some constraint on their relative magnitudes. Such a technique provides a more complete knowledge of the stress tensor and works even if none of the principal stresses is vertical.

In this paper we describe our technique of using many, differently oriented, nonvertical boreholes to constrain the principal stress directions and magnitudes of the stress tensor. The smallest data set applicable to this technique would most likely consist of a few, variably oriented wells logged with oriented caliper arm data. Offshore oil platforms provide good sources of these types of data, since the wells are drilled in many directions and at nonvertical deviations to fully develop the oil fields. Depending upon the number of wells and the horizontal extent of the caliper data, our technique determines a regional stress state localized over a spatial extent of kilometers to tens of kilometers.

Other authors have presented different techniques of using deviated boreholes to determine the local stress state. *Qian and Pedersen* [1991] applied a nonlinear inversion technique to a set of borehole breakout data. *Aadnoy* [1990a, b] examined fractures in deviated boreholes. *Peška and Zoback* [1995] developed a technique using leak-off tests, microfracture measurements, pore pressure measurements, breakout, and tensile fractures with theoretical borehole failure calculations to determine the stress directions and magnitudes from a single, deviated well. Neither *Peška and Zoback* [1995] nor the technique presented in this paper assumes a vertical principal stress direction. Multiple applications of their technique over a region would yield a more regional stress state tensor.

Theory

The theoretical basis of this technique has been recognized for nearly a decade, but it has only been applied in a few areas, perhaps because of the lack of strongly deviated drill holes in most regions. It is based on the elastic equations for stress surrounding an arbitrarily oriented cylindrical hole in a medium with known far-field stresses. Equations for the stress field surrounding a circular hole in an elastic plate subjected to plane strain are given by *Kirsch* [1898] and various other authors [e.g., *Hubbert and Willis*, 1957; *Timoshenko and Goodier*, 1970; *Jaeger and Cook*, 1979]. The equations for the stress components at the wall of a cylindrical hole in a polyaxial stress field are given by *Hiramatsu and Oka* [1962], *Youngdahl and Sternberg* [1966], *Fairhurst* [1968], *Daneshy* [1973], *Richardson* [1983], *Mastin* [1988], and *Qian and Pedersen* [1991].

If a drill hole is parallel to one of the principal stress directions, the rock strength and the relative magnitudes of the remaining two stresses affect the presence or absence of breakouts but not their azimuth in the borehole reference frame. The magnitudes of the principal stresses must be inferred by another technique rather than just by observations of breakout orientation.

The breakout width of the hole after breakout formation is controlled by the relative magnitudes of the principal stresses, so that if one of the principal horizontal stresses is known, and the rock strength is known or estimated, the magnitude of the other principal horizontal stress can be estimated [*Moos and Zoback*, 1990; *Vernik and Zoback*, 1992].

However, in a nonvertical hole, or a hole oriented obliquely to the three principal stress directions, one does not necessarily need independent measurements of one principal stress to infer the relative magnitudes of another principal stress, because the magnitudes of the principal stresses, as well as their directions, influence the position of the maximum compressive stress at the borehole wall [*Richardson*, 1983] and hence the position at which breakouts would form. This fact was further elaborated by *Mastin* [1988], who showed stereographic projections [*Hobbs et al.*, 1976] indicating the direction of breakouts expected in variably oriented drill holes for different stress orientations and principal stress magnitudes. Thus, if several drill holes of different deviations are present in a given area, and if these drill holes are subject to the same stress tensor, the orientations of the breakouts in these holes may provide strong constraints on the orientations and magnitudes of the principal stresses at that location [*Zajac and Stock*, 1992].

To plot the breakout data from arbitrarily oriented boreholes and the calculated breakout positions for theoretical far-field stress states, lower hemisphere stereographic projections of the borehole azimuth and deviation (e.g., Figure 1) are used.

This dependence of breakout position on the far-field tectonic stress is illustrated in Figure 2, where we show patterns of breakout orientations that would be predicted for arbitrarily oriented drill holes subjected to certain characteristic stress fields. These are similar to the quadrant plots of *Mastin* [1988] and illustrate the degree to which an inversion or forward modeling of borehole breakout observations would constrain the stress regime for a given distribution of borehole orientations. The characteristic stress fields are defined by the orientations of the principal stresses S_1, S_2, and S_3