

Borehole Stress Measurement Methods: Experiences from Scientific Drilling

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Summary

A short review of some of the methods employed to quantitatively measure stress in the earth highlights borehole imaging, core logging, and hydraulic fracturing. A description of these methods is buttressed by experiences gained in scientific drilling projects in a variety of situations.

Introduction

Knowledge of the magnitudes and directions of stress in combination with fluid pressures in the earth is fundamental to our understanding of plate tectonics, the formation of faults, and the initiation and propagation of earth quakes at all scales [e.g., *Bell*, 1996]. Stress, too, also controls more local failures within underground structures and as such is ignored at the peril of workers. Stress magnitudes and directions are the primary control on hydraulic fracture stimulations. And finally, stress can influence the geophysical and hydrological transport properties in the subsurface. For example, the anisotropy of the principal stresses within the earth affects the anisotropy of electrical resistivity, seismic waves, and permeability. Conversely, remotely measuring these properties using geophysical methods might provide methods to better understand stress distributions.

The quantitative understanding of crustal stress is, unfortunately, elusive. Ideally, one would hope to be able to map the stress tensor in 3D within a volume of the earth. This is not so easily achieved; and often only indicators of stress are all that is available. Such indicators include the attitudes and directions of igneous dikes and sills and the tension and compression axes of earthquake focal mechanisms. Such methods do not directly quantitatively measure stress, however, nor are they even applicable in most geological situations and more direct methods of interrogating the earth are necessary. Here, some of the more popular techniques for estimating stress from core and boreholes as practiced in open-hole scientific drilling is reviewed and some recent experiences in stress determination shared. This review focuses on core fractures, borehole imaging, and hydraulic fracturing and as such because it reflects the author's experiences cannot be comprehensive. Other stress measurement techniques for deep boreholes not discussed here include anelastic strain recovery and shear wave anisotropy

Drilling Induced Core Fractures

Drilling induced core fractures [e.g., *Li and Schmitt*, 1998] result primarily from the stress concentrations induced by the complex 3D geometry of the drilled cavity. The shapes, orientations, and spacing of these fractures are often remarkably uniform; and they contain a great deal of information on the state of stress. The fracture shapes include 'petals', 'petal-centreline', 'saddle', 'cup' (or 'disc'), and 'scallop' (Fig. 1). Stress directions are indicated along the fracture symmetry planes, for example the locus of the points at the bottom of the saddle points in the direction of the greatest principal horizontal compression, as does the strike of a petal or petal centre-line fracture. The shapes, too, can provide qualitative information on the relative magnitudes of the in situ principal stresses (i.e. the faulting regime). The spacing of such fractures should be able to provide some indication of stress magnitudes but this is not yet completely understood.

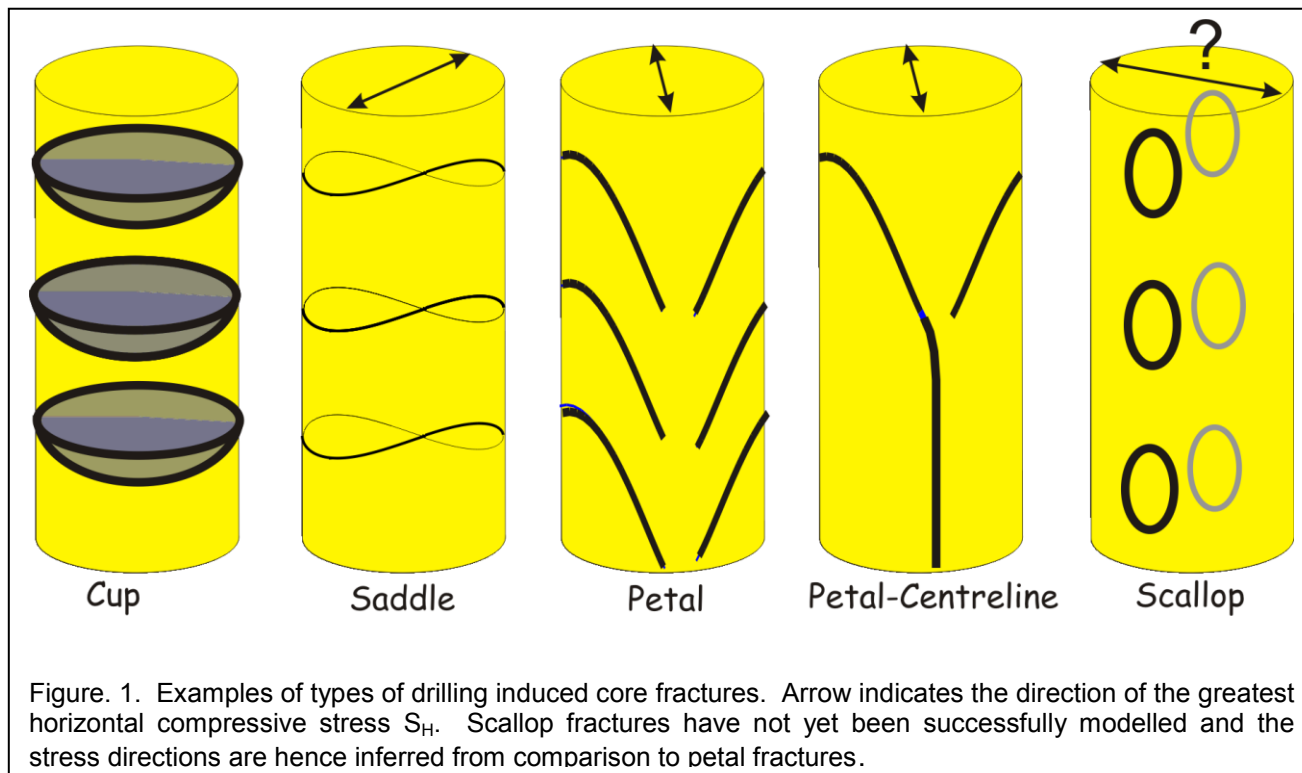


Figure. 1. Examples of types of drilling induced core fractures. Arrow indicates the direction of the greatest horizontal compressive stress S_H . Scallop fractures have not yet been successfully modelled and the stress directions are hence inferred from comparison to petal fractures.

The 3D shape of the cavity at the end of a core bit is, with regards to the development of a simple analytic solution, complex; and finite element methods are often employed to study the stress concentrations [e.g., *Corthesy and Leite, 2008; Li and Schmitt, 1997; Matsuki, et al., 2004*]. The sophistication of the numerical models have matured to account for changes in the stress distribution as the fractures evolve beneath the core stub. In summary, this work suggests that the drilling induced fractures are primarily purely tensile (although this remains under discussion), and that a combination of their shapes and initiation points can be interpreted to constrain the Andersonian faulting regime (i.e., the relative magnitudes of the three principal stresses). Under certain stress conditions, the tensile strength is exceeded at the interior of the core stub; and this will adversely bias any associated petrophysical measurements.

Borehole breakouts and drilling induced fractures

Observations of borehole breakouts [e.g., *Bell and Gough, 1979*] and drilling induced borehole wall fractures from geophysical logs are now a standard method for indicating stress directions. Tectonic stresses and wellbore fluid pressure are concentrated near a newly created borehole cavity with an ideally 'circular' cross-section. This stress concentration results in the greatest shear stress magnitudes at the two opposite azimuths aligned with the least compressive horizontal stress S_h (Fig. 3). Spalling of the rock at these azimuths occurs should this stress exceed the material shear strength; and this results in the well-known borehole breakouts. While these appear to be excellent indicators the direction of S_h the width and depth have been used by some workers to constrain stress magnitudes [e.g., *Zoback, et al., 2003*]. In contrast, tensile drilling induced borehole wall fractures also exist at azimuths orthogonal to the breakouts.

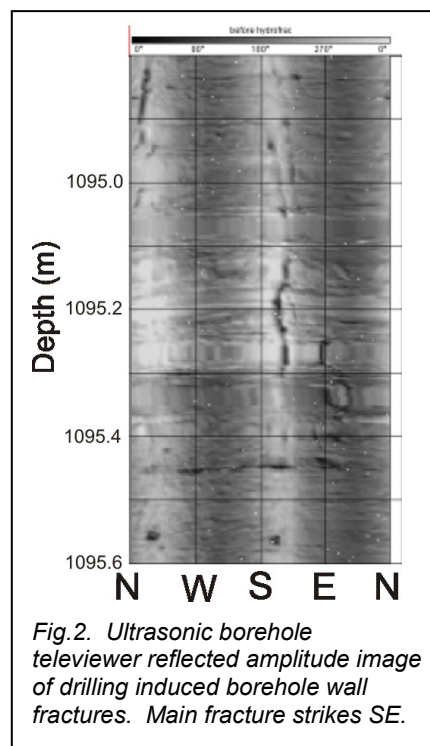


Fig.2. Ultrasonic borehole televiewer reflected amplitude image of drilling induced borehole wall fractures. Main fracture strikes SE.

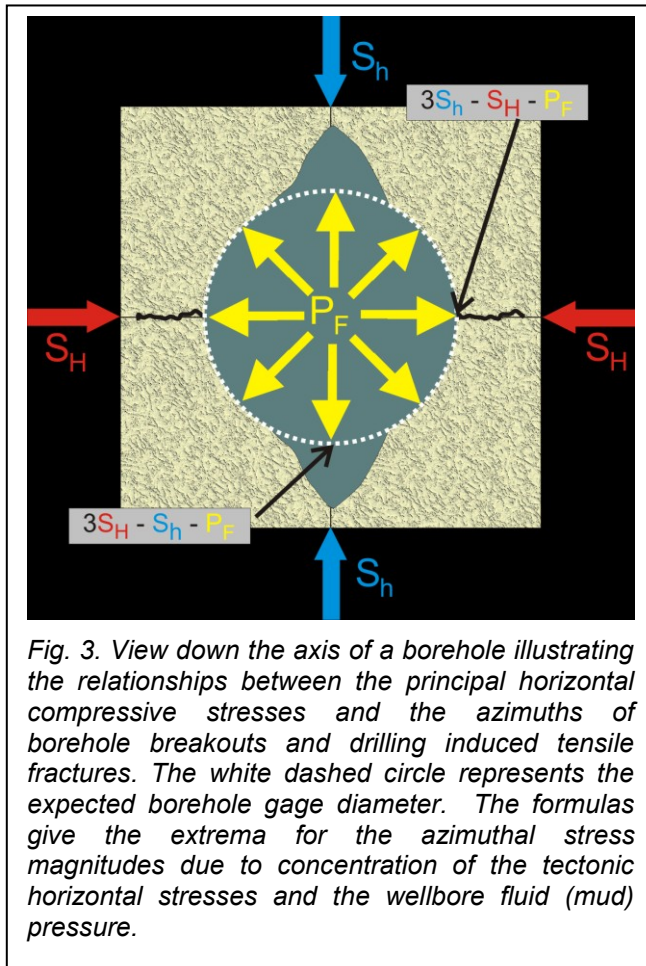


Fig. 3. View down the axis of a borehole illustrating the relationships between the principal horizontal compressive stresses and the azimuths of borehole breakouts and drilling induced tensile fractures. The white dashed circle represents the expected borehole gage diameter. The formulas give the extrema for the azimuthal stress magnitudes due to concentration of the tectonic horizontal stresses and the wellbore fluid (mud) pressure.

Although their relationship to induced core fractures remains to be determined, these features depend on the drilling fluid pressure; and as this can typically be relatively well estimated is able to give some additional constraints on stress magnitudes particularly if the borehole fluid pressure (P_F) is known. In the simplest criteria [e.g., Schmitt and Zoback, 1989], the drilling induced fracture initiates when

$$3S_h - S_H - P_F \leq -T \quad (1)$$

Where $T (>0)$

is the tensile strength of the rock. Essentially, given that S_H and S_h should not change, this means that increasing wellbore fluid pressure P_F will induce the fracture once the tensile strength is exceeded.

Hydraulic Fracturing

In the hydraulic fracturing stress determination method (also often referred to as a minfrac), a small interval along the borehole, isolated by a pair of inflated packers (Fig. 4), is rapidly pressurized until either a 'hydraulic' fracture is produced or an pre-existing fracture is reopened [e.g., Haimson and Cornet, 2003]. In this method, the downhole pressures within the interval

are carefully measured during pressurization (Fig. 5); and fracture initiation ('break-down' is indicated when a sudden drop in this pressure is noted).

The interval pressure then drops and stabilizes at the pressure presumed necessary to keep the fracture open. Hence, this 'shut-in' pressure is taken to be equal to the magnitude of the least compressive principal stress. The break-down pressure can also be used to constrain the magnitude of S_H although this value is substantially more uncertain. The simplest expression for S_H magnitude estimation is simply a rearrangement of Eqn. 1 where P_B is the interval pressure at 'breakdown' (Fig. 5).

$$S_H = 3S_h + T - P_B$$

Recently, a wireline mounted hydraulic fracturing unit has been deployed to depths greater than 1.5 km from the surface at ANDRILL (Antarctic Drilling) [Schmitt, et al., 2008]. This unit is intended primarily for use in open boreholes (NQ and HQ drill string standard dimensions) and can be deployed and moved from station to station relatively rapidly. This unit was able to make 17 high quality stress determinations in an approximately 20 hour period at the ANDRILL SMS site. Optimal use is obtained if the borehole can be logged with a televiewer both before and after the fractures are produced as the azimuth at which the fractures appear should also indicate the S_H direction.

Conclusions

The methods for estimating stress here are primarily from slim hole scientific drilling. However, there is nothing restricting them from being applied to other drilling. In particular, more use could be made of core fractures to infer stress states. However, geoscientists will need to be

more cognizant of crustal stress in the future particularly with regards to issues of public safety related to hydraulic fracture stimulations and the long term monitoring of geologically sequestered green house gases.

Acknowledgements

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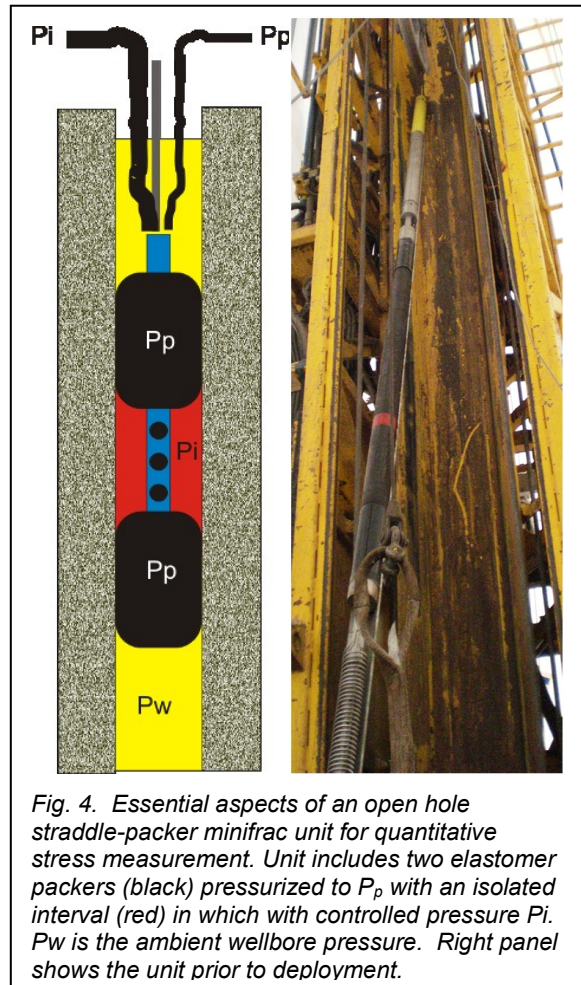


Fig. 4. Essential aspects of an open hole straddle-packer minifrac unit for quantitative stress measurement. Unit includes two elastomer packers (black) pressurized to P_p with an isolated interval (red) in which with controlled pressure P_i . P_w is the ambient wellbore pressure. Right panel shows the unit prior to deployment.