools. In that case drilling fluid might infiltrate the sheared zones surrounding the breakouts. By measuring the conductivity these zones show increasing.

According to such conductivity measurements at the borehole it can be distinguished between symmetrical or asymmetrical behaviour of borehole wall spalling. This cannot be done by interpreting the caliper distances that do not provide information on symmetrical or assymmetrical elongations. Only by using the values of the caliper logs, this cannot be distinguished.

As it was shown the determination of the stress field direction from borehole breakout analyses is a relatively new method which can provide good results in depth ranges where other methods cannot be applied. A detailed knowledge of the well conditions and regional tectonic regime is the base for a successful interpretation. So breakout analysis can provide stress results in various regions and serve for the mapping of the world's stress field.

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