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Effect of anisotropic borehole wall failures when estimating in situ stresses: A case study in the Nankai accretionary wedge

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A B S T R A C T

Breakouts observed in a vertical borehole (C0002A) drilled through two major tectonic sedimentary formations consisting of forearc basin (upper) and accretionary prism (lower) sediments in the Nankai accretionary wedge, Japan, exhibit distinctive geometric features in respective formations. Breakouts in the lower accretionary prism sediments are markedly wider than those in the forearc basin sediments, and breakout azimuths in the two units are horizontally rotated relative to one another. Breakout azimuths are widely used as a proxy for the determination of principal stress directions. However, strength anisotropies related to the presence of bedding planes may affect both breakout azimuths and widths, which can result in misleading in situ stress interpretations. While thinly bedded mudstones are the dominant lithology in both the forearc basin and accretionary prism sediments, bedding planes in the accretionary prism sediments are relatively steeper than those in the forearc basin sediments, with possible implications for breakout geometry and interpretations of principal stress directions. To investigate the effects of bedding planes on breakout geometry (azimuth and width), we conducted borehole wall failure analyses using a weak-plane failure model that incorporates material strength anisotropies. The model results show that breakout widths and orientations are strongly affected by steeply dipping (>40°) bedding planes in cases where dip directions are unaligned with the principal stress orientation. Our theoretical results suggest that variations in breakout azimuths in the C0002A site may be associated with bedding plane related strength anisotropy, and not associated with the rotation of stress field. That is, stress orientation is consistent throughout the borehole (down to the bottom-hole depth of 1495 m below sea floor). In addition, disregarding the effects of bedding planes tends to yield an overestimation of in situ stress magnitude.

1. Introduction

When drilling a hole into the earth crust subjected to in situ stresses, rock failures occur around the borehole if the local stresses induced there exceed rock strength (Haimson and Herrick, 1985; Zoback et al., 1985; Zheng et al., 1989). Two representative types of drilling-induced borehole wall failures observed in the field are breakouts (zones of compressive rock failure) and drilling-induced tensile fractures. In a vertical hole drilled into an isotropic and homogeneous rock formation, breakouts, which occur at diametrically opposite zones around the borehole, tend to be aligned with the direction of the minimum horizontal principal stress (σ_h), whereas the tensile fractures, which also occur at diametrically opposite sides of the borehole wall, tend to be aligned with the direction of the maximum horizontal principal stress (σ_H). Thus, these two types of drilling-induced failures have been widely and reliably used as indicators of the principal stress orientations in rocks (Bell and Gough, 1979; Hickman et al., 1985; Plumb and Cox, 1987; Shamir and Zoback, 1992; Brudy and Zoback, 1999).

In addition to the determination of principal stress axis orientations, efforts to estimate in situ stress magnitudes have also been attempted using both theoretical (Zoback et al., 1985; Zheng et al., 1989) and experimental (Haimson and Herrick, 1986; Haimson and Song, 1993) approaches. These approaches, as well as other related research (Herrick and Haimson, 1994; Haimson and Lee, 2004), have consistently demonstrated that breakout dimensions (specifically, breakout widths at the borehole wall) depend on far-field stress magnitudes. As a result, breakout widths, which can often be measured using borehole imaging tools, have been used to estimate σ_H magnitudes (Moos and Zoback, 1990; Morin et al., 1990; Vernik

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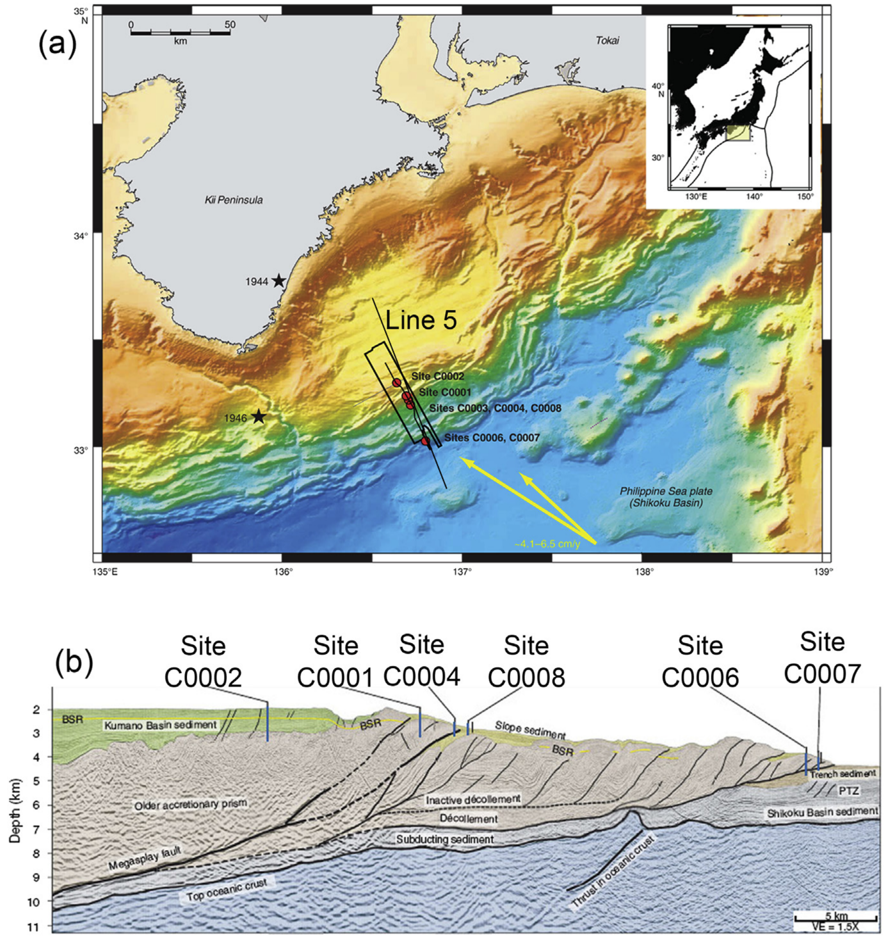

Figure 1. Map of the study area. (a) Locations of selected drilling sites of the Integrated Ocean Drilling Project (IODP) NanTroSEIZE Expedition 314 in the Nankai subduction zone off the coast of southwest Japan (after Tobin et al., 2009). Yellow arrows and labels show the directions and rates of convergence, respectively, between the Philippine Sea plate and Japan, which is on the Eurasian plate (Seno et al., 1993; Miyazaki and Heki, 2001; Zang et al., 2002). The rectangular outline shows the area of the 3D seismic survey. (b) Seismic reflection profile along the 2D survey line labeled "Line 5" in (a), and the locations of drilling sites (after Louis et al., 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and Zoback, 1990; Brudy et al., 1997; Brudy and Zoback, 1999; Haimson and Chang, 2002; Hickman and Zoback, 2004).

The use of borehole breakouts to estimate in situ stress orientations and magnitudes is relatively straightforward in isotropic and homogeneous rock materials; however, in mechanically anisotropic rock units, which is often caused by rock fabrics such as beddings and foliation, the resultant breakout patterns can be complex (Vernik and Zoback, 1990; Mastin et al., 1991; Aoki et al., 1993; Zou et al., 1996; Okland and Cook, 1998). Vernik and Zoback (1990) and Mastin et al. (1991) found that breakout shapes and orientations observed from scientific drillholes (e.g. KTB, Cajon Pass) are strongly altered by the degree of rock anisotropy and the relative orientations among the dip direction of weakness planes, borehole axis, and in situ stress orientation. They observed that breakouts created in anisotropic formations with steeply dipping weakness planes ($\geq 40°$) were much wider at the borehole wall than were those in formations with sub-horizontal to moderately dipping foliations ($<40°$), and also that the orientations of breakouts in such anisotropic formations do not match with regional stress orientations. Similarly, Aoki et al. (1993) and Zou et al. (1996), in studies of borehole failures in thinly laminated (or bedded) formations, found that shear failures within the rock matrix and failures along bedding planes both affected breakout orientation and size.

The effects of weak planes on breakout patterns are generally attributed to anisotropic failure mechanisms in rocks, the principles of which are well established thanks to many researchers (Chenevert and Gatlin, 1965; Donath, 1964; McLamore and Gary, 1967; Ramamurthy et al., 1993; Niando et al., 1997; Ajalloeian and Lashkaripour, 2000; Tien et al., 2006). Their works have demonstrated that failure strength varies as a function of the angle (ψ) between weakness planes and the loading axis of the major principal stress. Typically, the failure strength is a maximum at either $\psi = 0°$ or $90°$, and a minimum at $\psi \approx 30°$. The characteristics of rock failure modes also depend on relative loading directions. Shear failures within intact rock matrix are dominant in rocks loaded at angles of $\psi = 0°$ or $90°$, whereas slippage failure along weakness planes is more pronounced in rocks loaded at $\psi = 20–40°$.

We employ the concepts of anisotropic rock strength and failure behavior to investigate the significance of anisotropic effect on the borehole breakout formation and also on resulting in situ stress estimations based on the altered breakout geometry. We choose the Nankai accretionary complex, southwest Japan, as a study area because of its tectonic significance, as well as the observed features of borehole wall failures represented by widening and rotation of breakouts (Chang et al., 2010), which might result from the anisotropic effect. Here, we introduce a semi-analytical weak-plane borehole instability model that incorporates rock strength