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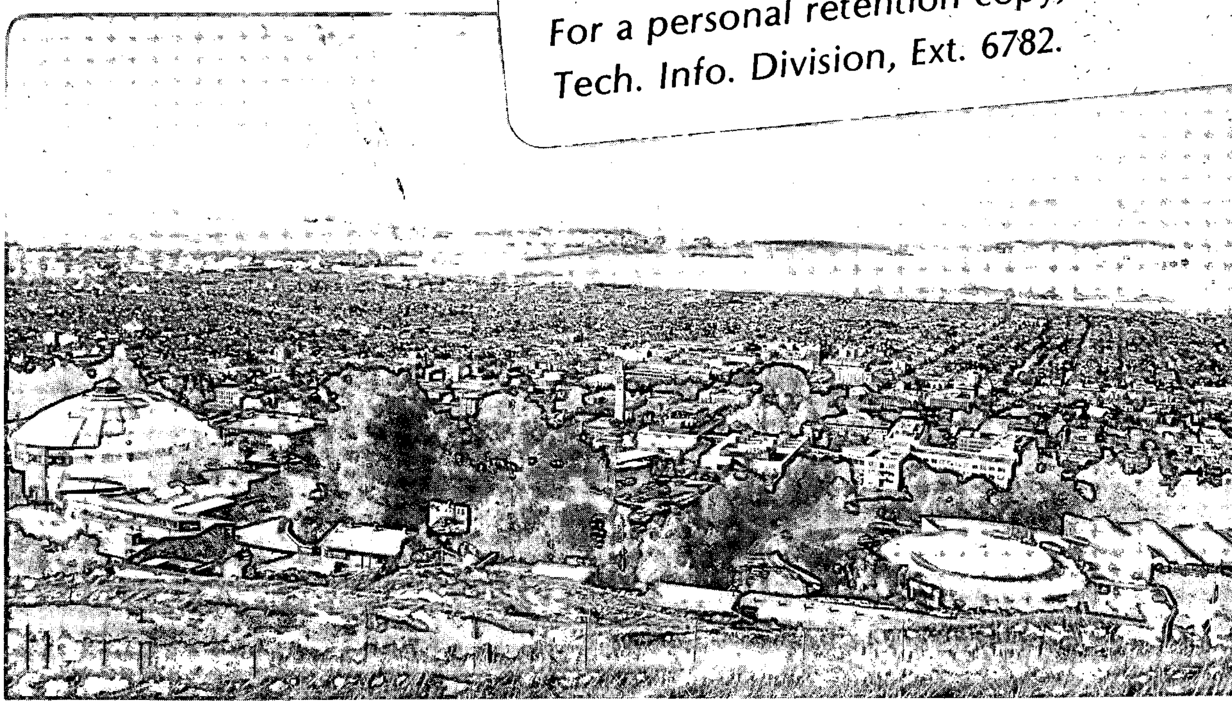

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LABORATORY HYDRAULIC FRACTURING STRESS MEASUREMENTS IN SALT

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ABSTRACT

This paper discusses the results of a laboratory testing program to determine the validity of hydraulic fracturing stress measurements in salt. Tests were performed on 15 cm diameter samples loaded under hydrostatic stress conditions to determine the influence of time, confining pressure, flow rate, borehole diameter, and packers on breakdown pressure. Tests were also performed in a polyaxial loading frame to determine whether or not hydraulic fracturing could be used to measure non-hydrostatic stresses.

The test results indicate that the breakdown pressure is not affected by time delays of up to 64 hours between the application of load and fracturing the rock. Breakdown pressures were found to fall short of predicted elastic values at higher confining pressures for the hydrostatic tests. The ratio of the horizontal stresses in non-hydrostatic tests had no effect on breakdown pressures. Flow rate and borehole diameter variations were found to have a marked effect on breakdown pressures. Shut-in pressure values, which are generally used as an indication of the minimum stress value, exceeded the applied minimum stresses by 10 to 60% depending on the method of determination used. The lack of a relationship between breakdown pressure and horizontal stress ratio may preclude hydraulic fracturing from being used in salt as it is conventionally applied in brittle rocks.

INTRODUCTION

Most conventional stress measurement techniques, such as overcoring and hydraulic fracturing, are based on elastic formulations which may not be applicable in salt, a rock well known for its non-elastic behavior. To determine the effects of non-elastic behavior on hydraulic fracturing stress measurements, we have performed a series of laboratory hydraulic fracturing tests in salt under controlled stress conditions.

The determination of the maximum horizontal stress by hydraulic fracturing is based on the breakdown pressure (the pressure required to fracture the rock) being equal to the minimum tangential stress concentration in the borehole wall plus a tensile strength. For non-porous, elastic materials, the minimum tangential stress is

$$\sigma_{\theta} = 3\,\sigma_{Hmin} - \sigma_{Hmax}$$

where σ_{θ} is the minimum tangential stress, σ_{Hmin} is the minimum horizontal stress, and σ_{Hmax} is the maximum horizontal stress.

If the material deforms in a linear viscoelastic manner, the stress concentrations around the hole should be the same as for the elastic case (Goodman, 1980). However, the tangential stress will be reduced from the elastic value if the deformation is non-linearly viscoelastic (Goodall and Chubb, 1970 ; Hata, 1975) or plastic (Robertson, 1955). If the deformation of salt is non-linearly viscoelastic, the tangential stresses in the borehole wall decrease with time, and the breakdown pressure should also decrease. In conventional interpretation of hydraulic fracturing, σ_{Hmin} is determined from the shut-in pressure and σ_{Hmax} is inferred from the magnitude of the breakdown pressure. The lower the breakdown pressure for a given shut-in pressure, the higher is the inferred value of the maximum stress. If the breakdown pressure is low because creep has reduced the stress concentration, the application of elastic theory to the stress measurement data reduction could result in significant errors, such as the inference of large non-hydrostatic stresses where the stresses are, in fact, hydrostatic.

We have calculated the decay in tangential stress with time for a borehole deforming by steady creep using formulations of Prij and Mengelers (1981). The calculation showed that we should expect approximately 20% decay in the tangential stress within 72 hours of the application of a 13.8 MPa load to a core containing a 25 mm diameter hole (Doe, Boyce, and Majer, 1984).

LABORATORY TESTING PROGRAM

We have performed a series of laboratory hydraulic fracturing stress measurements in salt using both hydrostatic and non-hydrostatic conditions. The salt samples were obtained from the Avery Island salt dome in Louisiana. For the hydrostatic tests, the cores had diameters of 15 cm and lengths of 22 cm. The radial loads were supplied by a USBM biaxial cell, and the axial loads were provided by a hydraulic press. The hydrostatic tests were run to investigate the effects of (1) hydrostatic stress magnitude, (2) time delay between application of load and the hydraulic fracturing, (3) flow rate of the fracturing fluid, (4) borehole diameter, and (5) use of inflatable packers.

The non-hydrostatic stress tests used prismatic blocks which were 30 cm x 30 cm x 46 cm and loaded using flatjacks in a polyaxial loading frame. The tests were run to investigate the effects of deviatoric stress conditions. A constant time delay (2 hours), borehole diameter (25mm), and flow rate (0.15 cm^3/s), were used throughout this series of tests.

The test zone of the borehole was isolated using a miniature borehole packer system similar to that designed by Roegiers (1975). Light hydraulic oil was used as the fracturing fluid.

HYDROSTATIC TEST RESULTS

The breakdown pressure values, as defined by the maximum pressure of the pressure-time records, are plotted as a function of time for confining pressures of 6.9 and 13.8 MPa in Figure 1. At neither confining pressure is there a time dependent decrease in breakdown pressure within 64 hours. Indeed there is a slight, though not clearly significant, increase in the breakdown pressure with time for the 6.9 MPa tests.

The effect of confining pressure on breakdown pressure for a delay time of 2 hours is shown in Figure 2. Assuming elastic behavior, the theoretical pressures would occur along the dashed line which has a slope of 2. At confining pressures greater than 7 MPa, the breakdown pressures are below the predicted elastic values.

The main evidence for evaluating elastic versus non-elastic controls on the stress distribution around the borehole comes from the time delay and confining pressure effects. If the salt is behaving elastically, then there should be no time effect, and the breakdown pressure should increase by a factor of 2 with confining pressure. If steady creep controls the stress distribution, the breakdown pressure should decrease with time, and the stress decay should be even faster at higher confining pressure.

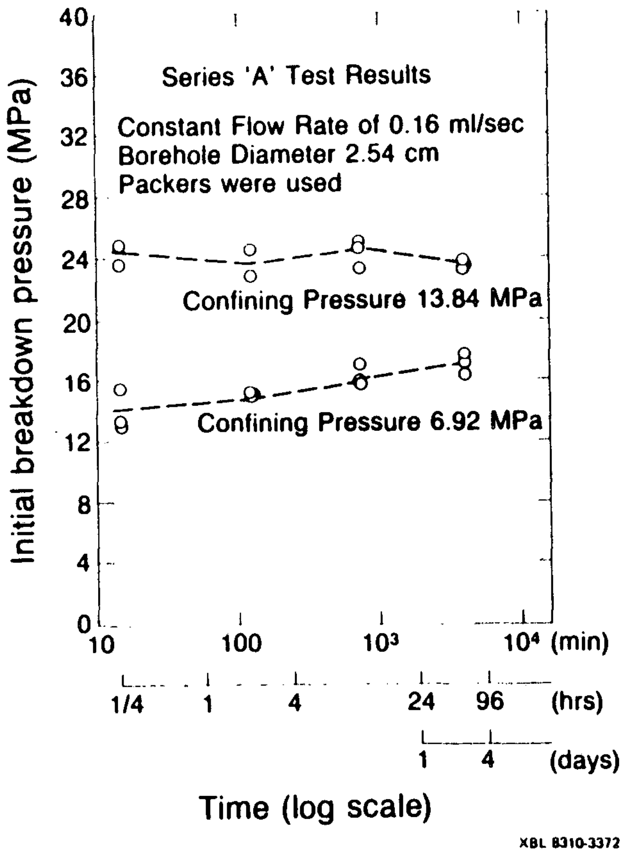

Figure 1. Breakdown Pressure as a Function of Delay Time Before Testing for Confining Pressures of 6.9 and 13.8 MPa.

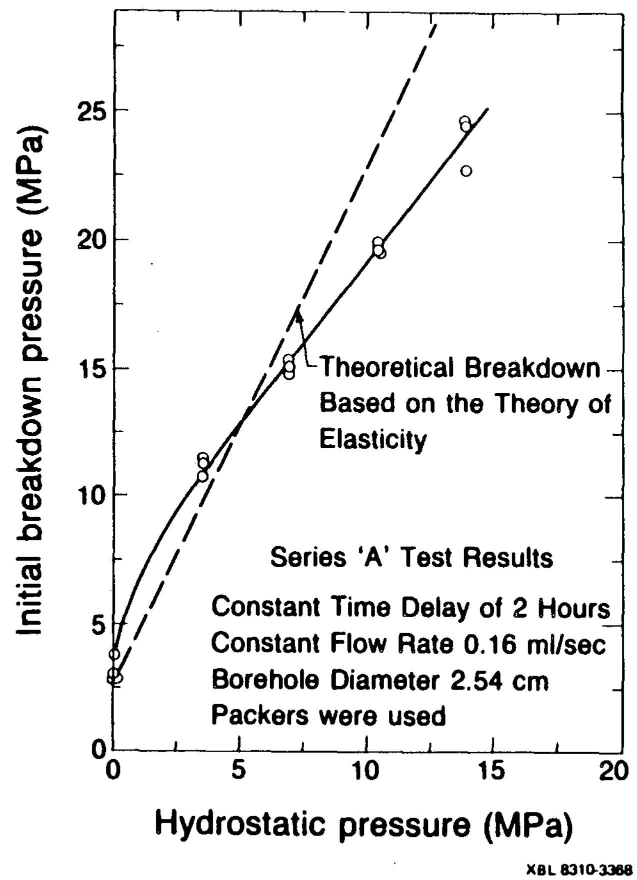

Figure 2. Breakdown Pressure as a Function of Confining Pressure for a Constant Delay Time of 2 Hours.

Our test data fit neither deformational model. The divergence of the breakdown pressures at higher confining pressures indicates that the salt is not behaving elastically, while of the lack of time dependence of the breakdown pressures is inconsistent with the steady creep model. Apparently, some other deformational mechanism is at work, possibly transient creep or a time-independent plastic deformation.

Our results for the variation of breakdown pressure with flow rate are consistent with those of previous investigations (Haimson, 1968) in showing an increase in breakdown pressure with flow rate. The variation in breakdown pressure with boreole diameter results are consistent with previous investigations (Haimson, 1968) in showing an increase in breakdown pressure with smaller borehole diameter. The breakdown pressure values were no different where inflatable packers or cemented steel plugs were used to isolate the test zone.

NON-HYDROSTATIC TEST RESULTS

The breakdown pressures are plotted against the ratio of horizontal stresses in Figure 3. The basic analysis of hydraulic fracturing for stress measurement from the Kirsch solution predicts that the breakdown pressure should decrease as the maximum stress increases for constant minimum stress. This behavior is represented by the dashed lines in Figure 3 for minimum horizontal stresses of 6.9 and 13.8 MPa. The results do not follow these lines, but are constant at the same breakdown pressure values obtained for hydrostatic tests at 6.9 and 13.8 MPa. In a few cases, the effect of the vertical stress was examined and found not to influence the results. The lack of a relationship between breakdown pressure and horizontal stress ratio suggests that the stress distribution around the borehole is not consistent with elastic behavior.

SHUT-IN PRESSURES AND FRACTURE CHARACTERISTICS

The shut-in pressure is generally considered to be a measurement of the minimum in-situ stress. The shut-in pressures were determined using semi-logarithmic plots of the pressure decay after shut-in versus time (Doe, and others, 1983). This method was successful in determining the minimum stress to within 15% for the hydrostatic tests. The method overestimated the minimum stress by as much as 60% when applied to the non-hydrostatic test data. The various other approaches to determining shut in pressure, as described by Zoback and Haimson (1982), were also checked and were found to produce values which were consistently too high.

The hydraulic fractures in the salt do not form as distinct, single cracks, as one would expect for a brittle material. Instead, the fractures appear to open along grain boundaries and form diffuse zones about 1-2 cm wide. The fracture zones were so diffuse that the dyed zones were very faint and often hard to find. The fracture planes were oriented normal to the minimum horizontal horizontal stress direction in the non-hydrostatic tests. This observation was consistent with the results obtained using acoustic monitoring to map the fracture growth (Figure 4).

CONCLUSIONS

Although we found that the behavior of the salt during hydraulic fracturing was not time-independent (up to 64 hours), elastic methods of fracture analysis were inadequate to explain either the low breakdown pressures we obtained for hydrostatic confining pressures over 7 MPa or the lack of dependence of breakdown pressure on horizontal stress ratio in non-hydrostatic tests.

Hydraulic fracturing, as it is applied in brittle rocks, may not be an effective stress measurement method in salt because of its insensitivity to non-hydrostatic stresses. The main source of error appears to be relaxation of the stress concentration around the borehole. When we began this work, we thought that if the stress relaxation were due to steady creep, there might be a period of time after applying load or drilling the hole during which the elastic formulations might hold. Instead, our data suggest that the elastic stress concentration is relieved virtually upon loading. We have not identified the deformational mechanism, but we suspect it may be transient creep or time-independent plastic yield.

The existence of non-hydrostatic stresses in salt may be inferred from hydraulic fracturing experiments, if the fractures have a consistent orientation that is not coincident with any planar weakness in the rock, such as the bedding. But the diffuse fractures may be hard to locate by conventional means, such as impression packers or borehole televiewer. Acoustic methods may prove to be the only effective means for determining fracture orientation (Doe, Boyce, and Majer, 1984).

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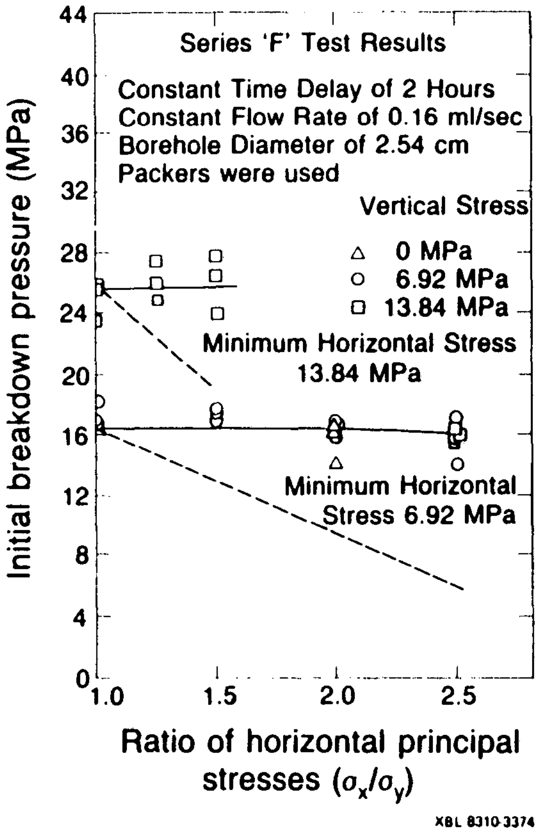

Figure 3. Breakdown pressure as a function of horizontal stress ratio for minimum horizontal stresses of 6.9 and 13.8 MPa. Dashed lines show expected decline in breakdown pressure for elastic rock.

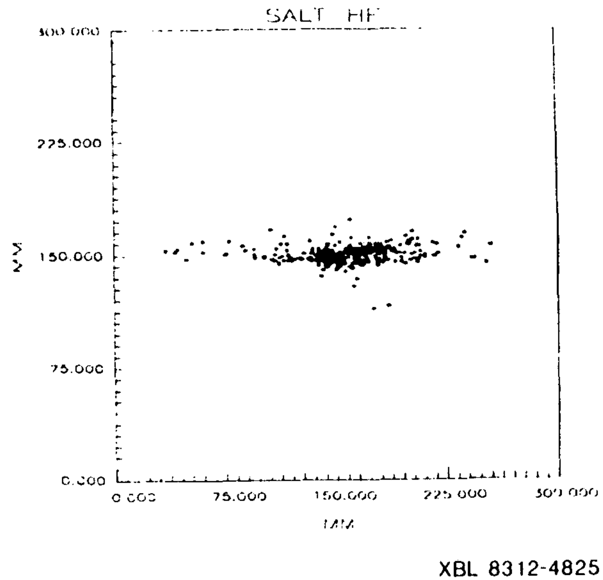

Figure 4. Plan view of salt block showing locations of acoustic events monitored during hydraulic fracturing. The borehole is located at the center of the figure and the maximum stress was applied on the right and left sides of the block.

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