Drilling-induced core fractures and in situ stress

Yongyi Li and Douglas R. Schmitt

Institute of Geophysics, Meteorology, and Space Physics, Department of Physics, University of Alberta
Edmonton, Canada

Abstract. The relationship between the shapes of drilling-induced core fractures and the in situ state of stress is developed. The stress concentrations at the well bore bottom are first determined using a complete three-dimensional finite element analysis. Existing in situ compressional stresses generate large tensions in the immediate vicinity of the bottom hole which are sufficient to rupture the rock. Tensile fracture trajectories within these concentrated stress fields are predicted using a simple model of fracture propagation. These modeled fracture trajectories resemble well the observed shapes of drilling-induced core dishing, petal, and petal-centerline fractures. Further, this agreement suggests that both the shape of the drilling-induced fracture and the location at which it initiates depends on the in situ stress state existing in the rock mass prior to drilling; the core fractures contain substantial information on in situ stress conditions. In all faulting regimes the coring-induced fractures initiate near the bit cut except for most cases under thrust faulting regime where the fracture initiates on the well bore axis. Further, under thrust faulting conditions only disk fractures appear possible. Both petal and dishing fractures can be produced in strike-slip and normal faulting regimes depending upon the relative magnitudes between the least compressive horizontal principal stress and the vertical overburden stress. The predicted fracture shapes are in good qualitative agreement with observations of drilling-induced fractures described in the literature from laboratory experiments and field programs in which in situ stresses are measured by other means. The relationship of the morphology of coring induced fractures and in situ stresses suggests that the fractures can be used as independent complementary indicators in identifying stress regimes.

1. Introduction

Drilling-induced core fractures appear in different shapes and are classified on this basis as dishing, petal, and petal-centerline fractures. Examples of these differing fractures are given in Figure 1. The uniform spacings and shapes and the consistent strike orientations of these drilling-induced fractures suggest that their morphologies are related to the stress conditions within the Earth. Indeed, it is well known empirically that the strike directions of these fractures coincide with the direction of the greatest horizontal compression. However, despite the obvious differences in the shapes between a disk and a petal fracture, little is known about the conditions under which these fractures form. Further study of these fractures is warranted as they may contain much information on in situ stresses and may in some cases be the only information that can be obtained, especially in deep drilling of the crust.

Many workers have been involved in the observation and study of these fractures [e.g., Pendexter and Rohn, 1954; Leeman, 1964; Jaeger and Cook, 1965; Obert and Stephenson, 1965; Durell et al., 1965; Sugawara et al., 1978; Gangarao et al., 1979; Stacey, 1982; Miguez et al., 1987; Plumb and Cox, 1987; Maury et al., 1988; Born et al., 1989; Perreau, 1989; Dyke, 1989; Lorenz et al., 1990; Kulander et al., 1990; Haimson and Lee, 1997; Bankwitz and Bankwitz, 1995; and Li and Schmitt, 1997a, b], but the relationship between the fracture morphology and in situ stresses remains to be determined.

This state of affairs arises in part due to theoretical difficulties associated with determining the stresses in the vicinity of the bottom hole. Drilling-induced core fractures result partially from the concentration of the in situ stress in the proximity to well bore bottom. As the bottom hole geometry is asymmetric, it does not lend itself to a closed-form analytic solution for the stress concentrations comparable to that given, for example, by Kirsch [1898] for a circular hole in a plate and employed in describing incipient well bore breakouts and hydraulic fractures. Consequently, in the past, numerical modeling has been employed case by case for core dishing fractures [e.g., Sugawara et al., 1978; Dyke, 1989] or for petal fractures [Gangarao et al., 1979; Lorenz et al., 1990]. The earliest attempt at modeling the morphology of coring induced fractures was carried out by Chǎng [1978] who assumed shear failure according to Mohr Coulomb theory and used strain energy densities [Sih, 1973] to predict fracture trajectories. In contrast, Stacey and Harte [1989] and Dyke [1989] used mappings of extensional strain to suggest possible fracture trajectories.

Another reason for the lack of information about drilling-induced fractures is difficulties in applying complex stresses to a rock specimen in the laboratory. In the early laboratory experiments [Jaeger and Cook, 1963; Obert and Stephenson, 1965], conventional triaxial rock tests with only a radial confining pressure and an axial load were applied to cylindrical samples. Only recently were Haimson and Lee [1997] able to apply complete polaxial states of stress to cubical samples.

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which were then cored under load. Even so, no petal, petal-centerline, or centerline fractures have been produced in the laboratory.

In this contribution we calculate the stress concentrations produced at the bottom of a vertical well bore containing the stub of a core being drilled into different in situ stress states as classified in faulting regimes by Anderson [1951]. We find that the predicted trajectories of the tensile fractures created in such concentrated stress fields are in good agreement with observed core fractures, consequently making apparent relationships between the fracture shapes, their locations of origin, and the state of in situ stress. These fracture trajectories are compared to core fractures observed in the existing, but limited, cases in the literature where stress states have been quantitatively measured by alternative means. Although these relationships are in need of laboratory validation, they suggest that the fracture morphology provides a simple and direct indicator of the relative magnitudes between the principal stresses.

2. Background

It is first important to discuss the morphology, the fractographic observations, and the assumed failure mechanism of drilling-induced core fractures. The reader is also directed to the reviews of Kulander et al. [1990] and Engelder [1993].

A collection of different drilling-induced core fractures is shown in Figure 1. These include the core disks with cupped and flat fracture surfaces in Georgia granite from the early
experiments of Obert and Stephenson [1965] (Figure 1a), saddle-shaped core disking fractures in metabasites from the Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland (KTB) drill site at a depth 3582 m [Borm et al., 1989] (Figure 1b), petal fractures in a metamorphic core from the Alberta Basement (Figure 1c), and a petal-centerline fracture from Pendexter and Rohn [1954] (Figure 1d). Fracture here describes where the core actually separates into two distinct pieces (e.g., Figures 1a, 1b and 1d) and where the core remains intact but with a visible and well-developed deformation zone along the fracture trace (e.g., Figure 1c). Obert and Stephenson [1965] preferred to distinguish this difference by referring to the latter case as a rupture.

As shown in Figure 1, core disking fractures have a variety of shapes and are uniformly spaced. On the basis of field observations, laboratory experiments, and numerical modeling, the thickness of core disks often ranges from 1/5 to 1/4 of the core diameter [e.g., Jaeger and Cook, 1963; Leeman, 1964; Obert and Stephenson, 1965; Zhu et al., 1985; Borm et al., 1989; Ishida and Saito, 1995; Li and Schmitt, 1997b]. The other major characteristic is that the trough of saddle shaped core disking fractures is aligned with the direction of the greatest horizontal compressive stress $S_H$ [e.g., Kulander et al., 1990; Haimson and Lee, 1994].

Petal fractures are often also uniformly spaced but the upper limit is greater than that of core disks. Random spacing is often observed. Chang [1978] measured a large number of petal fractures and found the dip angles of the fracture surface range from 30° to 45°. Petal-centerline fractures (Figure 1d) which finally propagate in the direction of the core axis may be considered as special cases of petal fractures. Kulander et al. [1979] divided the surface of petal centerline fracture into two morphological sections. The initial section near the core boundary dips from 30° to 75°, and the second section has a vertical inclination. The strike of the fracture surface is aligned with the direction of the greatest horizontal stress $S_H$ for both petal and petal-centerline fractures.

Fractographic features on the fracture surfaces contain further information. Figure 2 shows two typical examples of coring-induced fracture surfaces. In Figure 2a, the hackle structures indicate that the fracture originates at the center of the core along the well bore axis [Bankwitz and Bankwitz, 1995]. Such internally generated fractures have also been observed by Zanon [Maury et al., 1988] in X ray examinations of what appear to be otherwise intact cores. This contrasts with the fractures in Figure 1b which originate from outside the core.

The fracture morphology and the fractographic features in Figures 1c and 1d and Figure 2b indicate that both petal and petal-centerline fractures originate outside the core or near its boundary. The downward curved arrest lines in Figure 2b suggest that petal and petal-centerline fractures propagate downward into the core with slow progress possibly controlled by the drilling [Kulander et al., 1990]. A gradual evolution of core fracture morphology that begins from saddle-shaped core disks to petal fractures and finally to petal-centerline fractures, dependent upon the in situ stress, may exist.

In compressional stress regimes, substantial tensions are generated in the vicinity of the bottom hole. Drilling-induced core fractures appear to result primarily from tensional failure of the material as suggested by field observations, laboratory experiments, and numerical modeling. Jaeger and Cook [1963] conducted a series of experiments and suggested that the core disking fractures are produced under tension because the fracture surface always appears clear and unshered. Panet [1969] suggested core disking may initiate where tensional stress appears and, noting that rock tensile strength always is much smaller than its compressive strength, applied a tensile strength criterion to the experimental results of Obert and Stephenson [1965]. This was supported by the numerical modeling of Sugawara et al. [1978], Dyke [1989], and Li and Schmitt [1997a] which indicated that large tensions were generated in the vicinity of the bottom hole drilled into compressional stress states. A Mohr-Coloumb shear failure criterion is not consistent with the Obert and Stephenson's [1965] experimentally observed failure curves [Li and Schmitt, 1997b]. Finally, in recent tests, Haimson and Lee [1997] found no evidence for shear failure in the microscopic

Figure 2. Fractographic features of (a) a fracture initiating at the center of a core [after Bankwitz and Bankwitz, 1995] (reprinted with permission from Geological Society), and (b) a petal fracture surface [after Kulander et al., 1990] (© 1990, reprinted by permission of the American Association of Petroleum Geologists).
examination of the surfaces of core disking fractures produced in the laboratory as did Durham's (1993) profilometry of core disking surfaces from the KTB well bore. These are important points; in the analyses below, it is assumed that the drilling-induced core fractures are tensile.

In this study the in situ stress states are discussed in terms of faulting environment stress regimes [Anderson, 1951]. This Andersonian classification arranges the overburden $S_v$, the greatest compressive horizontal principal stress $S_H$ and the least compressive horizontal principal stress $S_h$ relative to the three major types of faulting in the crust (Figure 3). The characterizations are (1) in the normal fault regime, $S_v > S_H > S_h$; (2) in the strike-slip fault regime, $S_H > S_v > S_h$; and (3) in the thrust fault regime, $S_H > S_h > S_v$.

3. Numerical Calculations

3.1. Finite Element Modeling

Figure 4 illustrates coring process with a diamond drill bit. Details of a small portion of the three-dimensional (3-D) finite element mesh near the well bore and across the borehole axis are shown in Figure 4c. The ratio of core diameter $d$ to well bore diameter $D$ is 1/2. Since the well bore axis is parallel to the vertical, symmetry consideration allows the calculations to be carried out over only a single quadrant of the well bore.

This quadrant has dimensions of $15d \times 15d \times 15d$ in the $x$, $y$ and $z$ directions, respectively, and contains 3505 nodes and 3336 elements. The bottom of the vertical borehole is $7.5d$ below the top surface. The curved kerf (cut) is a semicircle with a radius equal to 1/2 its width. As the external boundaries are well removed from the well bore bottom, boundary effects may be ignored.

Improvements were made to the finite element model over earlier studies [Li and Schmitt, 1997a, b]. The size of the elements at the locations with high stress concentrations, such as the well bore bottom, were reduced. Further, more sophisticated types of elements were employed. The final model mainly consists of 8 node 3-D solid elements but 3-D 20 node isoparametric elements were used at the inner corner of the kerf to further enhance the resolution. Analysis of the results shows a smooth continuous transition from the 8 to the 20 node elements. Ground truthing of the results against analytic theory is not possible for the reasons already given. However, the stress concentrations in the horizontal plane at 2.5 borehole diameters above the bottom of the kerf are in very good agreement with the 2-D analytic solution of Kirsch [1898] with errors less than 2% in the concentrated stress magnitudes observed (Figure 5).

In all calculations the medium was assumed linearly elastic and isotropic, and a Poisson's ratio of 0.25 and a Young's modulus of 20 GPa were used. The modeling here assumes the

Figure 3. Faulting environments as characterized by Anderson [1951]: (a) the normal fault stress regime ($S_v > S_H > S_h$), (b) the strike-slip fault stress regime ($S_H > S_v > S_h$), and (c) the thrust fault stress regime ($S_H > S_h > S_v$).
well bore is vertical and parallel to one of the far-field principal stresses which within the context of the discussion is obviously \( S_v \). The well bore fluid pressure and the weight of drill bit are not taken into account in this modeling. As a result, the surface of the well bore cavity acts as a free surface.

Because the medium is linearly elastic and isotropic, the local stress tensors were calculated by superimposing the stress concentrations resulting individually from the three, appropriately scaled, principal in situ stresses \( S_v, S_H \) and \( S_h \) applied in the far field of the well bore [Li and Schmitt, 1997a]. Although the bottom hole geometry modeled in this previous study differs from that here, the general characteristics of the concentrated stress fields for both are similar, and the stress concentrations generated by these individual far field stresses will not be presented here.

The length of the core stub influences the stress concentrations [Li and Schmitt, 1997a, b]. Based on this earlier modeling, a core stub length \( l = d/4 \) was chosen for use here as for a given state of applied far-field stress; the greatest concentrated tensions are produced near this length.

### 3.2. Predicting Fracture Trajectories

The most often employed descriptions of fracture initiation include the maximum tensile stress theory, the maximum energy release rate theory, the minimum strain energy theory [Ingraffea and Hecze, 1980], and Griffith's [1921] theory. In the finite element modeling of rock fracturing, Ingraffea and Hecze [1980] compared the first three theories and found that the fracture trajectories predicted by the first two theories are in good agreement with their experimental observations. In this study the maximum tensile stress theory is used. The fracture (Mode I) initiates at the location of the greatest local tensional stress and propagates perpendicular to it once the material tensile strength is exceeded. As the fracture propagates, its orientation is controlled by the local direction of the tension. Superb examples of this effect are given by Lawn and Wilshaw [1975].

An automatic program for the fracture tracing was developed based on the maximum tensile stress theory of fracture initiation. The details of the algorithm are given in the appendix. Its procedure is summarized as the following. First,
Figure 5. Comparison of numerical (open and solid circles) to Kirsch's [1898] analytic (lines) principal stresses at the borehole wall 2.5 borehole diameters above the borehole bottom.

The orientations and magnitudes of the most tensile local principal stresses ($\sigma_2$) are interpolated from the finite element mesh into finer and regular grids. A search is conducted to find the location of the greatest tensile stress. The fracture is assumed to initiate from this location and then to propagate within the grid in the direction normal to $\sigma_2$. The direction of the trajectory is recalculated each time when the trace intersects a boundary between two grid cells. This procedure is carried out only in the 2-D cross-sectional planes which pass through the well bore axis and are aligned parallel ($\Phi = 0^\circ$) and perpendicular ($\Phi = 90^\circ$) to the direction of the greatest compressive horizontal principal stress $S_H$. Although the analysis relies on the results of full 3-D numerical calculations, the extremal stress magnitudes always occur within these two planes.

Note that in the present analysis only the relationship between a potential fracture trajectory and the in situ stress field are of interest. These trajectories are independent of the material strength and as a result within the text the potential fracture paths have been referred to as fracture trajectories.

4. Modeling Results

Stress concentrations were calculated under various states of far-field stress and are displayed in the form of stick diagrams: thin and thick sticks show the orientations of the compressional and tensile local principal stresses at their center points, respectively. Their length is directly proportional to their magnitude. The stresses are all presented in dimensionless form normalized by the magnitude of the greatest far-field compression. The magnitudes of local stresses for a given in situ stress condition can be recovered by multiplying the magnitude of the greatest far-field compression. Predicted fracture trajectories are shown in separate figures for a variety of stress conditions, in each figure the location of fracture initiation is indicated by an asterisk.

4.1. Normal Fault Stress Regime ($S_v > S_H > S_h$)

With high overburden stress and under highly anisotropic horizontal stresses (Figure 6a) large tensions parallel to the surface exist at the inner side of the kerf and at the top of the core stub at $\Phi = 90^\circ$. The tension is reduced substantially with increasing $S_h$, and only a small tension remains at the kerf when $S_h = S_H$ (Figure 6c).

The shapes of the predicted fracture trajectories evolve with the relative magnitudes between the horizontal stresses (Figure 7). In all cases of $S_H > S_h$, the fracture is expected to initiate at the kerf and at azimuths of $\Phi = 90^\circ$. When $S_H = S_h$, the fracture may initiate at any azimuth at the kerf. Fracture trajectories resembling steeply dipping petal fracture shapes are seen while the horizontal stresses remain highly anisotropic. As $S_h$ becomes larger, they evolve as the shallower angles and the trajectories appear to pass through stages similar to petal-centerline fractures and eventually become disking fractures. These disk-like shapes are primarily concave for smaller horizontal stress (Figure 7), but convex shapes appear at the cases with increased magnitude of the greatest horizontal stress (Figure 7b).

In addition, the strikes of the petal and the petal-centerline fractures and the direction of the deeper trough of the core disking fractures coincide with the direction of $S_H$. This is in agreement with the empirical field observations and indicates the utility of the core fractures as indicators of stress directions when oriented core is available [e.g., Kulander et al., 1990].

Figure 6. Orientations of local principal stresses in the normal fault stress regime with $S_v = 1$, $S_H = 0.5$ and (a) $S_h = 0.0$, (b) $S_h = 0.25$ and (c) $S_h = 0.5$. 
4.2. Strike-Slip Fault Stress Regime
(\(S_H > S_v > S_h\))

The principal stress orientations and magnitudes under strike-slip faulting conditions (Figure 8) are similar to those seen above under normal faulting. The greatest tensions appear at the surface of the inner side of the kerf at \(\Phi = 90^\circ\) or immediately at the top of the core stub. Tensile stresses progressively attenuate as \(S_h\) increases.

Under strike-slip conditions the greatest tension and presumed fracture initiation location always occur at the kerf at \(\Phi = 90^\circ\) (Figure 9). In many ways the fracture trajectories are similar to those for the normal faulting case. Petal fracture-like trajectories appear for highly anisotropic horizontal stresses while these pass through a petal-centerline stage and to a disk shape finally. Concave saddle shapes appear possible as indicated by the trajectories when \(S_h = 0.25\) with the high points of the saddle at \(\Phi = 90^\circ\) and the trough aligned with \(S_H\). Convex (Figure 9a) and nearly flat shapes (Figure 9b) are also seen. Fracturing local to the core surface may result under high and uniform values of \(S_h\) and \(S_v\) (Figure 9b).
4.3. Thrust Fault Stress Regime ($S_H > S_h > S_v$)

Concentrated stresses for a selected variety of conditions found within the thrust faulting regime are shown in Figure 10, and these suggest a differing behavior of core fracturing than in the other faulting regimes. In Figure 10a, the lone uniaxial horizontal compression generates relatively large tensions directed parallel to the inner surface of the kerf at $\Phi = 90^\circ$. However, once the least horizontal stress is increased, the location of the greatest tension migrates to the axis of the well bore into the material at the root of the core (Figures 10b - 10d). Inclusion of a vertical overburden load counteracts the axially directed and located tensions produced by the horizontal stresses (compare Figures 10c and 10d).

Only disk-like fracture trajectories appear under thrust faulting conditions (Figure 11). A saddle-shaped disk may be indicative of highly anisotropic horizontal stress conditions (Figure 11a). Essentially flat trajectories result for more uniform horizontal stresses but the trajectories become convex once a substantial vertical stress exists (Figure 11b). Another important observation is that, in most of the cases, the greatest tension exists not at the kerf but at the core axis. This is a crucial difference as the core fracture is expected to initiate within the rock mass and not on the well bore surface; a fracture initiation point on the core axis indicates thrust faulting stress conditions.

4.4. Preferred Location of Fracture Initiation

The results above give only an indication of the styles of fracture trajectories possible and the locations of fracture

Figure 9. (a) Predicted fracture trajectories in the strike slip fault regime with $S_H = 1, S_v = 0.5$, and $0.0 \leq S_h \leq 0.5$ at $\Phi = 0^\circ$ and $90^\circ$ and (b) with $S_H = 1, S_v = 0.75$, and $0.0 \leq S_h \leq 0.75$ at $\Phi = 0^\circ$ and $90^\circ$.

Figure 10. Orientations of local principal stresses in the thrust fault stress regime for $S_H = 1, S_v = 0$ with (a) $S_h = 0$ and (b) $S_h = 1$, and for $S_h = 0.5$ with (c) $S_v = 0$ and (d) $S_v = 0.5$. 

stress

0 2.0
initiation. A more thorough study of the latter is worthwhile as the results suggest that where the fracture initiates is a valuable additional piece of information. The magnitudes of the peak concentrated tensile stresses at locations either at the kerf, the top of the core stub, or at its root are shown in normalized form in Figure 12. In these plots the preferred location of the fracture initiation for a given stress state occurs at that location subject to the greatest tension.

Under normal faulting conditions where the vertical far-field stress is the most compressive, the largest tension exists either at the kerf or at the top surface of the core (Figure 12a). While $S_h$ remains small relative to $S_v$, the greatest tension is concentrated at the kerf. It is worth noting that the absolute value of the magnitude of this concentrated tension is greater than that for the overburden $S_v$ with small $S_h$. At increased values of $S_h$, however, the tensions at the kerf or at the top of the core are very close, indicating that the fracture initiation point could change easily between these two locations. The near equivalence of these tensious possibly explains the continued propagation of centerline fractures down the core.

In the strike-slip faulting regime, tensions exist at both the kerf and within the root of the core (Figure 12b). The tension at the kerf, substantially greater in almost all stress conditions, suggests that the resulting drilling-induced core fractures will initiate at the kerf.

In contrast, the preferred fracture initiation location under thrust faulting is nearly always at the core root (Figure 12c). Initiation at the kerf may be preferred under highly anisotropic stress states with a relative large magnitude for $S_v$.

4.5. Stress State Domains of Core Fractures

Information on the preferred fracture initiation locations plus the predicted fracture trajectories of Figures 6 to 11 and numerous additional trajectory tracings not shown are summarized in Figure 13. Here the type of fracture (petal or disk) and the fracture initiation locations (kerf or root) are displayed as fields over a graph of $S_v/S_H$ versus $S_h/S_H$. This mapping allows direct comparison of all the faulting regimes. The area covered by the normal faulting regime and lying above the horizontal line defined by $S_v/S_H = 1$ in this mapping is essentially infinite. The strike-slip field covers the area below this horizontal line but above the diagonal line defined by $S_v = S_h$ which extends from the origin. Finally, the area describing thrust faulting stress conditions lies below this diagonal. The small diagram inset in the upper left corner of Figure 13 highlights these different fields. Most in situ stress regimes encountered in practice will lie within the confines of Figure 13; only those cases with very high $S_v$ magnitudes cannot be shown, but all will be characterized by petal fracturing.

The advantage of the mapping is that the evolution of the different styles of the drilling-induced core fractures is apparent (Figure 13). This progression begins under thrust faulting conditions with only core disks, most of which initiate at the core root, through core disks all of which initiate at the kerf and generally associated with more uniform horizontal far-field stresses under both normal and strike-slip faulting, to finally petal fractures when more anisotropic horizontal stresses are encountered. Conversely, a description of a drilling-induced core fracture might quickly indicate the approximate state of stress under which the core fracture was created.

Derivation of the boundary lines between the different core fracturing behaviors is straightforward. The boundary between kerf and axis fracture initiation for core disks derives directly from the result of Figure 12. The boundary between petal and disk fractures is delineated by finding the points at which the fracture trajectories discontinuously shift from vertical (indicative of petal-centerline fractures) to horizontal (indicating disk fractures). No other fracture trajectory dips were found at the well bore axis.

5. Discussion

5.1. Comparison of the Modeling and Observations

Very broadly, the fracture trajectories predicted above are consistent with the shapes of drilling-induced core fractures
these fractures relative to in situ stress directions agree fully with observation. Although this agreement is encouraging, if the theoretical relationships between drilling-induced core fracture morphology and in situ stress state are to be useful, more quantitative comparisons are required. A comprehensive set of laboratory experiments to test the result of Figure 13 is not yet available, although Haimson and Lee [1997] and Song and Haimson [1996] have recently made substantial progress in this direction.

Here we compare observed core fractures with the states of stress from which they were recovered. However, there are few studies where simultaneously both good descriptions of the core fractures exist and in situ stresses have been quantitatively measured. Most often in the literature, descriptions of core fractures are only anecdotal, and their existence is justly taken by the authors to indicate high levels of in situ stress. The comparisons available to us, and summarized in Table 1, stem from both laboratory experiments and field drilling projects in which hydraulic fracturing measurements had been carried out, these will be discussed on a case by case basis in the context of the results of Figure 13. We note further that field stress measurements as conducted by the hydraulic fracturing method are still not perfect, and although determinations of \( S_h \) by a variety of methods [Engelder, 1993] are reliable, estimates of magnitude of \( S_h \) can be influenced by numerous material and pressurization rate dependent factors [e.g., Schmitt and Zoback, 1993] and are more prone to error.

Obert and Stephenson's [1965] experiments have been previously discussed in detail [Li and Schmit, 1997b]. They subjected to cylindrical samples of a variety of rock types progressively compressive radial and axial loads until core disking was observed. Their loading conditions fall entirely within the thrust fault regime but, as uniform radial stress exists, are limited only to the extreme righthand boundary of the graph where \( S_h = S_v \). The fact that they observed core disks is consistent with Figure 13; they did not provide additional details on the morphology of their disks, but the photographs as reproduced in Figure 1a indicate relatively flat disking surfaces which would be consistent with a state of uniform horizontal compression (Figure 11a). No information on fracture initiation locations was given, nor can this information be unambiguously extracted from their photographs.

Jaeger and Cook [1963] carried out simple experiments in which they subjected cylindrical test pieces, already centrally cored and containing an intact core stub, to an approximately radial uniform compression with no axial stress. They provide an example of one such resulting core disk fracture in a photograph. This fracture is nearly flat and is again consistent with the suggested core disking. Again, no information on where the fracture initiated was provided, although the uniform radial symmetry of the fracture and the fact that it extended to beneath the kerr suggests the fracture initiated at the core root.

Numerous experiments have recently been carried out by Haimson and Lee [1997] and Song and Haimson [1996] over a broader range of stress conditions (Table 1). They reported that saddle-shaped core disking fractures originating in the vicinity of the kerr were produced. The box shown in Figure 13 describes only the reported ranges of loads [Haimson and Lee, 1997] applied to their samples; details of which individual stress states were used are not yet available.
We have access to only published examples where both in situ stresses have been quantitatively measured and the core disks have been observed and sufficiently described. One of these studies consists of hydraulic fracturing tests in well bores near depths of 1000 m in the Columbia River basalts, Washington, by Paillet and Kim [1987]. Horizontal principal stresses were measured with hydraulic fracturing method (Table 1), and the predicted stress conditions lie immediately below the thrust/strike-slip faulting boundary and near the proposed root/k erf fracture initiation border. They observed extensive core disking again broadly consistent with Figure 13. One photograph shows a typical saddle-shaped core disk. The fracture initiation location of which appears to be near or outside the core in agreement with what might be expected. However, another photograph in their paper shows numerous core disks which may have flat fracture surfaces. No descriptions of additional core disks were provided, and it is unknown whether disks with fractures initiating at the root were observed since some of their reported stress conditions fall within this region. Regardless, the observation of core disking is in agreement with Figure 13.

The next set of pertinent observations come from the recently completed KTB well bore and include the descriptions of the drilling induced core fractures [Röckel, 1995], and the quantitative estimates of in situ stress from hydraulic fracturing measurements [Baumgärtner et al., 1990] in the KTB-VR pilot well bore and from a combined stress analysis in the KTB HB main well bore [Brady, 1995]. The hydraulic fracturing results to 3 km depth [Röckel and Natau, 1993; Brady, 1995] are summarized in Table 1 and plotted in Figure 13, but the quantitative studies indicate strike-slip faulting conditions exist to depths of almost 7 km. Röckel [1995] observes a few saddle shaped disking fractures above the depth of 3500 m in the pilot hole, but numerous core disking fractures occur below depths of 3560 m and the high points of which were used as indicators of the direction of \( S_h \). These core
TABLE 1. Field and Experimental Data of Drilling Induced Fractures

<table>
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<tr>
<th>Source of Data</th>
<th>Rock Type or Location</th>
<th>$S_H$ MPa</th>
<th>$S_v$ MPa</th>
<th>$S_H$ MPa</th>
<th>$S_h/S_H$</th>
<th>$S_v/S_H$</th>
<th>Type of Fracture</th>
</tr>
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<td>Obert and</td>
<td>Georgia granite</td>
<td>66.5–137.9</td>
<td>66.5–137.9</td>
<td>0.0–82.0</td>
<td>1.0</td>
<td>0–0.59</td>
<td>Core</td>
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<td>57.8–106.8</td>
<td>0.0–82.0</td>
<td>1.0</td>
<td>0–0.77</td>
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<td></td>
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<td>1.0</td>
<td>0–0.5</td>
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<td>Jaeger and</td>
<td>Rand quartzite</td>
<td>120.0</td>
<td>120.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0</td>
<td>Core</td>
</tr>
<tr>
<td>Cook [1965]</td>
<td>Wombeyan marble</td>
<td>48.0</td>
<td>48.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0</td>
<td>disking</td>
</tr>
<tr>
<td></td>
<td>Dolerite</td>
<td>110.0</td>
<td>110.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0</td>
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</tr>
<tr>
<td>Haimson and</td>
<td>Luc du Ronnet granite</td>
<td>92.5–231.2</td>
<td>20–50</td>
<td>25–60</td>
<td>0.1–0.54</td>
<td>0.1–0.65</td>
<td>Core</td>
</tr>
<tr>
<td>Lee [1995]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>disking</td>
</tr>
<tr>
<td>Brady [1995]</td>
<td>KTB pilot hole (805 m – 3011 m)</td>
<td>25.0–48.7</td>
<td>49.4–98.7</td>
<td>22.5–84.3</td>
<td>0.5–0.51</td>
<td>0.46–0.93</td>
<td></td>
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<tr>
<td>Röckel and</td>
<td>KTB pilot hole (3582 m)</td>
<td>102.4</td>
<td>48.8</td>
<td>102.0</td>
<td>0.48</td>
<td>0.99</td>
<td>Core</td>
</tr>
<tr>
<td>Natau [1993]</td>
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<td></td>
<td></td>
<td></td>
<td>disking</td>
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<tr>
<td>Paillet and</td>
<td>Borehole DC-4: basalts</td>
<td>59.9</td>
<td>30.8</td>
<td>24.4</td>
<td>0.51</td>
<td>0.41</td>
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<tr>
<td>Kim [1987]</td>
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<td>61.2</td>
<td>34.8</td>
<td>26.2</td>
<td>0.56</td>
<td>0.43</td>
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<td></td>
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<td>60.6</td>
<td>34.5</td>
<td>26.3</td>
<td>0.57</td>
<td>0.43</td>
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<tr>
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<td>Borehole RIJ-5: basalts</td>
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<td>33.0</td>
<td>27.8</td>
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<td>Evans [1989]</td>
<td>Western New York</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.46–0.86</td>
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<tr>
<td>Hickman et al.</td>
<td>Western New York</td>
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fractures are in good agreement with that expected in Figure 13. However, it must be noted that Röckel [1995] also describes a few isolated appearances of petal and centerline fractures. The petal fractures are not in agreement with the general results of Figure 13, although some of these fractures may be related to the foliations of the metamorphic rocks cored.

Finally, numerous stress studies have been published with regards to the Appalachian region of the United States stretching along the sedimentary basin through New York, Pennsylvania, Ohio, West Virginia, and Kentucky. Extensive centerline fractures were observed in oriented cores, mostly of Devonian age, in the Eastern Gas Shales Project (Cliffs Minerals Inc., 1982). The cores were recovered from 21 wells from northern Pennsylvania to eastern Kentucky and from depths of 100 m to 2000 m. Plumb and Cox [1987] noted that these centerline fractures strike predominantly N80°E indicating the direction of $S_H$ in agreement with those predicted from well bore breakout orientations.

Research quality hydraulic fracture measurements have been carried out in a number of locales. In the vicinity of Auburn, New York, Hickman et al. [1985] made four hydraulic fracture determinations (Table 1) which indicates that a shallow strike-slip regime changes to normal faulting at depth. Engelder [1985] noted that their results may indicate a low value of $S_h$ at shallow depth. At nearby South Canisteo, New York, Evans et al. [1989] made 75 hydraulic fracture measurements in three closely spaced wells to depths of 1037 m. Although the stress state was found to depend to some degree on lithology, in general they observed borderline strike-slip/thrust faulting conditions at shallow depths which abruptly changed to a strike-slip and nearly normal faulting regime below a specific geologic horizon (Table 1). Evans [1989] further provides a summary of instantaneous shut in pressure tests acquired from industrial databases; these provide a measure of the ratio $R_h = S_h/S_v$ which does not, unfortunately allow for estimation of $S_v$. In the uppermost Devonian intervals, $0.35 < R_h < 1.5$, with the smaller values of $R_h$ generally observed in the deeper more southerly determinations, indicates that either normal or strike slip faulting regimes are likely there. In contrast, larger values of $R_h$ are seen in the more northerly areas, and these are possibly indicative of either strike-slip or even thrust faulting environments. For clarity, the Appalachian results are superimposed in Figure 13. All of the estimated stress states fall mostly within the strike-slip region and into the thrust faulting region. These results are apparently discrepant with the numerous observed centerline fractures.

A possible reason for this discrepancy is that Figure 13 may not appropriately consider the possibility of pure centerline fractures; Figure 13 presumes that a centerline fracture must first occur as a petal fracture. Another possibility exists when small $S_h$ magnitudes are found and especially when a well bore fluid pressure is present [Li and Schmitt, 1997a]. Under these conditions, large tensions can also be generated at the center of the well bore bottom in the direction of $S_H$. This tension is offset by the overlying fluid pressure. When these two horizontal stresses, $S_H$ and $S_h$, are equal, the resultant stress state is what is isotropic and the centerline fractures are initiated without upper tilted petals may also be a
possibility in cases of low $S_h$ as occurs in the Appalachian region.

5.2. Additional Considerations

A number of other factors which possibly influence the morphology of the core disks have to this point been purposely ignored in order that the dependencies of the drilling-induced core fractures on the in situ stress state are clear. Some additional complications which will not be discussed here but will influence the stress field in the core and near the bottom hole arise due to the change of local stress field with the propagation of the fracture, to the nonlinear elastic behavior and yielding of rock, to torque loading imposed by friction forces of the rotating core barrel, to anisotropy of the elastic properties or of the tensile strength (foliation or bedding plane), to deviation of the well bore axis from a principal stress direction, to hydraulically driven fracture propagation by pressurized well bore fluid, and to thermoelastic and poroelastic stresses resulting from contact and transfer of drilling fluid with the rock mass. We address some of the more general influences below.

In theory, the trajectory of a fracture is determined by the stress field it encounters. The fracture tends to propagate in a direction normal to the direction of principal tension. However, as the fracture propagates, it perturbs the earlier stress state and the intensity of the stress field will change. This change in the overall stress field is expected to influence the fracture growth and final shape. However, the agreement between the modeling and the observed fracture morphologies suggests that the present approximation is valid.

If the medium is not homogeneous, the core disking fracture may not initiate along the core axis or at the boundary of the core. Stresses are additionally locally concentrated by inclusions with differing elastic properties [e.g., Tapponnier and Brace, 1976]; additional tensile stresses could consequently be generated very near these inclusions from which fracturing might originate. One such example, in Devonian shale core from Appalachian basin, Kentucky, is given by Kulander et al. [1990] in which a core disking fracture originates at a pyrite nodule which is neither at the axis or near the core boundary. Bankovic and Bankovic [1995] give a further example from the KTB well bore where the disking fracture initiated at an inclusion midway between the core axis and boundary.

The loads imposed by the weight of the drill string and from the pressure of the well bore fluid (i.e. drill mud weight) have been previously described in a simpler, but less realistic, square bottom hole geometry [Li and Schmitt, 1997a]. Substantial concentrated tension is generated at the square inner corner of the kerf for both of these loads; but this tension remains highly localized to a small region near the kerf. The concentrated stresses within the rock mass which will become the core are largely compressive.

Although the tension induced by these influences could promote fracture initiation from the kerf, the states of stress concentrated by these loads should not assist continued propagation. Common anecdotal descriptions of the existence of core disking depending on the rate of penetration (i.e., on which drill crew was employed) may be related to a potential trigger effect here; speculatively, a higher rate of penetration requires a greater bit load generating a greater local tension at the kerf, making fracture initiation more likely. In the more realistic geometry used in the present finite element modeling (Figure 4) with the loads distributed over a smoothly curving surface, these concentrated tensions will be even more attenuated. However, the effect of drill bit weight should not be immediately dismissed; it may result in a shift of the hypothetical boundaries between the different types of petal and disk fractures in Figure 13.

Pore pressure is an important consideration in the brittle failure of rock. Under quasi-static loading conditions the influence of pore pressure in promoting tensile failure is described by the relationship first described by Terasaki [Schmitt and Zoback, 1992]:

$$S + (T - P_p) < 0$$

(1)

where $S$ is the most tensional principal stress at the point of failure, $T$ is the material dependent tensile strength, and $P_p$ is the pore pressure at the point of failure. Inclusion of a pore pressure serves here only to diminish the compression or effective stresses, the shapes and fracture initiation locations (assuming uniform pore pressures) remain dependent on the concentrated total stresses.

The effects of the geometry of bottom hole due to use of drill bit with different dimensions and shape or of the length of core stub is of obvious importance. Both will influence the concentrated stress field at the bottom hole [Li, 1997]. As regards the former, the relative diameters between core and well bore and the shape of the bottom hole are important parameters. Some modeling carried out by us to test this indicates that these parameters do not have a large influence on the characteristic of the stresses concentrated near the core for a reasonable range of relative kerf thicknesses [Li, 1997]. The shape of bottom hole, however, has significant influence on the magnitudes of the concentrated stresses and the magnitude of the greatest tensional stress is reduced to nearly half when a semicircular cut replaces a flat cut [Li, 1997] although the overall character of the concentrated stress field remains essentially the same.

The length of the core stub has considerable influence on the stress concentrations. The length used here (Figure 4) is close to that for the greatest spacing between incipient core disking fractures. The previous studies [Li and Schmitt, 1997a, b] showed that smaller spacings between the fractures will occur at higher stress levels, whereas no macroscopic core fracturing is expected for greater spacings in homogenous rock. Interpretation of core disk fractures in light of the results given in Figure 13 should account for this. This is especially true for petal and petal centerline fractures because they often have larger spacings relative to those observed for core disking fractures.

6. Conclusions

A simple model of tensile fracture propagation within the concentrated stress field produced at the bottom hole is developed. The calculated fracture trajectories resemble well the shapes of observed drilling-induced petal, petal-centerline, and disking fractures. This agreement suggests that the shape of the core fractures contain substantial information on the relative magnitudes of the in situ states of stress. The location at which the fracture initiates, whether at the core axis or near its outside boundary, is an additional piece of information. Further, there is a gradual, stress state dependent evolution of the fracture morphology made apparent by the mapping of Figure 13 from petal fractures to petal-centerline fractures to
disking fractures. The present modeling does not account for purely centerline fractures which possibly result when one horizontal stress is of low magnitude [Li and Schmitt, 1997a] and as may have been observed in the Appalachian basin [Plumb and Cox, 1987].

The modeling here also confirms field and laboratory observations related to the orientation of the drilling-induced core fractures. The strike of the fractures is parallel to that for the greatest horizontal compression, whereas the azimuth of the high points on petal and saddle-shaped disks coincides with the direction of the least compressive horizontal principal stress.

The relationships between in situ faulting environments and core fracture shape are promising and indicate that the core fractures can provide important complementary qualitative information to more quantitative methods such as hydraulic fracturing and overcoring. The spacings of the core fractures are known to depend on stress magnitudes, and detailed relationships between stress magnitudes and fracture spacings are possible when the applied stress conditions are known [Li and Schmitt, 1997b]. However, carrying out this procedure for more complex shaped core fractures produced under anisotropic stress conditions and in consideration of the influence of geometry would be tedious; some type of interactive modeling of the core fractures in which the variety of controlling parameters can be rapidly changed and the resulting core fractures would be useful in this regard and form part of the basis for future work. The above results, although in relatively good agreement with the limited observations, remain theoretical; both additional experimental tests and comparisons with field observations in light of these results are necessary.

Appendix: Fracture Trajectory Calculation

The stresses calculated by finite element modeling are irregularly distributed with the nodes of the mesh of the finite element model. In the fracture trajectory determination procedure, the magnitudes and orientations of the most tensile principal stress (σ3) within the two planes perpendicular and parallel to the greatest horizontal compression and intersecting at the well bore axis were first interpolated into a finer grid. In each plane, the fracture was assumed to initiate at the grid point with the largest tension, opening of the fracture occurs parallel to the direction of σ3 and the subsequent propagation of the fracture is perpendicular to this.

The determination of the fracture trajectories follows a procedure reminiscent to that employed in simple Snell's law seismic ray-tracing algorithms. Figure A1 illustrates the process of the fracture tracing, where Ax and Ay (Δx = Δy) are the spacings within the interpolated grid in the x (horizontal) and y (vertical) directions. They have a dimension about 1/100 of the core diameter. The fracture tracing starts at the grid node 1 also denoted as A; the line from A to B represents a small segment of the fracture trajectory across the cell, and its orientation is dictated by the orientation of σ3 at A. The segment intersects the boundary between two adjacent cells at point B which lies between the grid positions 2 and 3 where σ3 is known. The magnitude and direction of σ3 at B is then linearly interpolated from these two locations; the next segment of the fracture trajectory continues based on this orientation to location C. Location C lies on a horizontal boundary between two cells and here the new direction of the fracture tracing from C is determined by linear interpolation using the data at grid nodes 3 and 4. Continued propagation halts when the fracture trajectory either intersects the well bore axis or when σ3 is no longer tensional. The procedure is carried out in both planes only if the initial fracture trajectory leading from the location of the greatest tension in both intersects the wellbore axis. The petal-fracture-like trajectories in Figures 7, 9, and 11 are examples in which the calculations were only carried out in one plane.

A drawback of the present arrangement is that cases of stable fracture propagation may not be adequately handled. For example, a stably growing fracture with a distinct opening and loss of cohesion (as opposed to a rupture as mentioned earlier) will of itself change the geometry of the fracture and consequently also must influence the stress concentrations. Dealing with such situations from such a fracture mechanics perspective in relatively complicated geometries is still not necessarily straightforward. Although such studies should remain a goal for the future, the good correspondence between the predicted fracture trajectories and coring induced fractures suggests that this simplified approach is valid.

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References


Y. Li and D.R. Schmitt, Institute for Geophysics, Meteorology and Space Physics, Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2E1. (e-mail: youguy@phys.uabberca.ca, doug@phys.uabberca.ca)

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