Drilling Induced Core Fractures and Crustal Stress

Lei Zhang, Claire A. Currie, and Douglas R. Schmitt
Department of Physics, University of Alberta, Edmonton, Alberta, Canada

Summary

Drilling induced core fractures, usually ignored in standard core logging, contain substantial information on the directions of horizontal stresses and the relative magnitudes of the three principal stresses. These fractures have a variety of shapes, variously referred to as petal, petal-centreline, saddle, cup, and scallop. Surprisingly, the morphology of the fractures suggests they are produced under a pure tensional stress, despite the fact that in almost all in situ conditions the state of stress is entirely compressive. Earlier numerical modeling has demonstrated that such pure tensions result from complex stress concentrations around the cylindrical geometry of a core stub before it is broken from the rock mass. In addition to the fracture shapes, the points at which they initiate indicate the natural stress state in the Earth. Here, we describe some new finite element models of the stress distributions at the bottom of a borehole being cored. This builds on earlier work of Li and Schmitt (1997) but is focused on the development of an interpretive tool.

Introduction

The stress regime in the crust controls crustal deformation, the initiation of earthquakes and micro seismicity, landslides, wellbore stability, natural fracture permeability, and hydraulic fracture initiation and propagation. However, it is difficult to make direct measurements of in situ crustal stress. Common techniques for assessing crustal stress include the study of borehole breakouts and controlled hydraulic fracturing ('mini-fracs'). Another indicator that is less well known, but not completely unrecognized, is the drilling induced core fractures (e.g., Li and Schmitt, 1998). These Fractures can provide an additional, independent constraint on principal stress directions and the relative magnitudes of the principal stresses (i.e., the Andersonian faulting regime). Further, these fractures usually appear along the core at uniform spacing; presumably this must contain additional information on the absolute stress magnitudes. An example of a petal-centreline fracture is shown in Fig. 1, but distinct patterns have been categorized as petal, petal center-line, saddle (or Pringles™ potato chip), cup, disc, and scallop (Fig. 2).

Figure 1. Example of severe petal-centreline fractures. Core from ANDRILL South McMurdo Sound. Photo by D.R. Schmitt.

It is proposed that the distribution and morphology of borehole fractures is related to the in-situ crustal stress. Consequently, a better understanding of these fractures requires detailed quantitative knowledge of the distribution of stresses within the rock at the bottom hole during coring. However, the 3D bottom-hole geometry particularly if a still attached core stub remains is a formidable challenge to an analytic solution and a numerical one must be employed. In this study, we have used 3D finite element models to investigate the origin of drilling-induced fractures and the stress conditions under which they form. While many aspects of the modeling itself are not new, this work aims to extend previous results by incorporating the calculations into the development of a tool useful for the interpretation of such fractures in terms of the stress states under which they will originate.

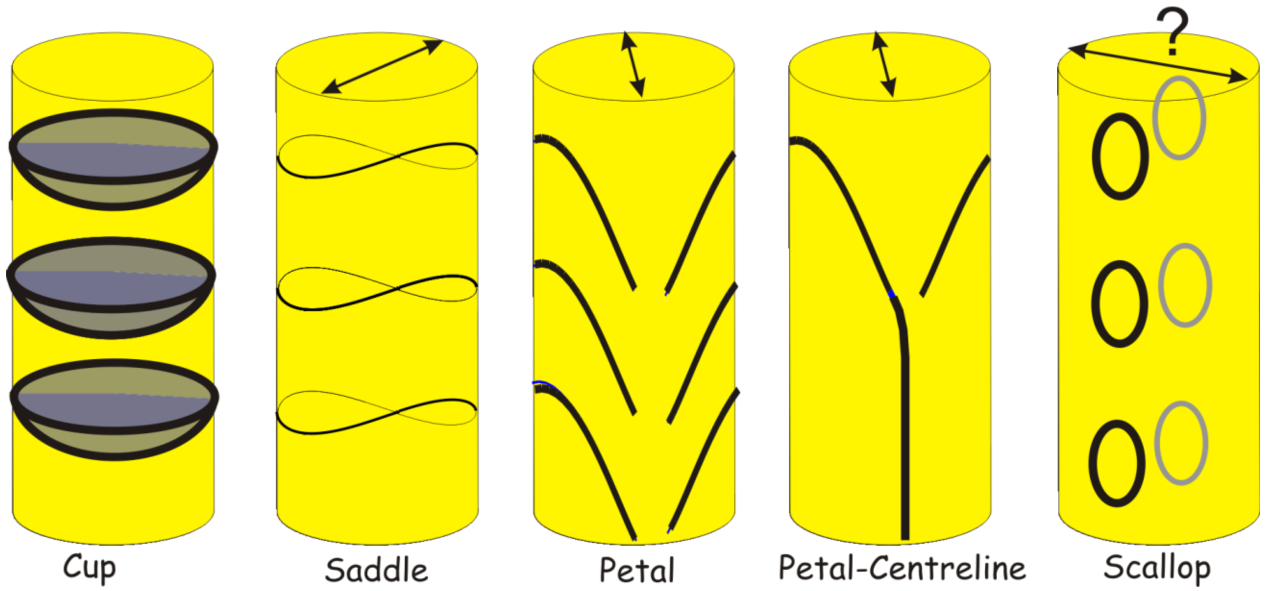

Figure 2. Types of drilling induced core fractures. Double-headed arrow represents the direction of the greatest horizontal compression that falls along the strike of the fractures. Stress directions only inferred for scallop type fractures.

Calculation of stress field

As a borehole is drilled into the crust, the pre-existing in-situ stress field will be modified in the vicinity of the borehole, resulting in stress concentrations which may lead to fracturing. We first calculate the stress distribution near the bottom of a vertical borehole for different stress configurations. The numerical solution for the stress distribution is obtained through a finite element package (the ANSYS™ program). To simplify the model, linear, elastic and isotropic materials are used with Young's modulus and Poison's ratio close as that in the real rock. In this model, in situ stress is incorporated through boundary conditions, with its three stresse components of orthogonal direction SV, SH and Sh respectively corresponding to the vertical over burden stress, maximum horizontal compression, and the minimum horizontal compression (Fig. 3). Here, different

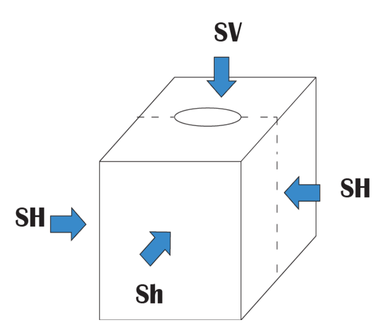

Figure 3. Principal in situ stresses

stress ratios are assigned to the boundary in the numerical model to simulate the various in-situ stresses. From the perspective of obtaining a direct analytical solution, this geometry is complex (Fig. 4a).

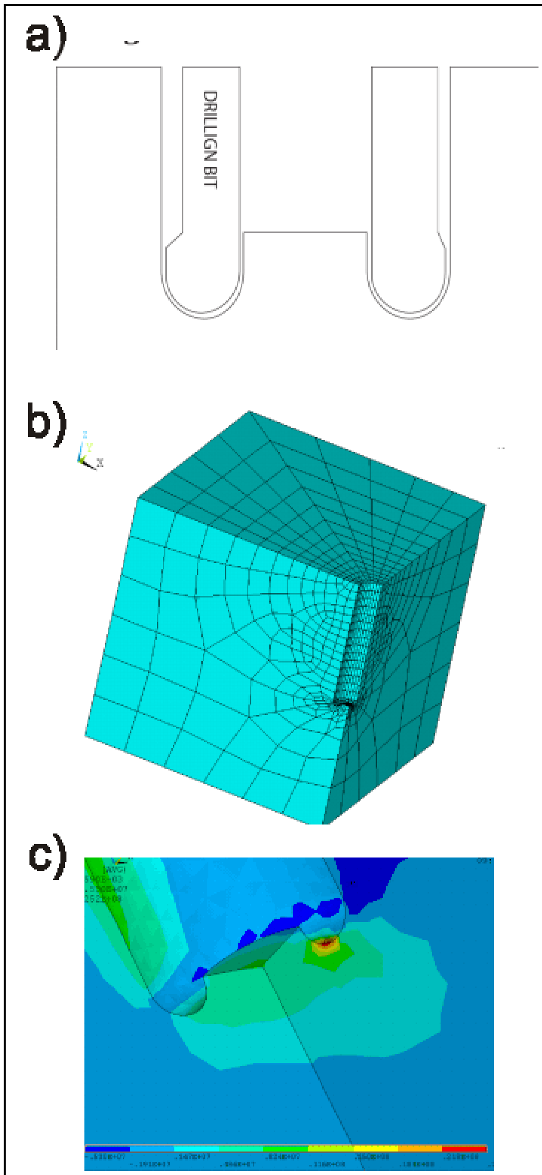

Figure 4: a) Bottomhole geometry with bit and core stub. b) Finite element mesh constructed to model geometry. c) Example stress calculation (SV=1, SH=0.5, Sh=0). Red shows regions of maximum tensile stress.

Since stress varies the most around the boundary (Jaeger, Cook and Zimmerman 2007), high density numerical solutions need to be obtained to accurately show the stress variations. Considering of the regularity of the geometry boundary, we use a specific meshing method to set many closely-spaced nodes in the vicinity of the borehole (Fig. 4b). This then allows an accurate numerical solution of the stress field, which can be visualized in various forms using the postprocessor in ANSYS™. For example, the contour plot of stress distribution (Fig. 4c) clearly shows the spatial distribution of stress and can be used to rapidly determine the tensile stress zone and maximum tensile stress location (shown in red in Fig. 4c). In this case, the tensile stress zone is located near the inner corner of the drilling bit while the maximum tensile stress is located on the inner corner boundary.

Fracture Modelling

The calculated stress distribution is then used to evaluate the development of fractures within the core sample. Linear interpolation of the stress magnitudes and directions are used to create a regularly spaced grid from the original finite element mesh of variable element size. This allows the principal stress tensor to be determined at each grid point; this information is necessary in order to construct a fracture trajectory. The location of the maximum tensile stress is assumed to be the starting point of the crack. The location of this point varies as per the boundary conditions, but usually it locates on the inner boundary of the drilling bit or the central line of the core. In our model, the crack initiates at the point of the greatest tension, opening in the direction of this tension. This sets the initial propagation direction which is followed to the next set of nodes at which point it is re-evaluated and the direction shifted. This model can be extended into a practical tool in which a base solution is developed, and all the calculations are united into one body. The user then only needs to enter the relevant stress distribution and Poisson's ratio parameters to reconstruct the fracture shapes quickly.

Example

At this writing, we have developed a model of fracture propagation on a 2D plane aligned with one of the in situ principal stresses. Fig. 5 is an example the fractures trajectory for the case where the in-situ stress is under the conditions SV=1, SH=0.5, Sh=0. The plane of the figure corresponds to the Sh direction. The computed fracture geometry corresponds to the petal morphology observed in core samples.

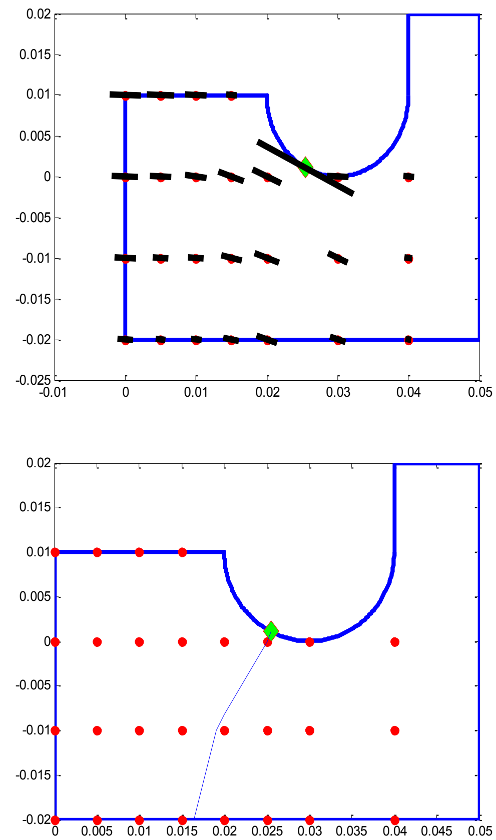

Figure 5. Top Panel, magnitude and direction of the principal tension at the grid points for the fracture trajectory calculations. The maximum tensile stress is 25Mpa when compressive in situ stresses SV=20Mpa, SH=10Mpa, Sh=0Mpa. Bottom Panel, close up view of the fracture trajectory (blue line).

Conclusions

Our study confirms the results of earlier work (e.g., Li and Schmitt, 1998) that borehole core fractures are related to the in-situ crustal stress field. Finite element models demonstrate the occurrence of stress concentrations in the vicinity of a borehole. Fractures may initiate at the point of maximum tensile stress and propagate according to tensile stress theory. Thus far, numerical models of 2D fracture propagation under different in situ stress conditions have yielded fracture patterns that correspond to petal, petal centerline, saddle and disk morphologies (Fig. 2). We have not yet been able to model the development of scallop fractures. Fracture morphology and spacing in borehole cores therefore provide a constraint on the crustal stress regime. Current work includes a more accurate numerical solution based on a full 3D fracture propagation model as well as development of an interpretation tool.

Acknowledgements

This work is in part funded by an U.S. NSF grant for studies of stress in the ANDRILL SMS core hole and by NSERC for CC and DRS. Assistance with Dr. Moussa in the Dept. of Mechanical Engineering at the University of Alberta with the finite element code ANSYS™ is greatly appreciated.

References

Li, Y.Y., 1997, Drilling Induced Core Damage and Its Relationship to the Crustal Stress States and Rock Properties, Ph.D. Dissertation, University of Alberta, 231.

Li, Y.Y., and Schmitt, D.R., 1998, Drilling-induced Core Fracture and In Situ Stress, Journal of Geophysical Research, vol.103, No. B3, 5225-5239.

Jaeger, J.C., Cook, N.G.W., and Zimmerman, R.W., 2007, Fundamentals of Rock Mechanics, 4th edition.