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Hydraulic-Fracture Propagation in Layered Rock: Experimental Studies of Fracture Containment*

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ABSTRACT

Fracture geometry is an important concern in the design of a massive hydraulic fracture treatment for improved natural gas recovery from tight gas sands. Possible prediction of vertical fracture growth and containment in layered rock requires an improved understanding of the parameters which may control fracture growth across layer interfaces. We have conducted laboratory hydraulic fracture experiments and elastic finite element studies which show that at least two distinct geologic conditions may inhibit or contain the vertical growth of hydraulic fractures in layered rock; 1) a weak interfacial shear strength of the layers and 2) a compressional increase in the minimum horizontal stress in the bounding layer. The second condition is more important and more likely to occur at depth. Variations in the horizontal stress can result from differences in elastic properties of individual layers in a layered rock sequence. A compressional increase in the minimum horizontal stress can occur in going from high shear modulus into low shear modulus layers.

INTRODUCTION

In 1949 Clark[1] introduced the concept of hydraulic fracturing to the petroleum industry, and since then hydraulic fracture treatment to enhance oil and gas recovery in tight reservoir rocks has become standard practice. More recently, as a result of an increased need for better recovery techniques, massive hydraulic fracturing has been used in low-permeability, gas-bearing sandstones in the Rocky Mountain region and Devonian shales of the Appalachian region, where it is uneconomical to retrieve gas in the conventional manner[2]. Massive hydraulic fractures (MHF) are designed to extend as much as 1000 m radially from the wellbore and generally require up to 3 x 10^3 m^3 of fracture fluid. Massive hydraulic fracturing has been developed by trial and error, and its results are uncertain in many situations. Some of these large-scale stimulation efforts have been successful, but others, extremely disappointing failures. The reasons for these failures are not clear, but it seems likely that improved understanding of the fundamental mechanisms of hydraulic fracturing should

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suggest ways of improving the efficiency and reliability of the MHF stimulation technique or at least indicate where this technique can be successfully applied.

Among the many technological problems encountered in massive hydraulic fracturing, two very important questions must be answered properly to design a hydraulic fracture treatment and to site production wells successfully for optimum gas recovery in a particular field. What is the azimuthal direction of the fracture, and what is the shape of the fracture?

The first question requires a knowledge of both the in-situ stresses (since hydraulic fractures propagate normal to the minimum principal compressive stress) and the fracture anisotropy (if any) of the reservoir rock. The second question deals with the problem of whether or not the induced hydraulic fracture will propagate into formations lying above or below the producing zone. A hydraulic fracture usually grows vertically and propagates above and below the packers as well as laterally away from the wellbore. Vertical propagation is undesirable whenever the fracturing is to be contained within a single stratigraphic interval. An example would be the containment of a hydraulic fracture within a low-permeability producing sandstone without fracturing through the underlying shale into another sandstone which is water bearing. In addition, if the hydraulic fracture is not contained within the producing sandstone and propagates in both the vertical and lateral directions (an elliptical fracture), then there is an effective loss of the expensive fracture fluid and proppant used to fracture the unproductive formations. It is therefore of great economic importance to the gas industry to understand the parameters which may control the vertical propagation of massive hydraulic fractures.

There are several parameters which are considered to have some effect on the vertical growth and possible containment of hydraulic fractures. Simonson et al. (1976)[3] have shown in theoretical studies using elastic fracture mechanics that a hydraulic fracture propagating from a low modulus material into a high modulus material would be arrested at the interface between the two materials because the stress intensity at the crack tip approaches zero as the interface is approached. However, Sandia National Laboratories' in-situ stimulation and mineback experiments in tuff at the Nevada Test Site have shown that material property interfaces alone may have little effect on containment of hydraulic fractures[4]. In these experiments it has been demonstrated that the in-situ stresses have the dominant effect on fracture behavior and direction of fracture growth. Specifically, this study has shown that containment of a hydraulic fracture is most likely to occur as a result of an increase in the minimum horizontal compressive stress. These results are consistent with calculations by Simonson et al. (1976)[3] which also show that a boundary layer of higher minimum compressive stress should restrict fracture growth. In addition, experimental studies by Daneshy (1978)[5] suggest that fracture containment may be more a result of the nature and shear strength of the layer interface rather than any difference in material properties on either side of the interface.

These previous studies indicate that there are at least three parameters which may control fracture growth in layered rock: 1) differences in the mechanical properties of the formations on either side of the interface, 2) changes in the horizontal stress state across the interface, and 3) shear strength of the interface. To date, no systematic experimental work has been done incorporating all three of these parameters for the purpose of determining their relative influence on vertical fracture growth and possible fracture containment in layered rock.

Accordingly, we have conducted laboratory experiments and elastic finite element studies which clearly show that fracture propagation in layered rock is strongly influenced by all three parameters in a consistent and predictable manner. First, containment can occur whenever the shear strength of the layer interface is sufficiently weak relative to the tensile strength and the minimum horizontal compressive stress of the bounding layer that the fracture more easily becomes an interfacial fracture than extending across the interface into the bounding layer. The second and more important condition for containment is due to a compressional increase in the minimum horizontal stress in the bounding layer. Differences in elastic properties of the formations in a dilithologic layered rock sequence may be the dominant factor in determining the horizontal stress state in individual layers with a possible compressional increase in the horizontal stress in going from high shear modulus to low shear modulus layers.

EXPERIMENTAL PROCEDURE

Hydraulic fracture experiments were conducted on rectangular composite 3-layer specimens 24 cm in length, 20 cm thick, and 20 cm wide (Figure 1). The individual layers were 8 cm in length. The composite specimen has a 0.68 cm borehole in its center, with the axis of the borehole perpendicular to the layer interfaces. A hollow steel packer (0.65 cm in diameter and 13 cm long with a 0.22 cm injection hole) was inserted 11 cm into the borehole and cemented by expoxy. A solid steel packer (0.65 cm in diameter and 11 cm long) was cemented by epoxy into the other end of the borehole, leaving a 2 cm open-hole section in the center of the middle layer. This specimen configuration assured fracture initiation in the central layer when fluid pressure was applied to the sealed borehole through the hollow steel packer. In each experiment the open-borehole was filled with fracturing fluid (40 weight oil) which was then quickly pressurized by an 80 MPa hand pump (fracturing occurred within 60 seconds). The fluid pressure was monitored by a transducer (with an accuracy of 0.1 MPa) and recorded on a pressure/time recorder. Experiments were conducted on monolithologic and dilithologic (that is, outer layers A and C were different from middle layer B) specimens by applying a stress up to 20 MPa normal to the layer interfaces. Rock types used in the experiments include Arizona, Berea, Coconino, and Tennessee sandstones and Lueders limestone. The porosity, permeability, and a brief physical description of these rocks are given in Table 1. The surface roughness of the interfaces were varied by polishing them with 20, 40, 80, and 240 grit abrasives. Average surface roughness was measured with a surface profiler.

In order to relate fracture growth to the mechanical properties of the different rocks, room temperature, unconfined compression tests were conducted on right-circular cylinders (4.76 cm in diameter and 10 cm long) with axial and lateral strain gages to determine the uniaxial compressive strength, Young's modulus, and Poisson's ratio. In addition, indirect tensile strengths were determined from Brasil tests. The mechanical properties of the rocks used in this study are given in Table 2.

EXPERIMENTAL RESULTS

Monolithologic Experiments

In order to determine the influence of layer interfaces on hydraulic fracture growth, a series of experiments were conducted on monolithologic layered specimens as a function of normal stress. Since the layers on either side of the interface have identical mechanical properties, the relative importance of the shear strength of the interface (resulting from the frictional effect of the applied normal stress) and the material properties of the layers can be assessed.

Compressive normal stress can be transmitted across an interface, but the amount of shear stress transmitted across the interface will depend on the inherent shear strength and frictional properties of the interface. For an unbonded interface the inherent shear strength is essentially zero and the shear strength of the interface is solely dependent on its frictional properties. Experimental studies on the frictional properties of rock have shown empirically that the shear strength of a sliding surface fits a linear relation

$$\tau = \mu\sigma$$

where τ is the shear strength, μ is the coefficient of friction, and σ is the normal stress[6]. The coefficient of friction at the initiation of slip is largely independent of lithology and generally has values ranging from 0.4 to 1.0. This variation is mainly attributed to the strong dependence of friction on surface roughness. Several studies[6,7,8] have shown that the coefficient of friction increases with increasing surface roughness, particularly at low normal stresses (less than 15 MPa). Accordingly, a series of experiments were conducted on monolithologic specimens of Tennessee sandstone and Berea sandstone which had layer interfaces of different surface roughness.

For each rock type and surface roughness there was a critical interfacial normal stress that must be exceeded before fracture growth across the interface occurred (Figure 2). Below this critical normal stress the fractures became interfacial fractures and did not penetrate the bounding layers. Fracture containment at monolithologic interfaces at low normal stresses clearly demonstrates the importance of the interface on hydraulic fracture growth in layered rock. Moreover, as shown in Figure 2, for each rock type the critical normal stress required for fracture propagation across the layer interface decreases with an increase in the surface roughness of the interface (and hence an increase in the coefficient of friction). Thus, for layered rock (with a given surface roughness interface) the frictional shear strength of the interface increases with increasing normal stress, suggesting that fracture growth in layered rock is dependent on the frictional shear strength of the interface.

These experiments clearly demonstrate that the applied normal stress only indirectly influences fracture propagation in monolithologic layered rock specimens, and that the frictional shear strength of the interface is an important parameter which governs whether or not a fracture will cross an interface. Furthermore, these experiments show that the tensile strength (or some other mechanical property) of the layers is also an important factor in determining whether or not a fracture will cross an interface. Berea sandstone, which has a lower tensile strength and shear modulus than the Tennessee sandstone, consistently required a lower normal stress for fracture growth across the interface than Tennessee sandstone at all surface roughnesses.

Dilithologic Experiments

A series of experiments were conducted on dilithologic specimens as a function of normal stress in order to determine the relative influence of differences in mechanical properties of the layers and changes in the induced horizontal stress field on either side of the interfaces on the propagation of hydraulic fractures. In sharp contrast to the monolithologic specimens the horizontal stress field across layer interfaces is not uniform. Elastic finite element calculations of the stress field within the uniaxially loaded dilithologic specimens show changes in the horizontal stress as a result of changes in elastic properties of the different layers (Figure 3 and Table 3). When a normal stress is applied to the dilithologic specimens a large horizontal stress field is induced at the material interface. Specifically, the horizontal stresses in the layer with a low shear modulus (due to a low elastic modulus and/or high Poisson's ratio) are compressional in contrast to tensional stresses set up in the layer with a high shear modulus (due to a high elastic modulus and/or low Poisson's ratio) immediately across the interface. (In this study the shear modulus is used because it is a single elastic parameter that properly defines the effect of both the elastic modulus and Poisson's ratio on the induced horizontal stress state in dilitholoic specimens.) The induced horizontal stresses increase linearly with increasing normal stress. In our experiments these horizontal stresses had magnitudes as great as 30 percent of the normal stress (Table 3).

Two general types of dilithologic experiments were performed: Type I, fracture initiation in low shear modulus material bounded by high shear modulus material, and Type II, fracture initation in high shear modulus material bounded by low shear modulus material. Containment and propagation are two competing mechanisms in these experiments. In the Type I experiments, it is commonly believed that the high shear modulus bounding material would hinder fracture propagation across the interface whereas the induced tensional stress field in that same material would encourage such propagation. The reverse is true for Type II experiments where the compressional stress in the weak bounding rock would hinder fracture propagation across the interface, but the mechanical properties of the same rock might encourage propagation. Increasing the normal stress increases the induced horizontal stresses and the interfacial shear strength, so for a given rock type (mechanical properties), we can readily examine the effect of changing horizontal stress magnitude and the frictional effect.

Figures 4 and 5 present our data and interpretations for a number of dilithologic specimens. In the Type I experiments (Figure 4), we found no indication that mechancial properties control fracture containment. In going from containment region A to propagation region B in Figure 4, containment only resulted from weak interfacial shear strength because the fracture always became an interfacial fracture. It is not clear if a mechanical property containment region also exists but is masked by the weak interface containment field. Our present research is examining this possibility.

The Type II experiments (Figure 5) show conclusively that horizontal stresses can arrest the vertical propagation of a hydraulic fracture. There is shear strength containment in region C, and fracture propagation across the interface from the high shear modulus material to the low shear modulus material occurs when a critical normal stress level is exceeded (region D). However, further increase in the normal stress causes containment once more (region E). This containment results from a critical increase in the compressional horizontal stresses induced in the low shear modulus bounding layers. The nature of this type of fracture containment is very different from weak interface containment. In region E, the fracture remains vertical but bounded by the interfaces until it breaks out of the side of the sample. Therefore, the shear strength of the layer interface is not controlling containment in region E.

DISCUSSION AND SUMMARY

The experimental results indicate that at least two distinct geologic conditions may inhibit or contain the vertical growth of hydraulic fractures in layered rock. First, containment can occur whenever the shear strength of the layer interface is sufficiently weak relative to the tensile strength and the minimum horizontal compressive stress of the bounding layer; then the fracture can more easily become an interfacial fracture than extending across the interface into the bounding layer. A low shear strength interface can occur at low overburden stresses due to the frictional effect of the applied stress on the interface, provided that the overburden stress is sufficiently greater than the horizontal stresses to produce a vertical hydraulic fracture.

The second condition for containment is due to a compressional increase in the minimum horizontal stress in the bounding layer. We consider this geologic condition to be the more important of the two and more likely to occur at depth. For a sequence of rocks subjected only to gravitational loading (or an applied normal stress as in our experiments), the magnitude of the horizontal stresses in individual layers increases with increasing depth (and applied normal stress). The relative difference in the magnitude of the horizontal stress from one layer to another will be a function of the relative difference in elastic properties of the layers. A possible compressional increase in the minimum horizontal stress may occur in going from a layer with a high shear modulus (due to a high elastic modulus and/or low Poisson's ratio) into a layer with a low shear modulus (due to a low elastic modulus and/or high Poisson's ratio).

In our experiments the critical magnitude of compressional increase in the horizontal stress required for complete hydraulic fracture containment was about 5 MPa. However, for large scale, in situ hydraulic fractures the critical, minimum horizontal stress difference may be different. Factors which may influence the required compressional stress difference across layer interfaces necessary for containment may be the size and geometry of the fracture, the fracture pressure, or fluid leakoff. The effect of these parameters are uncertain. We plan to evaluate these factors and others in larger laboratory hydraulic fracture experiments and in further evaluation of Sandia National Laboratories in-situ and mineback hydraulic fracture experiments at the Nevada Test Site (NTS). Recent in-situ stress measurements at NTS[9] have shown that a mini-hydraulic fracture (50 gallons of fracture fluid)[4] was contained due to elastic property differences that produced a 3 MPa compressional increase in the minimum horizontal stress. Containment occurred as the fracture was propagating from high shear modulus material into low shear modulus material.

In summary, the results of this study have important implications to the gas industry and can be applied to actual field hydraulic fracture treatments. It is suggested that core and log analyses may be useful in determining the possible existence of weak interfaces or large variations in elastic properties that may affect the horizontal stress state when the appropriate boundary conditions are considered. An assessment of the stratigraphic sequence of potential tight gas sands and bounding shales in terms of the above two geologic conditions, particularly elastic properties, may improve the efficiency of the hydraulic fracture treatment design or at least indicate where the fracture treatment can or cannot be successfully applied.

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FIGURE CAPTIONS

Figure 1.	Schematic diagram of the specimen configuration for hydraulic fracture experiments.
Figure 2.	Relation of normal stress to surface roughness of monolithologic interfaces of Berea sandstone (B) and Tennessee sandstone (T) on the extent of hydraulic fracture propagation.
Figure 3.	Horizontal stress state in dilithologic specimens determined from elastic finite element calculations. a) Shear modulus (G) of middle layer is lower than outer layer, b) Shear modulus of middle layer is higher than outer layer.
Figure 4.	Fracture propagation and containment regions in dilithologic specimens in which shear modulus (G) of the middle layer is lower than the outer layer, Type I experiments. Increasing the applied normal stress (σ_N) produces a tensional (positive) increase in the induced horizontal stress change from the middle to outer layer.
Figure 5.	Fracture propagation and containment regions in dilithologic specimens in which shear modulus (G) of the middle layer is higher than the outer layer, Type II experiments. Increasing the applied normal stress (σ_N) produces a compressional (negative) increase in the induced horizontal stress change from the middle to outer layer.

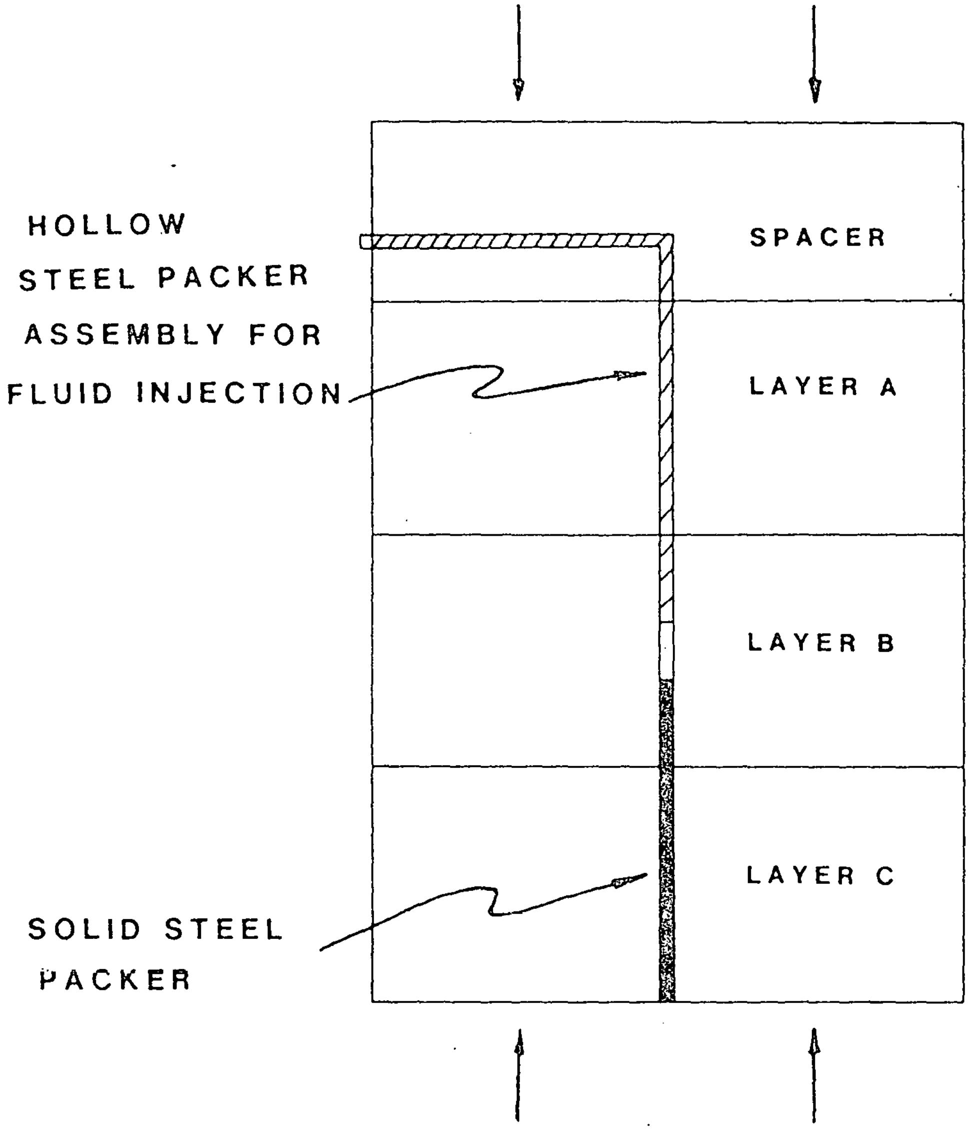

HOLLOW STEEL PACKER ASSEMBLY FOR FLUID INJECTION
SPACER
LAYER A
LAYER B
LAYER C
SOLID STEEL PACKER

Fig. 1

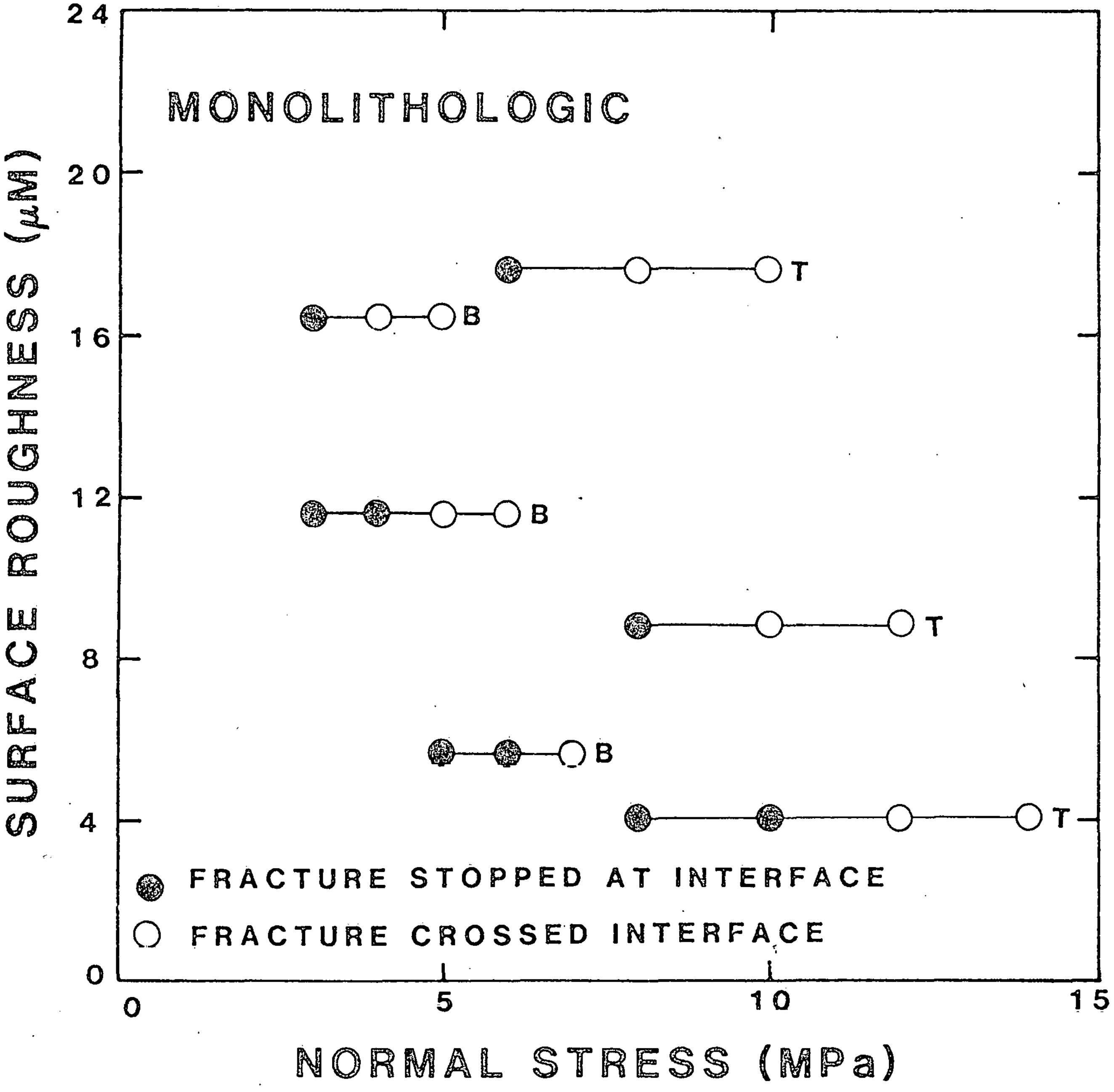
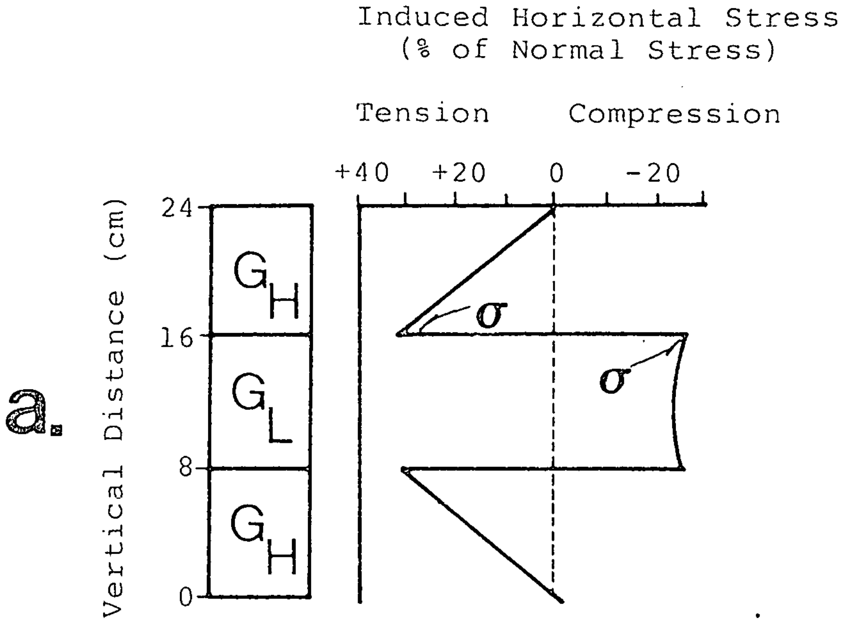
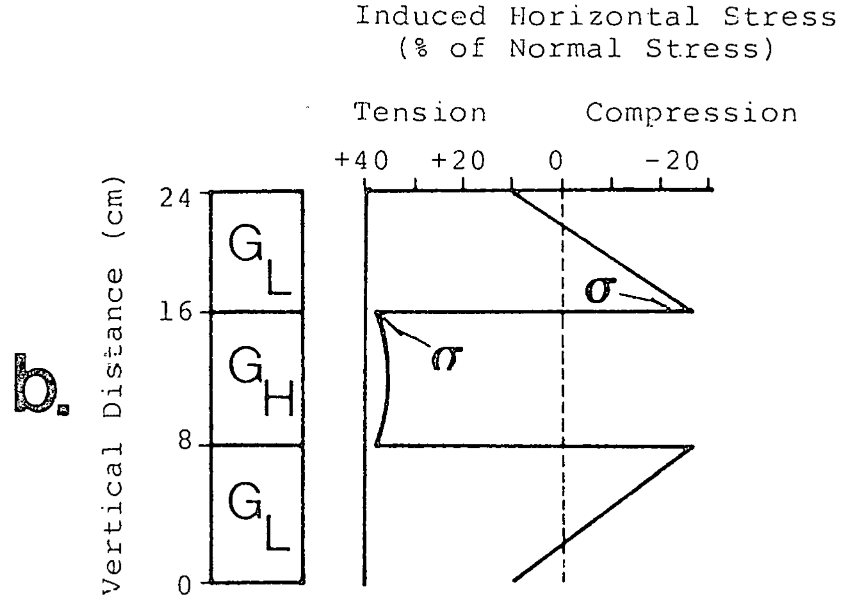

MONOLITHOLOGIC
SURFACE ROUGHNESS (μM)
NORMAL STRESS (MPa)
0
4
8
12
16
20
24
0
5
10
15
T
B
B
T
B
T
FRACTURE STOPPED AT INTERFACE
FRACTURE CROSSED INTERFACE

Fig 2



(Stress Distribution shown for case where $G_H/G_L = 0.37$)



(Stress Distribution Shown for case where $G_H/G_L = 2.69$)

Fig 3

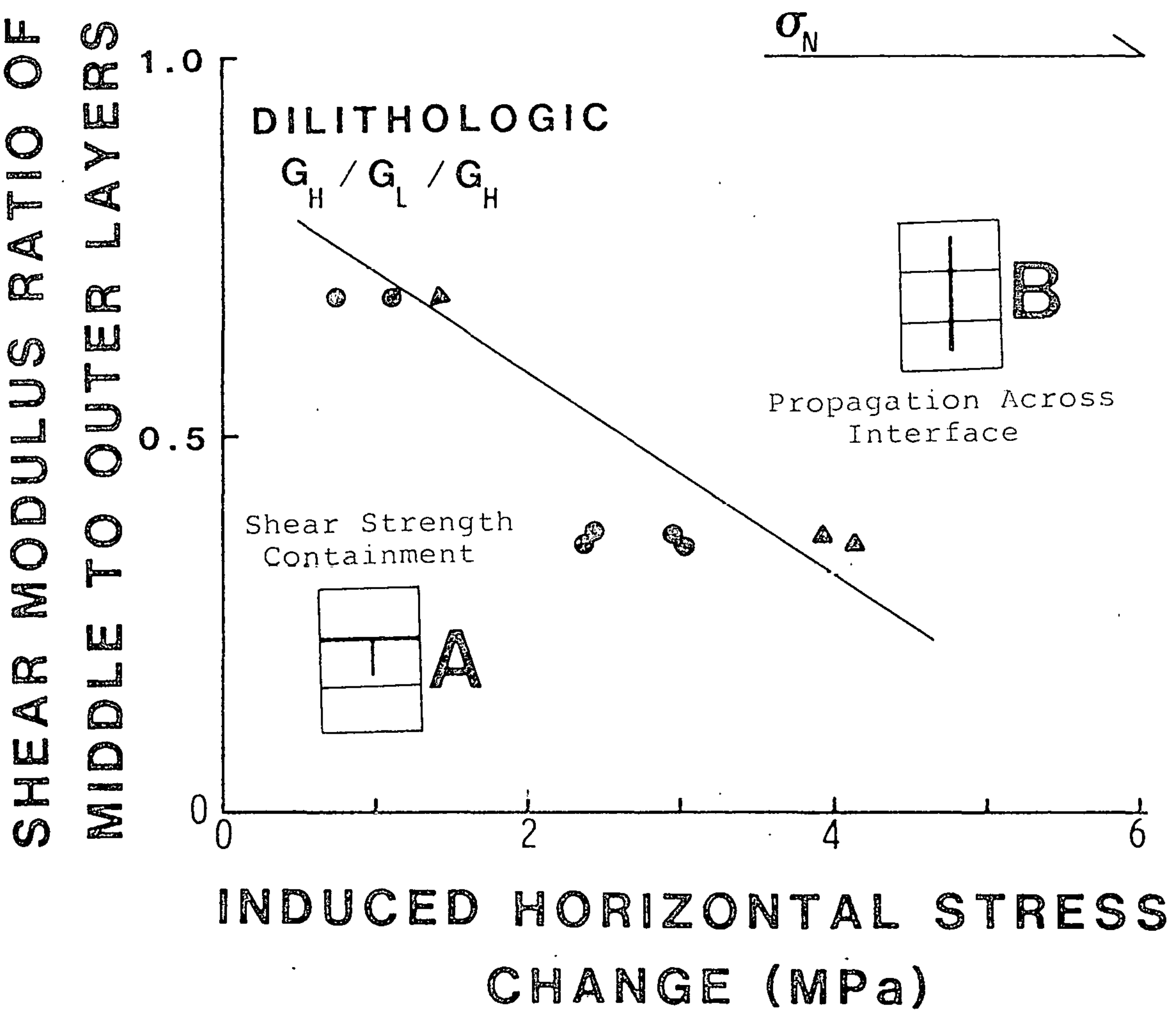

σN
DILITHOLOGIC
$G_H / G_L / G_H$
B
Propagation Across Interface
Shear Strength Containment
A
SHEAR MODULUS RATIO OF MIDDLE TO OUTER LAYERS
1.0
0.5
0
0
2
4
6
INDUCED HORIZONTAL STRESS CHANGE (MPa)

Fig 4

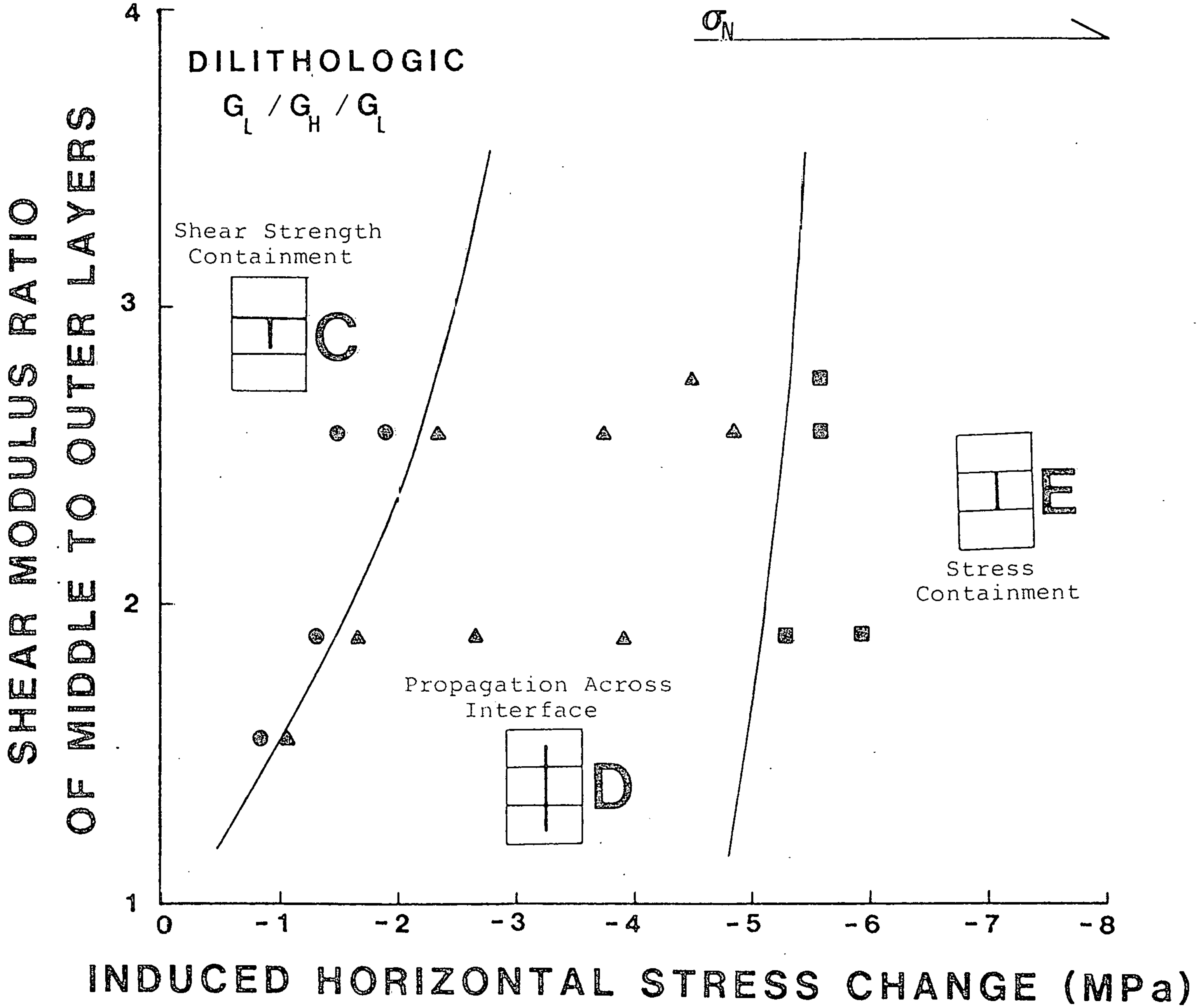

DILITHOLOGIC
$G_L / G_H / G_L$
σ_N
Shear Strength Containment
C
E
Stress Containment
Propagation Across Interface
D
SHEAR MODULUS RATIO OF MIDDLE TO OUTER LAYERS
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
INDUCED HORIZONTAL STRESS CHANGE (MPa)

Fig 5

Table 1. Physical properties of rocks used in this research.

Rock Type	Porosity (percent)	Permeability (air, md)	Description
Arizona sandstone	5	8	A pink, fine-grained, well-sorted, and silica-cemented, rock composed of 93% quartz, 6% rock fragments, and 1% clay
Berea sandstone	17	205	A tan, fine-grained, rock composed of 79% quartz, 9% clay, 10% feldspar, and 2% calcite.
Coconino sandstone	12	160	A pink, medium-grained, well-sorted and silica-cemented rock composed of 88% quartz, 11% rock fragments, and 1% clay.
Lueders limestone	15	3	A grayish tan fine-grained roc consisting chiefly of calcium carbonate in the form of micrite, diagentically altered organic particles, fossil fragments and sparry calcite cement.
Tennessee sandstone	1	0.1	A tan, fine-grained, well-sorted, and silica-cemented rock composed of 97% quartz an 3% rock fragments.

Table 2. Mechanical properties of rocks used in this research.

	Unconfined Compressive Strength (MPa)	Tensile Strength* (MPa)	Young's Modulus (GPa)	Poisson's Ratio	Shear Modulus** (GPa)
Arizona sandstone	160	8.8 ± .3	42.1	0.18	17.8
Berea sandstone	80	4.9 ± .2	24.0	0.28	9.4
Coconino sandstone	110	6.4 ± .3	34.5	0.24	13.9
Lueders limestone	55	4.0 ± .2	20.7	0.30	9.7
Tennessee sandstone	260	12.8 ± .3	58.4	0.12	26.1

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*Average ± one standard deviation from 10 tests.

**Calculated from $\frac{E}{2(1+\nu)}$, where E is Young's modulus, ν is Poisson's ratio.

Table 3. Induced horizontal stress state in dilithologic specimens.

Dilithologic Specimen		Shear Modulus Ratio of Middle to Outer Layers	Horizontal Stress*		Horizontal Stress Change Across Interface* (% normal stress)
Middle Layer	Outer Layers		Middle Layer (% normal stress)	Outer Layers (% normal stress)	
Lueders limestone	Tennessee sandstone	0.37	-27	33	60
Berea sandstone	Tennessee sandstone	0.36	-21	28	49
Arizona sandstone	Tennessee sandstone	0.68	-3	11	14
Lueders limestone	Berea sandstone	1.03	2	12	10
Coconino sandstone	Berea sandstone	1.48	19	-2	-21
Arizona sandstone	Berea sandstone	1.89	26	-7	-33
Tennessee sandstone	Berea sandstone	2.78	33	-14	-47
Tennessee sandstone	Lueders limestone	2.69	39	-17	-56

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[*] In this study compression is negative and tension is positive.