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ANDRILL Experiences with a Wireline Hydraulic Fracturing System for Minifrac Stress Measurements in Indurated Sediments

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Summary

The tectonic regime within Antarctica is only poorly understood due to a general lack of seismicity and the extreme dearth of deeper drilling that has occurred on this continent. To overcome this situation in general, and to better understand the state of stress in McMurdo Sound, hydraulic mini-fracing tests were included as an important component of the Antarctic Drilling (ANDRILL) program. A double packer wireline system was developed and deployed in the South McMurdo Sound borehole in late 2007. Stress states were measured with this system in open hole conditions at 17 stations along the borehole at depths as great as 1500 m from the surface. Station locations were predetermined using both the complete recovered core and ultrasonic televiewer imaging. Induced fractures were found by rerunning the televiewer and these provide information on the direction of the in situ stresses. Analysis of breakdown, shut in, and fracture reopening curves provided a consistent set of stress magnitudes that suggest an Andersonian strike-slip stress environment. The field tests were run in highly indurated, low permeability, glacially compacted sediments that may provide a good analog for mini-frac measurements in tight shales.

Introduction

The hydraulic fracturing technique is one of the few ways to obtain quantitative information on stress magnitudes. In concept, the method is relatively simple only requiring that an interval of the borehole first be isolated using a pair of inflatable packers. This interval is then rapidly pressurized until a fracture initiates at the borehole wall at the breakdown pressure. The dropoff in pressure is then monitored to obtain the shut in pressure which gives a good value for the minimum compressive stress. The breakdown pressure can then, under a series of assumptions, be used to give an estimate of the greatest horizontal compression (from a vertical borehole).

Measurements that focus on obtaining values of the in situ stress are often called 'minifracs'. Although simple in theory, application of this technique to real world situations is complicated by borehole stability and geometry and by the time and costs involved. Wireline hosted minifrac systems have the potential to overcome a number of these limitations. Here, we describe the deployment of such a wireline system to depths near 1500 m from the surface in open hole conditions through indurated sediments.

Theory

Hydraulic fracturing (HF) has been used for stress measurement now for a number of decades. In order to understand the process of the fracture initiation, it is perhaps best to first consider the simplest system of a vertical borehole drilled into a formation subject to the regional greatest and least compressive principal stresses S_H and S_h, respectively. The azimuthal, or hoop, stress $\sigma_{\theta\theta}$ concentrations of these is derived from Kirsch's elastic solution for a hole in a plate of radius a to give

$$\sigma_{\theta\theta} = \frac{S_H + S_h}{2}\left(1+\frac{a^2}{r^2}\right) - \frac{S_H - S_h}{2}\left(1+\frac{3a^4}{r^4}\right)\cos(2\theta) \qquad \text{Eqn. 1}$$

where the azimuth θ is measured with respect to the S_H direction and r is the distance from the borehole axis. Here, the standard convention in the geosciences in which a compressive stress is given positive sign is used. This stress will be 'most tensile' at $\theta = 0^\circ$ and 180° along the S_H direction. Application of fluid pressure P_w within the wellbore will further make $\sigma_{\theta\theta}$ more tensile such that once the tensile strength T (here taken to be positive) of the rock is reached a fracture initiates and 'breakdown' at wellbore pressure P_B is achieved. The simplest breakdown equation thus takes the form

$$S_H = 3S_h - P_B - T \qquad \text{Eqn. 2}$$

Hence, with measurement of P_B and Sh from the hydraulic fracturing record and knowledge of T the magnitude of S_H can be estimated. There is insufficient space here to look at modifications to this aside to say that the formula may need to be modified by pore fluid pressure (e.g., Hubbert and Willis 1957), time dependent poroelastic effects (e.g., Haimson and Fairhurst 1967; Detournay and Cheng 1988) , and even dilatancy leading up to failure of the rock (e.g., Schmitt and Zoback 1992).

Field Measurements

The HF technique together with measurements of density were used to estimate all three principal stresses in the earth during the ANDRILL 2006-07 drilling season. A specially constructed wireline system (Downhole Systems, Piermont, NY) was used; this consisted of a wireline-supported straddle packer system allowing for a 1 m pressurization interval, and two 2-km long hoses used for separate pressurization of the packers and of the interval, respectively. The packer and the interval pressures are digitally recorded from four separate pressure transducers both at the surface and within an instrument package immediately above the straddle packer rig. Flow rates into and out of the interval are also measured.

Typical protocols for HF measurements have been summarized by *Haimson and Cornet* (2003) and Zoback (2007). Briefly, once the packers are set at the desired depth, a typical HF test consists of first raising the interval pressure P_I rapidly until a fracture initiates at the wellbore wall sufficiently that the interval pressure drops drastically. The maximum pressure reached here is called the 'break-down' pressure P_B. At this point pumping ceases and the pressure is allowed to decay the 'shut in' pressure (here designated P_{FP} assumed to represent the point at which the newly induced fracture closes. This is an important value as it is provides a quantitative measure of the least compressive stress. Once the pressure has equilibrated for a few minutes, the interval pressure is vented and it returns to ambient in the wellbore. This pressurization cycle is repeated a number of times to confirm the observed pressures.

Over 20 locations along the borehole were selected using ultrasonic borehole televiewer images in order to avoid breakouts and natural and drilling-induced fractures. One example pressurization curve taken from the measurement at 1401 m below the rig floor highlights a number of features. Note that the pressure signal is unfortunately contaminated with a periodic but unknown electrical noise believed to come from the pressure transducer, this complicates but does not greatly influence the interpretation of these data.

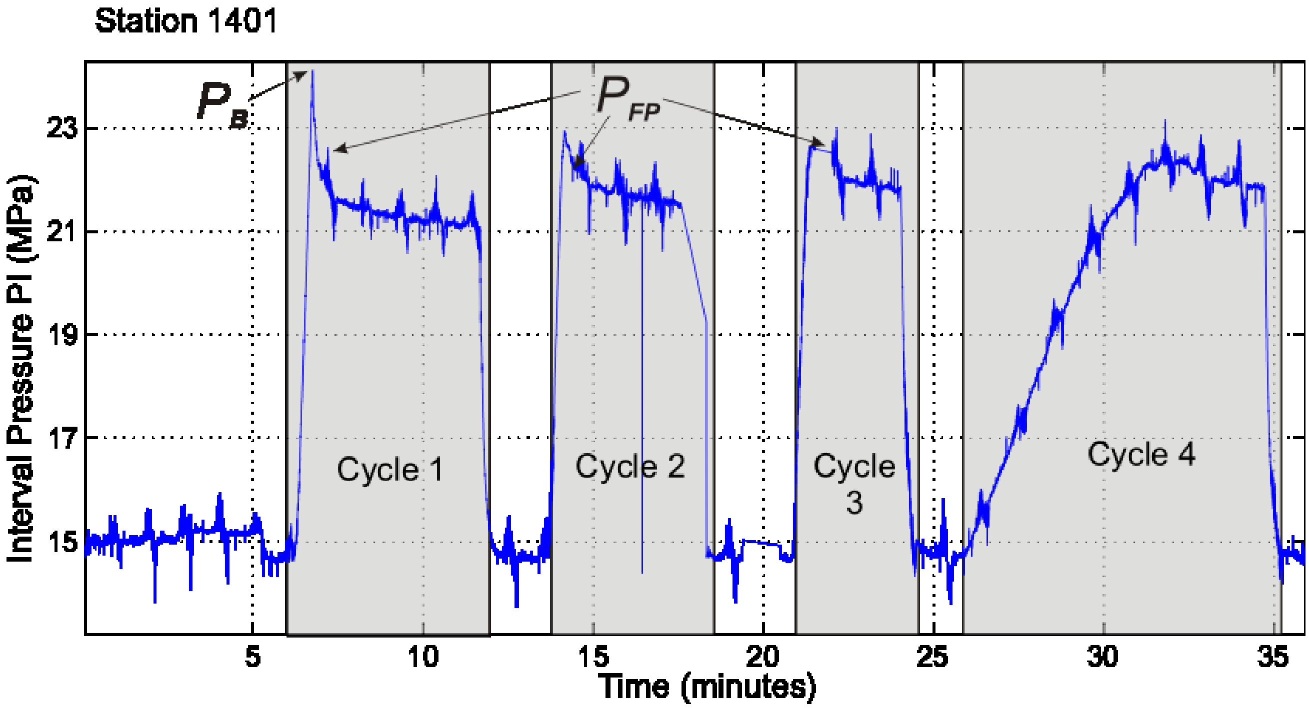

Figure 1: Observed interval pressurization curve measured downhole from a depth of 1401 m from the rig floor versus time. PB and PFP are the break-down and shut-in pressures, respectively. The first three cycles were carried out at a constant flow rate while in Cycle 4 the flow rate was increased incrementally.

In the case shown in Fig. 1, $P_b = 24.1$ MPa and $P_{FP} = 22.0$ MPa $= S_h$. Assuming Eqn. 2 describes break-down and with a tensile strength T = 5 MPa as estimated from laboratory measurements on core, the gretest horizontal principal stress SH is estimated to be about 37 MPa. When considered together with the estimated vertical stress from core density logging of $S_V = 26$ MPa, this suggests that a strike slip faulting environment exists with SH > SV > Sh. This was confirmed in the subsequent tests in this series. The observed shut in pressures were surprisingly consistent and uniform along the depths where the measurements were made further supporing the validity of the observations.

Conclusions

A profile of hydraulic fracturing 'minifrac' meausurements allowed for quantitative profiling of the state of stress along a vertical borehole drilled through hard and indurated glacial sediments. The open hole measurements were carried out using a wireline supported system that allowed for rapid movement of the hydraulic fracturing tool between depth stations. There is no reason why this tool could not be applied to more regular measurements through perforated casing although it is expected that a great deal of sensitivity would be lost relative to the direct open hole measurements here.

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