28. ORIENTATION OF *IN SITU* STRESSES NEAR THE COSTA RICA RIFT AND PERU-CHILE TRENCH: DEEP SEA DRILLING PROJECT HOLE 504B[1]

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ABSTRACT

Analyses of borehole televiewer (BHTV) records from DSDP Hole 504B have provided an estimate of the direction of horizontal principal stresses in the oceanic crust, which has implications for the relative influence of plate driving mechanisms. Breakouts are borehole elongations caused by preferential spalling at an azimuth perpendicular to the maximum horizontal principal stress direction. DSDP Hole 504B is located about 200 km south of the east–west trending Costa Rica Rift and about 350 km northwest of the southwest-trending Peru-Chile Trench. Processing of borehole televiewer data from DSDP Hole 504B has revealed breakouts that show a consistent direction of N114E ±16°. When corrected for magnetic declination at the site, the breakouts indicate a maximum horizontal principal stress direction of N20E ±16°. The data imply that at this site both the slab pull forces associated with subduction of the Nazca Plate and the ridge push forces from the Cocos-Nazca spreading axis contribute to the *in situ* stress field.

INTRODUCTION

The walls of some boreholes often preferentially spall, leaving intervals of borehole elongation in which the average azimuth of the long dimension is consistent in a given well or field (Cox, 1970; Babcock, 1978). These intervals are called "breakouts" in the petroleum industry when the short dimension is equal to the drill bit size (Babcock, 1978). Breakouts exhibiting well-grouped azimuths have been reported in several parts of North America (Cox, 1970; Babcock, 1978; Schafer, 1980; Brown et al., 1980; Gough and Bell, 1981, 1982; Springer and Thorpe, 1981; Bell and Gough, 1979, 1982; Plumb, 1982; Healy et al., pers. comm. 1982; Hickman et al., 1982; Gough et al., 1983, Fordjor et al., 1983).

Cox (1970) first documented the remarkable uniformity of directions of breakouts over much of Alberta using data provided from magnetically oriented 4-arm dipmeter logs. Babcock (1978) attributed breakouts to the intersection of pre-existing vertical fractures by the boreholes. Bell and Gough (1979, 1982) hypothesized that breakouts are caused by shear fracturing in the zone of stress amplification close to the borehole wall and proposed that the azimuthal grouping of breakouts is a result of unequal horizontal principal stresses in the rock intersected by the borehole. This mechanism for borehole elongation implies that horizontal stresses are not equal and that the shear stress concentration has exceeded the strength of the formation. Zoback et al. (pers. comm., 1983) extended and modified this theory, demonstrating that the breakouts will be bounded by the size of the zone in which the stresses exceed the rock's strength and that the individual failure surfaces will be curved because of the changing orientations of the principal stresses near the wellbore.

In March and April 1982, a United States Geological Survey experiment was run in which intensive geophysical logging and open-hole hydraulic fracturing stress measurements were performed in a deep geothermal well in Auburn, N.Y. The breakouts occurred at the orientation of the minimum horizontal stress, which is to our knowledge the first direct test of the breakout hypothesis in a single well (Hickman et al., 1982; Plumb, 1982; Plumb and Singer, pers. comm., 1983). Thus, there is evidence that breakouts can be used as a reliable indicator of the orientation of the horizontal principal stresses.

The first studies of *in situ* borehole breakouts involved analysis of dipmeter logs, which provide two orthogonal wellbore diameters as a function of depth. Breakouts are only recorded if they are large enough for the caliper pads to become entrenched in them. In addition, cable torque can cause the caliper arms to ride along the edges of a breakout, causing bias in the predicted stress direction. This study uses the borehole televiewer, the only wireline logging tool capable of providing a continuous 360° record of the borehole wall.

The borehole televiewer (BHTV) contains a rotating piezoelectric transducer that emits and receives an ultra-high-frequency (1.3 MHz) acoustic pulse in a 3° beam 1800 times a second as it rotates three times a second and is pulled up the hole at a rate of about 2.5 cm/s (Fig. 1). Zemanek et al. (1970) describe the operation of the tool in detail. The amplitude of the reflected acoustic pulse can be plotted on a 3-axis oscilloscope as a function of beam azimuth and vertical position in the hole, producing an image of wellbore reflectivity or "smoothness." A fluxgate magnetometer in the tool trig-

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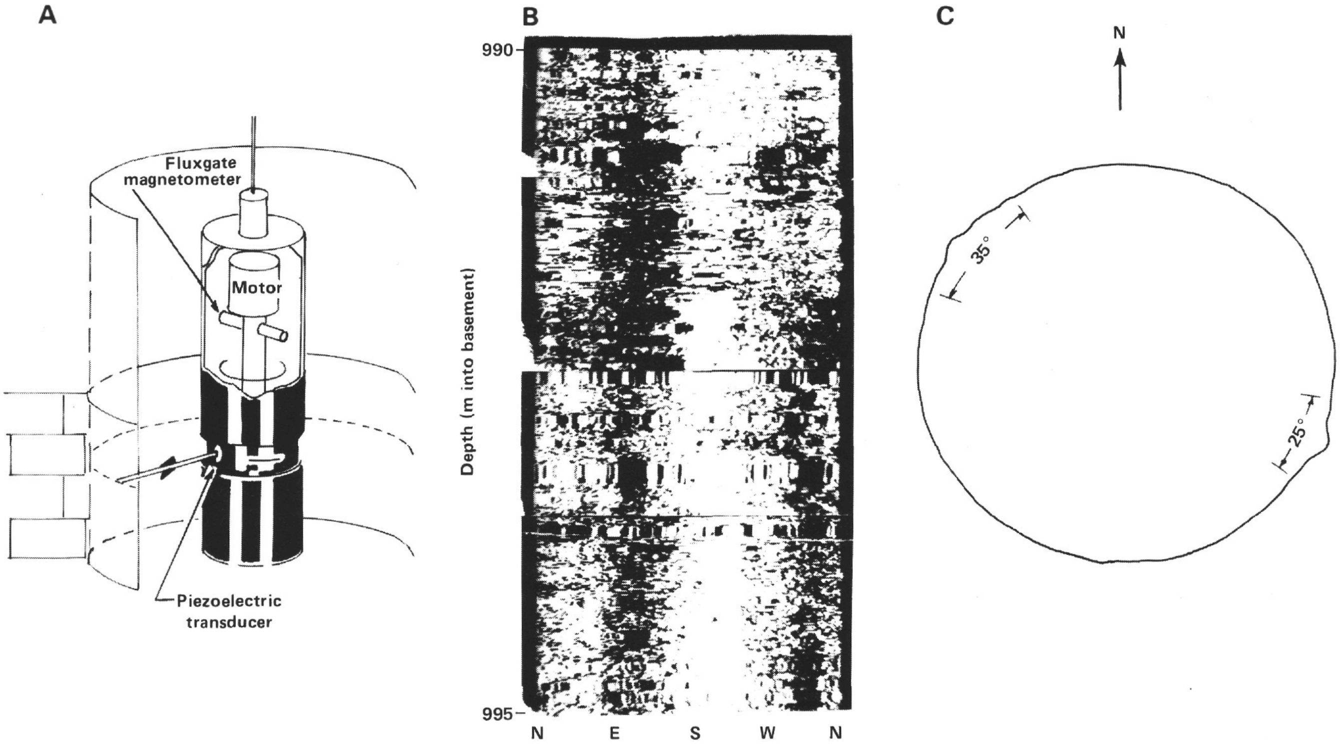

Figure 1. A. Schematic of the borehole televiewer (after Zemanek et al., 1970). B. Amplitude borehole televiewer record of 5 m of Hole 504B, presented in plan view. Width across image is about 1 m. Dark vertical bands oriented ESE–WNW are breakout zones. C. Cross-section of Hole 504B at a depth of 944 m into basement, showing breakout.

gers the scope trace at magnetic north so that the orientation of observed features can be determined. Resolution of the tool depends on hole diameter, wall conditions, reflectivity of the formation, and acoustic impedance of the wellbore fluid. For Hole 504B, the optimum resolution (excluding such factors as ship's heave and changes in acoustic impedance of the wellbore fluid with depth and temperature that would degrade the resolution) is 0.17 cm per firing (horizontal) and 0.83 cm per revolution (vertical), which results in a horizontal/vertical resolution ratio of 0.20.

Borehole televiewer reflectivity records have been used previously in the study of fractures intersecting wellbores at depth (Seeberger and Zoback, 1982); for identifying lithostratigraphic features in deep ocean boreholes (Zoback and Anderson, 1982; Newmark et al., this volume); and, recently, in identifying zones of borehole breakout (Hickman et al., 1982). In addition, analysis of the traveltime of the reflected acoustic pulse provides us with detailed cross-sectional images of the wellbore in breakout intervals. The BHTV reflectivity records obtained in Hole 504B can be found in Appendix A of Newmark et al. (this volume).

EXPERIMENTAL DATA

During DSDP Leg 83, the *Glomar Challenger* completed drilling Hole 504B to a depth of 1350 m, 1075.5 m of which was into basement (Anderson et al., 1982) (Fig. 2). The upper 100 m of basement is composed mainly of pillow basalts and thin flow units and has been described as seismic Layer 2A (Newmark et al., this volume). The next 550 m is composed of pillows, breccias, and flows; is a site of intense fracturing; and contains extensive secondary alteration. It has been described as seismic Layer 2B. The bottom 350 m of the hole is composed mainly of massive, "welded" units, or sheeted dikes of Layer 2C (Newmark et al., this volume).

Borehole televiewer images run in Hole 504B suggested the presence of breakouts at many intervals down the hole. Analysis of the BHTV records was confined to the lower 350 m of the hole, however, because the borehole walls in the lower part of the hole are relatively smooth in comparison to the pitted, broken nature of the wellbore in the upper zones of pillows and breccias. In analyzing the BHTV records, cross-sectional images were produced every few centimeters along the lower 350 m of the hole. The criteria for confirmation of breakouts included the following: (1) the wellbore must have two bands of spalling at an orientation of 180 ±20° to each other; (2) the evidence of the same cross-sectional outline and orientation must persist over several (>4) consecutive rotations of the tool (sweeps through 360°), indicating continuity of several centimeters for each measurement. Because of the high temperatures encountered downhole, the compass triggering circuit ran erratically, causing occasional skips in the record. This prevents us from analyzing the full length of breakout intervals downhole. Because of the imperfect nature of the plan-view images, breakouts may be more continuous through the hole.

Figure 1B shows a reflectivity record of a 5-m-long interval from Hole 504B. The right and left edges of the

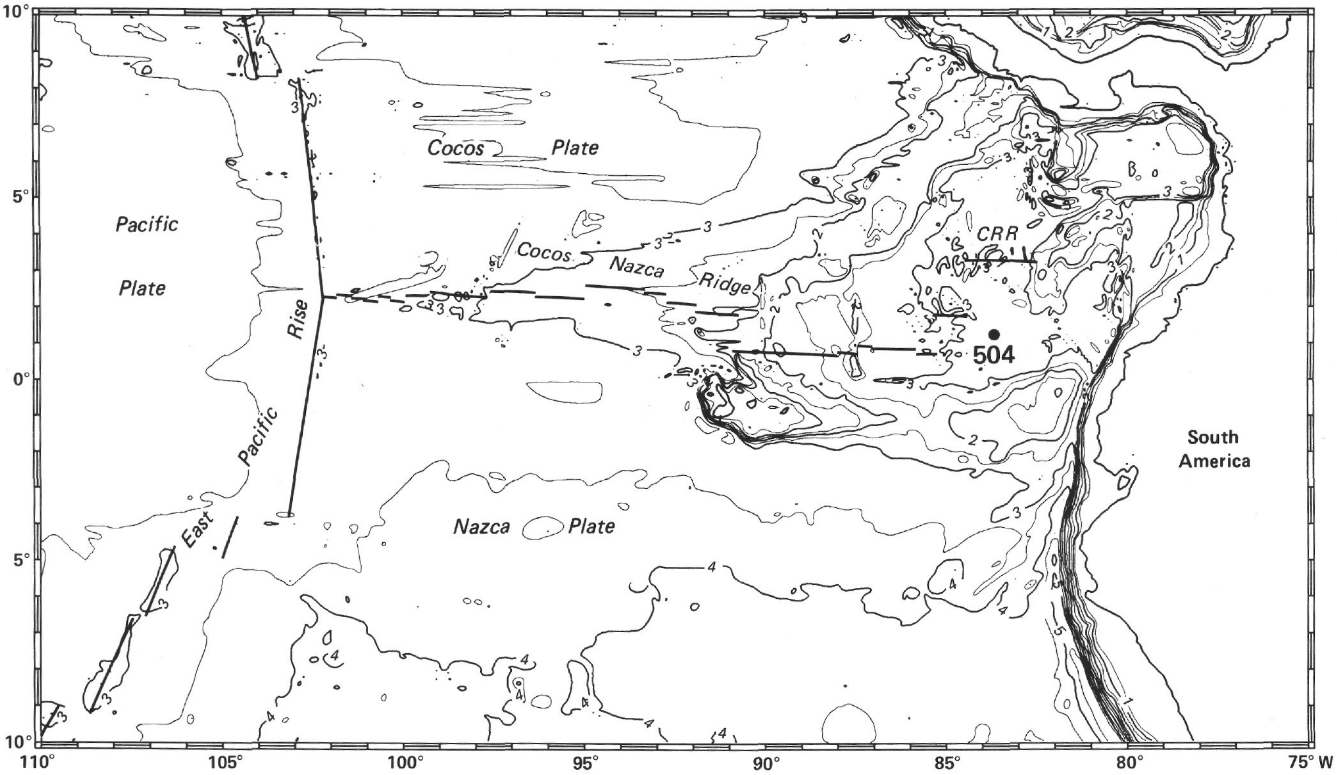

Figure 2. Location of DSDP Site 504 on the south flank of the Costa Rica Rift (CRR), easternmost segment of the Cocos-Nazca spreading axis. East Pacific Rise and Cocos-Nazca Ridge crests shown for reference.

image are magnetic N. In these images, hard, smooth surfaces produce white zones from high-amplitude reflectance. Fractures, voids, and soft material that absorb or scatter much of the signal result in low-amplitude reflectance, producing dark zones. Note the vertical dark bands seen at azimuths of about 120 and 300°. These are breakout zones. Figure 1C shows a cross-sectional view of the breakout at a depth of 944 m into basement.

In all, 65 measurements of orientations of breakouts that conformed to the criteria for breakouts were made in the records obtained in the lower 350 m of Hole 504B. Figure 3 shows examples of breakout cross-sections at other depths through this depth interval. The azimuths of the midpoints of each breakout zone are plotted with depth in Figure 4. The mean elongations are N112E ± 16 and N296E $\pm 16°$ with a mean separation of 184 $\pm 11°$. This indicates an average maximum horizontal compression orientation of N24E magnetic, which, when corrected for magnetic declination at the site, results in maximum horizontal compression at N20E $\pm 16°$.

DISCUSSION

The location of Hole 504B is reasonably well suited to test the relative importance of two postulated driving mechanisms for the motions of plates: ridge push and slab pull (Fig. 2). Hole 504B is located 200 km due south of the east–west-trending Costa Rica Rift, about 350 km northwest of the northeast–southwest-trending Peru-Chile Trench and over 2000 km east of the East Pacific Rise. Ridge push from the Costa Rica Rift should produce a southward compression at the site and that from the East Pacific Rise should produce eastward compression. The net slab pull, or the sum of driving and resisting slab forces, should produce southeastward tension at the site (Fig. 5). The observed principal horizontal stress directions from Hole 504B breakouts are consistent with both a ridge push force from the Costa Rica Rift and a slab pull force associated with subduction of the Nazca Plate along the Peru-Chile Trench acting at the site.

It is tempting to compare the observed directions of principal horizontal stresses to the various predictive models for plate stresses such as those of Richardson (1978) and Richardson and Cox (1983). However, detailed studies of stresses acting in young lithosphere indicate that the stresses may be due to local stress perturbations rather than regional stress patterns (Wiens and Stein, 1983; pers. comm., 1983). Such local stress perturbations in young lithosphere could include thermal stresses associated with contraction of the lithosphere (Turcotte and Oxburgh, 1973) and stress concentrations resulting from complex ridge-transform geometries (Fujita and Sleep, 1978), both of which may affect the stress regime in Hole 504B.

The major importance of this work is the demonstration that stress orientations can be reliably determined from borehole breakouts in the oceanic crust. Similar measurements in multiple boreholes at sites located with respect to major plate boundaries and away from the immediate ridge axis will allow us to define more clearly the relationships between the driving forces of plate tectonics.

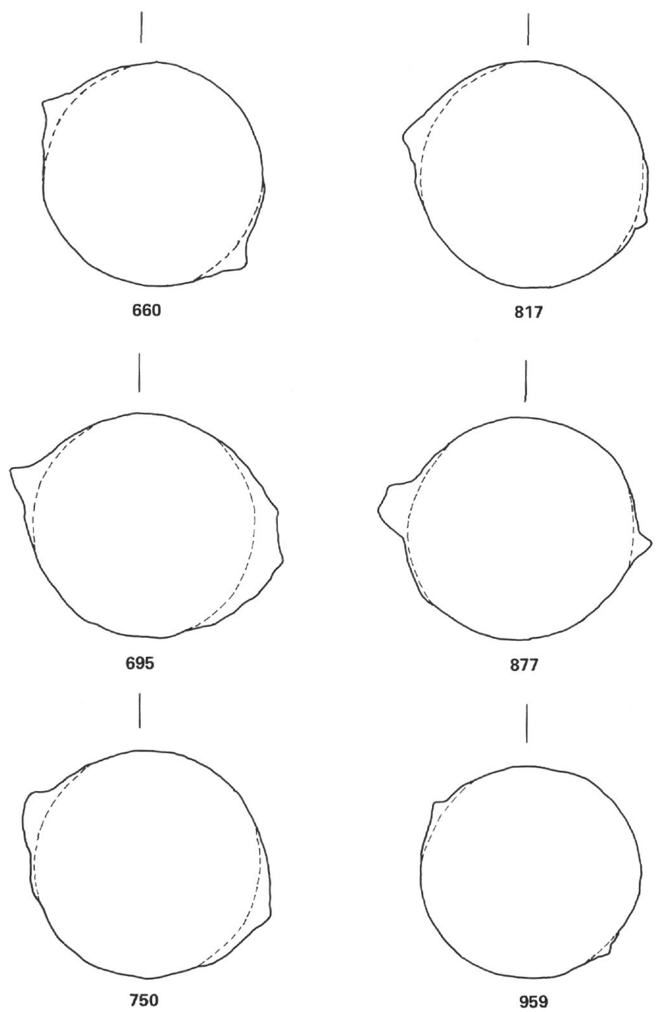

Figure 3. Examples of breakout cross-sections from Hole 504B. Vertical lines indicate true north. Numbers indicate depth in meters into basement.

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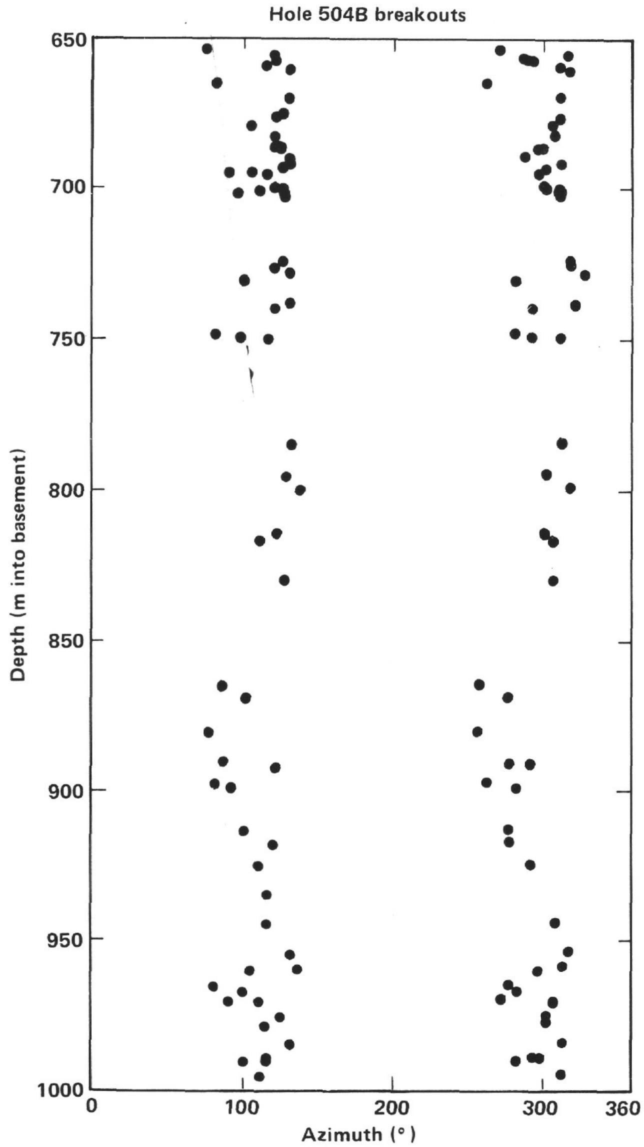

Figure 4. Midpoints of zones of borehole breakout vs. depth in Hole 504B. Mean azimuths are N112E ±16.4 and N296E ±16.2 degrees.

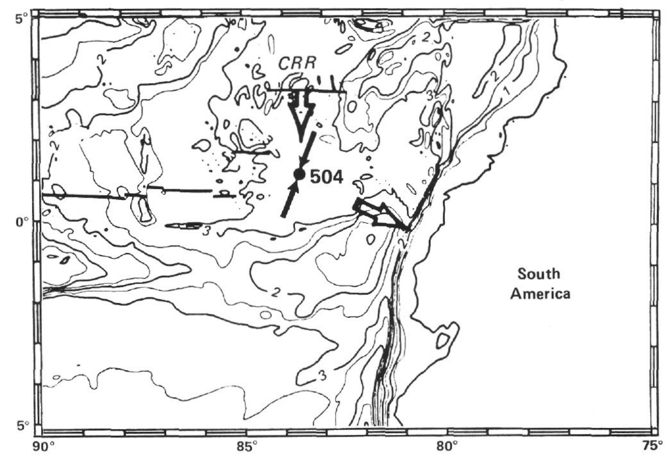

Figure 5. Stresses near Site 504. Solid arrows indicate the maximum horizontal compressive stress direction determined from breakout directions in Hole 504B. Open arrows show the direction of ridge push force from the Costa Rica Rift (CRR) and the direction of the slab pull force from the Peru-Chili Trench.