BABHY—A New Strategy of Hydrofracturing for Deep Stress Measurements

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Paradox

Hydraulic fracturing in a vertical borehole induces fractures that will be vertical and normal to the minimum horizontal stress S_h (parallel to the maximum horizontal stress S_H), if there is no influence of natural fractures. The induced fractures close with venting and open with re-pressurization. At those times, there appear two kinds of critical borehole pressure, the reopening pressure P_r and the shut-in pressure P_s, which characterize the variation of borehole pressure during the test. The conventional theory tells us that those two pressures are related to the two stress components of S_H and S_h as follows (Haimson and Cornet, 2003):

$$P_r = 3S_h - S_H - P_p \quad (1)$$

$$P_s = S_h \quad (2)$$

Note that P_p is pore pressure in the fracture before opening. Those two equations give the principle for the two values of S_H and S_h to be determined from the two measured pressures of P_r and P_s.

The interpretation of Eq. (2) for P_s is supported by considerable experimental and theoretical works. On the other hand, if the interpretation of Eq. (1) for P_r is also correct, the measured values of P_r and P_s should change independently in response to the combination of S_H and S_h which will vary site by site. However, the data of field tests so far indicate that incidences where the measured reopening pressure lies close to the shut-in pressure (i.e., $P_r = P_s$) are far more numerous than can reasonably be expected (Lee and Haimson, 1989). This strange phenomenon could happen if the crust is in a stress condition of $(S_H - P_p)/(S_h - P_p) = 2$. Nevertheless, it is hard to consider that such a condition has been held everywhere in the crust. It may be more reasonable to consider that, contrary to the conventional theory, the measured reopening pressure does not coincide with the "true" reopening pressure (the borehole pressure at which the fracture truly begins to open from its mouth at the borehole wall) and that pressure takes the same value with the shut-in pressure (i.e., with S_h). If this is true, we could estimate with hydraulic fracturing only the minimum component of stress S_h but not the maximum component of stress S_H, which is the most desired concern in the stress measurement. Furthermore, a serious problem may occur should such a large error be included in the estimates of maximum stress S_H based on the reopening pressure so far.

True and Apparent Reopening Pressures

In order to explain the paradox described above, we have to take into account two factors which have been ignored in all conventional theory. Those factors are (i) residual aperture of fracture, and (ii) hydraulic compliance of test systems C. The C corresponds to an amount of fluid required to elevate fluid pressure in a test system by a unit magnitude, and it can be represented equivalently as $C = ßV_{eff}$, where $ß$ is the fluid compressibility, and V_{eff} is the effective system volume. While the details of explanation have been described by Ito et al. (1999, 2005, 2006), they can be outlined briefly as follows.

The residual fracture aperture causes pressure penetration into the fracture prior to opening. Evidence of this has already been shown by laboratory studies (Cornet, 1982; Durham and Bonner, 1994; Zoback et al., 1977). The pressure penetration will be almost wholly transmitted to the fracture surface since the net area of contact of the two surfaces is usually a small fraction of their nominal area. Thus, the third component in Eq. (1) should be borehole pressure rather than P_p. The borehole pressure at fracture opening is defined as P_r, and so substituting P_p with P_r in Eq. (1) yields

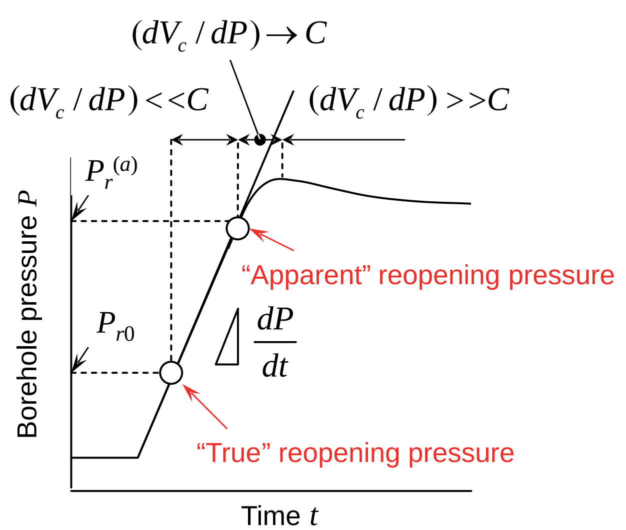

Figure 1. Effect of the system compliance C and fracture opening on borehole pressure variation.

$$P_r \equiv P_{r0} = \frac{1}{2}(3S_h - S_H) \qquad (3)$$

Thus, the effect of including pressure penetration into the fracture prior to opening is to reduce the reopening pressure by a factor of almost two from the value expected using conventional theory (the reduction is precisely two when pore pressure is negligible). We will refer the borehole pressure given by Eq. (3) to the true reopening pressure P_{r0}.

On the other hand, the influence of the compliance C on fracture opening is more problematic; it is concerned with the correct identification of the true reopening pressure from the borehole pressure P minus time t curves. Note that the reopening pressure is usually detected as the borehole pressure P at which the P - t curve is seen to deviate from linearity (Fig. 1). The effect of fracture opening on the borehole pressure variation can be expressed as follows (Ito et al., 1999):

$$\frac{dP}{dt} = \frac{Q}{(dV_c/dP) + C} \qquad (4)$$

where dV_c is the change in pressurized fluid volume due to fracture opening. Since the flow rate Q and the system compliance C are constant, Eq. (4) indicates that deviations of the P - t curve from linearity are governed by changes in the value of dV_c/dP and its relative value with respect to C. That is, prior to fracture opening, dV_c/dP is zero and the borehole pressure P increases linearly with t. After fracture opening, dV_c/dP becomes greater than zero, and the P - t curve will deviate from linearity to some degree or other. However, even if a flexible hydraulic tube with small ID (less than 10 mm) is used to convey fracturing fluid from a pump to a test section in a borehole, C is considerably large. As a result, at the early stage of fracture opening, dV_c/dP should be very small compared with C so that no detectable change occurs on the P - t curve, as shown schematically in Fig 1. When P reaches a level of S_h, the stress acting normally to the fracture surface becomes almost equal to or less than the value of S_h anywhere. Such a balanced stress condition leads to the criticality that the fracture aperture increases abruptly with a small increment in borehole pressure. As a result, dV_c/dP becomes a larger value compared with C, and finally the P - t curve begins to deviate from the initial linear trend. The same process occurs regardless of the S_H value. Thus, we provide an explanation as to why incidences where the apparent (or measured) reopening pressure coincides with P_s (i.e., the minimum stress S_h are so common as described above). We will denote hereafter the apparent reopening pressure as $P_{r(a)}$.

A Strategy for the Maximum Stress Measurements

Thus the strange observation of $P_r^{(a)} = P_s$ in field tests arises because the compliance of typical hydraulic fracturing systems is far larger than that of fracture until P reaches a level of minimum stress S_h. However, it should be recalled here that the compliance in concern is that of the volume between the flow meter and the fracture mouth. Taking this into account, if the flow meter is placed as close as possible to the test interval, as illustrated in Fig. 2, the system compliance C can be reduced drastically, and a more objective measure of flow entering the fracture can be obtained. In this case, it is not a matter of course what kind of tubing (drill pipe)—flexible tube or stainless pipe with small ID—is used to convey fracturing fluid from a pump to a test interval. To demonstrate this idea, we developed a test system with a downhole flow meter (Ito et al., 2002). The system is basically the same as the conventional one except that the transducer to measure flow rate of injection is installed at the top of a straddle packer tool. Due to this modification, we succeeded in reducing the system compliance C drastically. The straddle packer tool is conveyed in boreholes on 6-conductor wireline. A single high-pressure hose is used to supply pressure from a hydraulic pump at the ground surface to the packer elements and the straddle interval so that a switch valve controllable from the surface is attached to the straddle packer. The system is designed to use in a borehole with 101 mm (HQ size) diameter at depths up to 1 km.

However, such a modification as above is still not sufficient to achieve the stress measurement at depths more than 1 km because of the following reasons.

(a) The stress measurement at deep depths cannot be done, of course, without deep boreholes, which generally have a large diameter, and accordingly the straddle packer tool needs to be large. The large size of the straddle packer tool leads to an increase in the system compliance C.

(b) For monitoring and recording flow rate and pressure during tests of the transducer installed on top of the straddle packer tool, the transducers should be connected with a data acquisition system placed at the ground surface by wires. To do this, it is appropriate to convey the straddle packer tool in

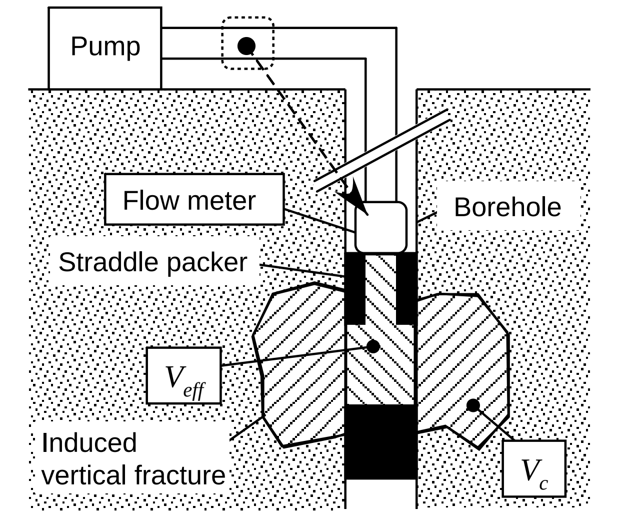

Figure 2. A concept to reduce the system compliance C (i.e., the volume, Veff) by placing the flow meter just above the straddle packer tool.

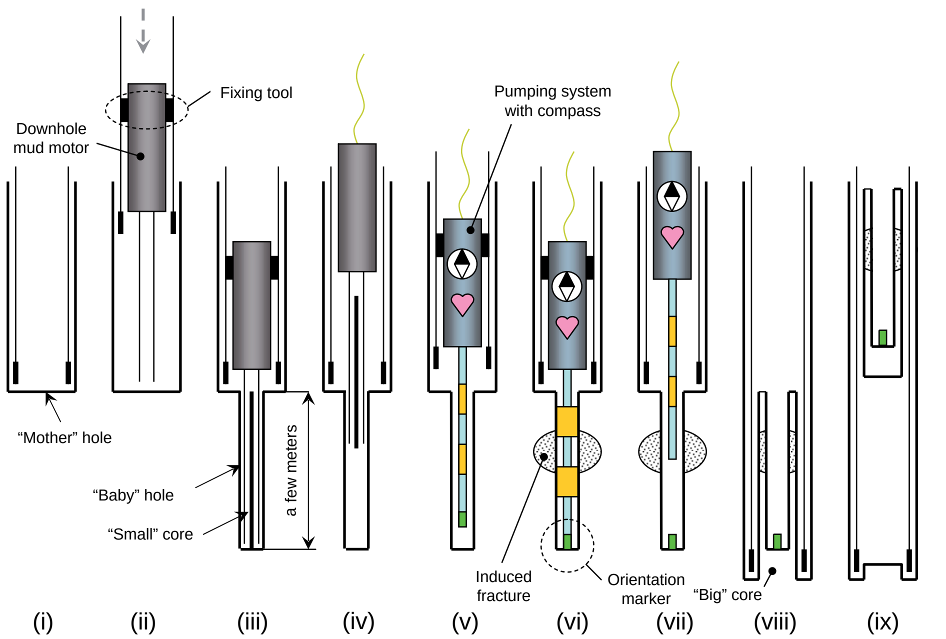

Figure 3. Proposed new strategy, BABHY, to achieve stress measurements by hydraulic fracturing at depths of more than 1 km, and its procedures. The procedure consists of three parts as follows: (i–iv), drilling the baby hole; (v–vii), *in situ* testing of hydraulic fracturing; and (viii–ix), extending the mother hole and retrieving the large core.

boreholes on wireline. The use of wireline is also effective to save the time for the tool running in boreholes. However, as the depth of measurement becomes greater, so does the risk for the tool to become stuck in the borehole. The financial risk in losing the advantages of wireline logging is very severe. For this reason, the straddle packer tool has generally been conveyed so far on drill pipe in the case of deep measurement, but the use of drill pipe makes it hard to arrange the wires connecting the downhole transducers and the surface data acquisition system.

Realistic Proposal: BABHY

Such a dilemma could be solved by a new strategy appropriate for the stress measurement at deep depths, as shown in Fig. 3. There are two components used in the strategy: (i) the compact drilling tool with a built-in mud motor, and (ii) the straddle packer tool with a pump and a digital compass. Each is conveyed in drill pipe on wireline. The compact drilling tool is used to drill an additional hole, several tens of millimeters in diameter and a few meters in length, at the bottom of an original borehole, and the hydraulic fracturing is carried out in the drilled hole by using the small packer tool. The additional hole and the original borehole are referred to the "baby" hole and the "mother" hole, respectively. The procedure can be outlined as follows.

i) Set drill pipe with coring bit in the mother hole.

ii) Lower the compact drilling tool in drill pipe on wireline and fix it onto the drill pipe.

iii) Pump drilling mud through the drill pipe to drive the mud motor in the compact drilling tool, and drill the baby hole at the bottom of the mother hole.

iv) Retrieve the compact drilling tool and the small core, inspect pre-existing fractures in the core, and determine the depth of test section(s) in the baby hole.

v) Lower the straddle packer tool in the drill pipe on wireline, and fix it onto the drill pipe.

vi) Lower the drill pipe slightly to squeeze the packer element for isolating the test interval, and pressurize the test interval to induce axial fractures by using the pump installed in the tool. During the test, the pressure and flow rate of injected fluid and the tool orientation are monitored by the transducers installed in the tool and transmitted through wireline to the data acquisition system at the surface.

vii) Retrieve the straddle packer tool while leaving the orientation marker at the bottom of the baby hole.

viii) Lower and set a core barrel, and drill out the test section for getting the big core.

ix) Retrieve the big core, and inspect the fractures induced by pressurization in step (vi). The fracture orientation can be determined from the orientation marker in the core and the tool orientation recorded in step (vi).

Subsequently, the reopening pressure $P_r^{(a)}$ and the shut-in pressure P_s will be detected from the records of pressure and flow rate during the test. Finally, the stress magnitudes S_H and S_h will be estimated from those detected pressures based on Eqs. (2) and (3), assuming $P_r^{(a)} = P_{r0}$, since the system compliance is to be sufficiently small, and the stress orientation will be estimated from the fracture orientation

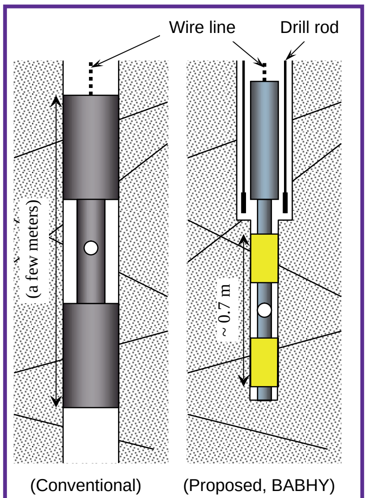

Figure 4. The compact size of the BABHY system makes it easy to find the test section free from pre-existing fractures.

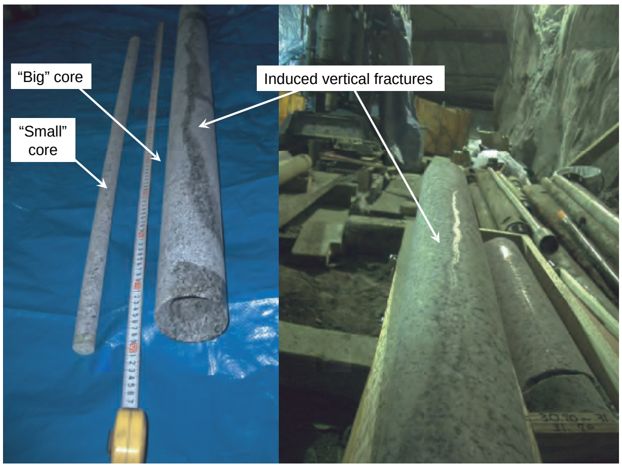

Figure 5. "Small" core (AQ size) retrieved by the baby hole drilling and "big" core (PQ size) retrieved by the over-coring. Hydraulically-induced fractures appeared in the big core.

detected in step (ix). We call this strategy Baby Borehole Hydrofracturing, BABHY for short.

This strategy will allow us to improve many defects in the conventional method as follows. It is easy to reduce the system compliance sufficiently because of a very compact size of the straddle packer tool (Fig. 4). The test section being free from pre-existing fractures can be chosen with certainty by the inspection of the small core, and then the straddle packer tool can be adjusted as the pressurized interval to be located at the chosen test section rightly. Note that the axial length between the top of the upper packer element and the bottom of the lower packer element is very short (less than 1 m) compared with that of a few meters for the conventional tool. The shorter length will make it much easier to choose the test section. We have already completed development of the compact drilling tool, and we are now developing the straddle packer tool. They are designed to be used in the mother holes with diameters larger than 101 mm (HQ size). As a part of the development process, we carried out a field test to confirm the procedure of step (vi) in particular (installing the straddle packer in the baby hole and carrying out hydraulic fracturing) at the Kamioka mine in Japan. For this test, we used a vertical borehole with 123 mm (PQ size) diameter and about 30 m deep drilled from the floor of a chamber at a depth of about 500 m from the ground surface. The baby hole with 47 mm (AQ size) diameter and 1 m length was drilled at the bottom of the borehole. The test succeeded quite well so that a pair of typical fractures in axial direction was induced, and the shape and orientation of the induced fractures were clearly detected from the large retrieved core (Fig. 5).

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