WESTERN GAS SANDS PROJECT STIMULATION RESEARCH

Quarterly Report
October 1, 1980 - December 31, 1980

I. In Situ Hydraulic Fracturing Experiments (Mineback)

A. Formation Interface Fracture Experiment

The final activity associated with the Hole #6 Formation Interface Fracture Experiment is the determination of the vertical distribution of the minimum principal in situ stress. These results will be important for determining the extent to which the in situ stresses affected fracture growth. In situ stress measurements were made using small volume hydraulic fractures (minifracs) to provide an instantaneous shut-in pressure (ISIP) which is equivalent to the minimum principal in situ stress. These were conducted by isolating a short section of an open hole with straddle packers, pumping a small volume of water to break down the formation, and shutting the zone in to obtain the pressure decline. Accuracy is usually ±20 psi although different areas may vary considerably.

Minifracs were conducted in two of the exploratory core holes which were cored to locate the extent of the Hole #6 fractures. Fourteen zones were fractured in EV6-24 at locations from 30 ft below the interface to 250 below the interface in the ash-fall tuff. Seven zones were fractured in EV6-29 at two locations in the welded tuff above the interface and five others above the -welded zone to a point about 130 ft above the interface. Data' from these tests are shown in Figure 1.

It can be seen that there are large and quite rapid changes of stresses throughout the 350 ft of section studied. Also, the stress in the densely welded tuff is quite low. This distribution of stresses can be explained qualitatively if one considers the mesa in its present condition and forgets for the moment its geologic history. Essentially, the mesa consists of tens or even hundreds of ash-fall tuff layers of varying thickness and properties with two thin, high-modulus, welded tuff strata at widely separated locations. At the present point in geologic time, the layers are stacked, well-bonded and predominantly gravity-loaded. This results in a compressional loading.of the layers and effectively tries to squeeze the tuffs out the sides of the mesa. The ash-fall tuff, which has a very low Young's modulus and a high Poisson's ratio is squeezed out much farther than higher modulus rocks. Since the strata are well bonded, the ash-fall tuff drags the narrow welded tuff layer out with it resulting in a decreased compressional state or even tensional state of stress in the high modulus, low Poisson's ratio, wleded tuff. This also explains why the welded tuff is so

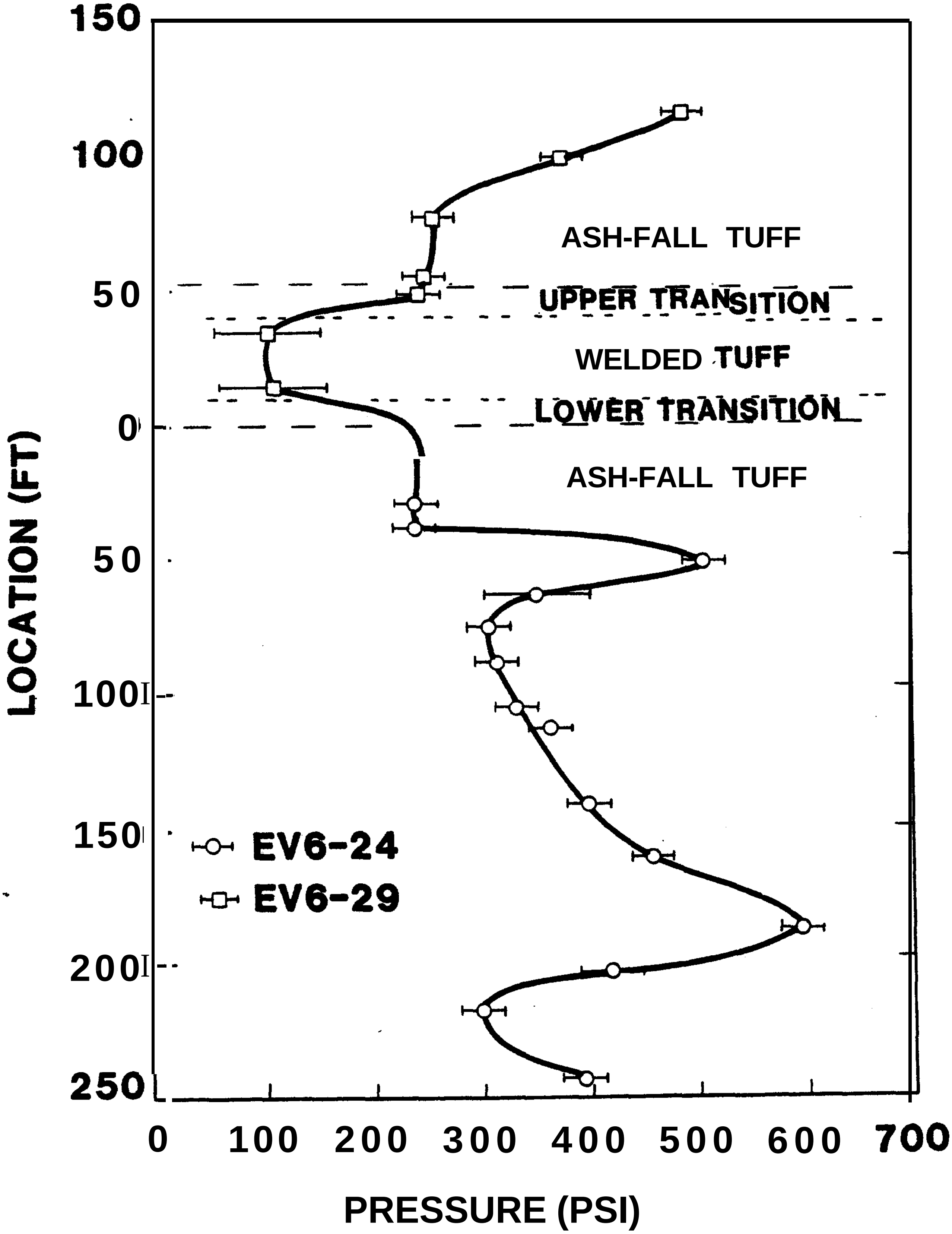

Figure 1. In Situ Stress Measurements Near the Hole #6 Formation Interface Fracture Experiment.

uniformly fractured. Of course, the geologic history, such as cooling phenomena of the tuffs, erosional relief of the mesa, alteration, and other factors will affect the local structure of the stresses and specific magnitudes and orientations. Also, factors such as creep and the limited effect of tectonics may have affected the stress state in the welded tuff since the time it was fractured and, effectively, relieved. Nevertheless, the general stress state can be easily explained by this simple model, and finite element calculations by J. Clark (Sandia) have shown this. This would suggest that the high stress regions below the interface in Figure 1 are probably the result of stratigraphy, although this has not been confirmed.

It appears the stress peak at 50 ft below the interface correlates well with the point of termination of the lower tip of the first fracture. The stress peak at 180 ft correlates well with the point of termination of the second fracture. It appears that the in situ stress state was the predominant factor controlling the overall fracture geometry. The low stress state in the welded tuff may explain why the first fracture propagated so readily into this rock. One would suspect that with the much higher modulus it would require significantly higher pressures than in the ash-fall tuffs to open a fracture to the necessary widths for injecting grout, even with the natural fracture system. Perhaps the much lower stress state compensates for this. The end result appears to be that in an experiment to test fracture behavior at a geologic interface, the in situ stresses had a much more significant effect.

A final report on this experiment is now being prepared. It will include results of mineback, coring, and in situ stress measurements.

B. Fluid Mechanics/Proppant Transport Experiments

The initial phase of this program is an experiment to measure the width and pressure in a propagating hydraulic fracture. This test is presently in the fielding stage. A horizontal experiment hole, PTE-3, has been drilled to 55 ft and cased to 40 ft. A seven foot open hole zone was fractured in October with 30 gal of dyed water. It was expected that this would result in a fracture of at least 20 ft radius.

After completion of the initial dyed water fracture, a coring program was initiated to locate the fracture. This is shown in the plan view in Figure 2. The design was such that six coreholes were to be drilled and these would be used for instrumentation packages containing pressure transducers and LVDT's for measuring the width of the fracture. Another corehole would contain a device for detecting the fracture when it passes that location. These packages would be grouted in place across the fracture using a tuff-matching cement system. The proposed location of these holes in a vertical cross section through the experiment hole is shown in Figure 3.

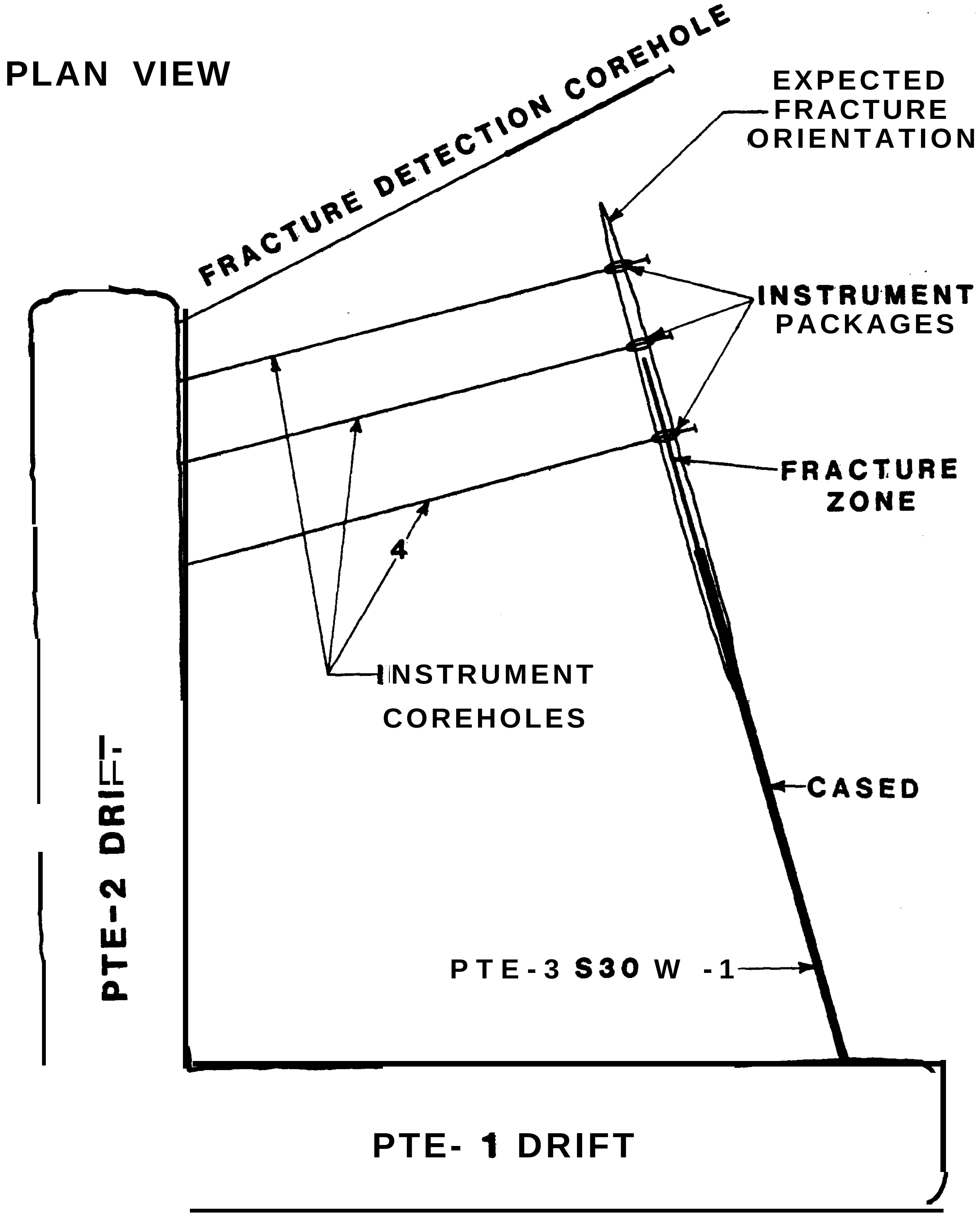

Figure 2. Plan View of Fluid Mechanics Experiment.

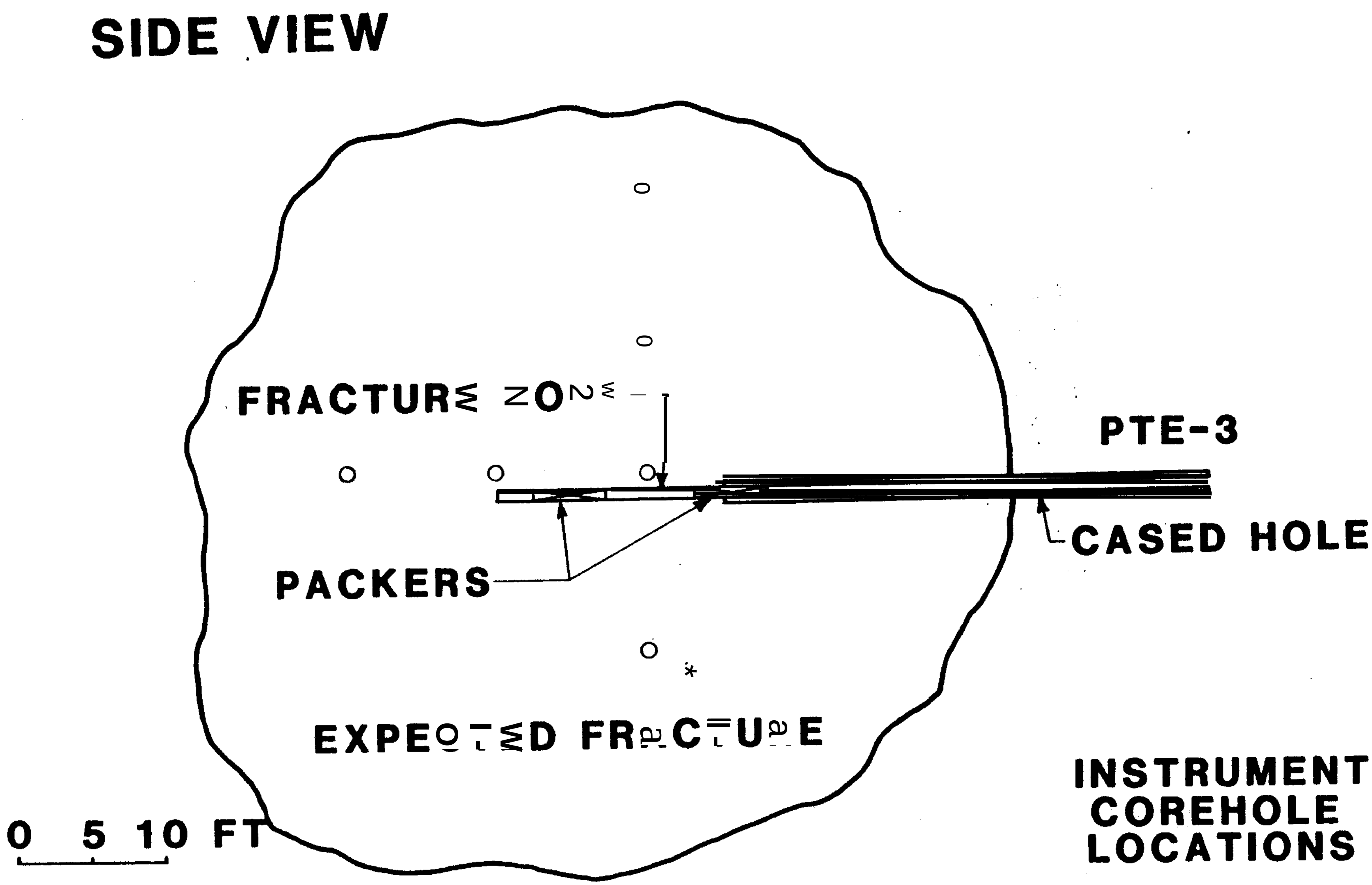

Figure 3. Side View of Instrument Corehole Locations

Results from several of these coreholes show that the fracture was much smaller than expected, possibly because of a much higher fluid leakoff than was anticipated. In order to rectify this, the experiment was refractured in December. In order to monitor the fracture's progress, the three coreholes at 10 ft from the center of the fracture zone were packed-off, filled with water, and monitored with pressure guages during fracturing. The hole at 20 ft above the packed-off zone was left open for observation of fluid loss. The experiment hole was then refractured with 135 gal of dyed water at 10-13 gpm. A pressure increase was observed in the lower corehole after only about 5 gal of fluid was injected, and a similar signal was obtained in the corehole which was situated 10 ft laterally outward after about 25 gal. However, the fracture was never observed in the two coreholes above the experiment hole. There is good reason to believe that this is due to a high stress region about 5 ft above the experiment hole. There is a soft, apparently low modulus tuff layer beginning at this point and stress magnitudes in the mesa often correlate well with modulus (low modulus layers have high stress).

This does not overwhelmingly affect the experiment as long as the principal directions of fracture growth are known. The revised corehole locations are shown in side view in *Figure 4.* It is expected that most of the future fracture growth will be horizontal and downward. If the overlying layer is more highly stressed, it should continue to contain the fracture. Two of the old coreholes will be grouted up and two others left open for observation. Six new coreholes will be situated as shown in Figure 4 and instrumentation packages will be grouted in these. The actual experiment to record pressure and width should take place next quarter.

C. In Situ Stress Measurements by Hydraulic Fracturing Through Perforations

The most feasible technique for obtaining in situ stress measurements at depth in a wellbore is by fracturing through perforations and recording the instantaneous shut-in pressure (ISIP) which is equivalent to the minimum principal in situ *stress.* However, it has never been shown that this technique yields reliable stress values, In order to be certain that performing these tests through perforations will yield accurate, reproducible data, an experiment is being conducted in G-tunnel to compare this method with fracturing openhole.

As shown in Figure 5, two cased holes have previously been perforated and fractured (one of which the data is suspect because of a poor cement job which resulted in leaks around the casing) and in situ stress data were obtained. In October, five zones were fractured in PERF-2 which is an uncased hole about 6 ft from the cased holes. The in situ stress data from comparable zones in the three holes is shown in Table 1. Fracturing pressures in the zones with two perforations are much higher than in the open hole

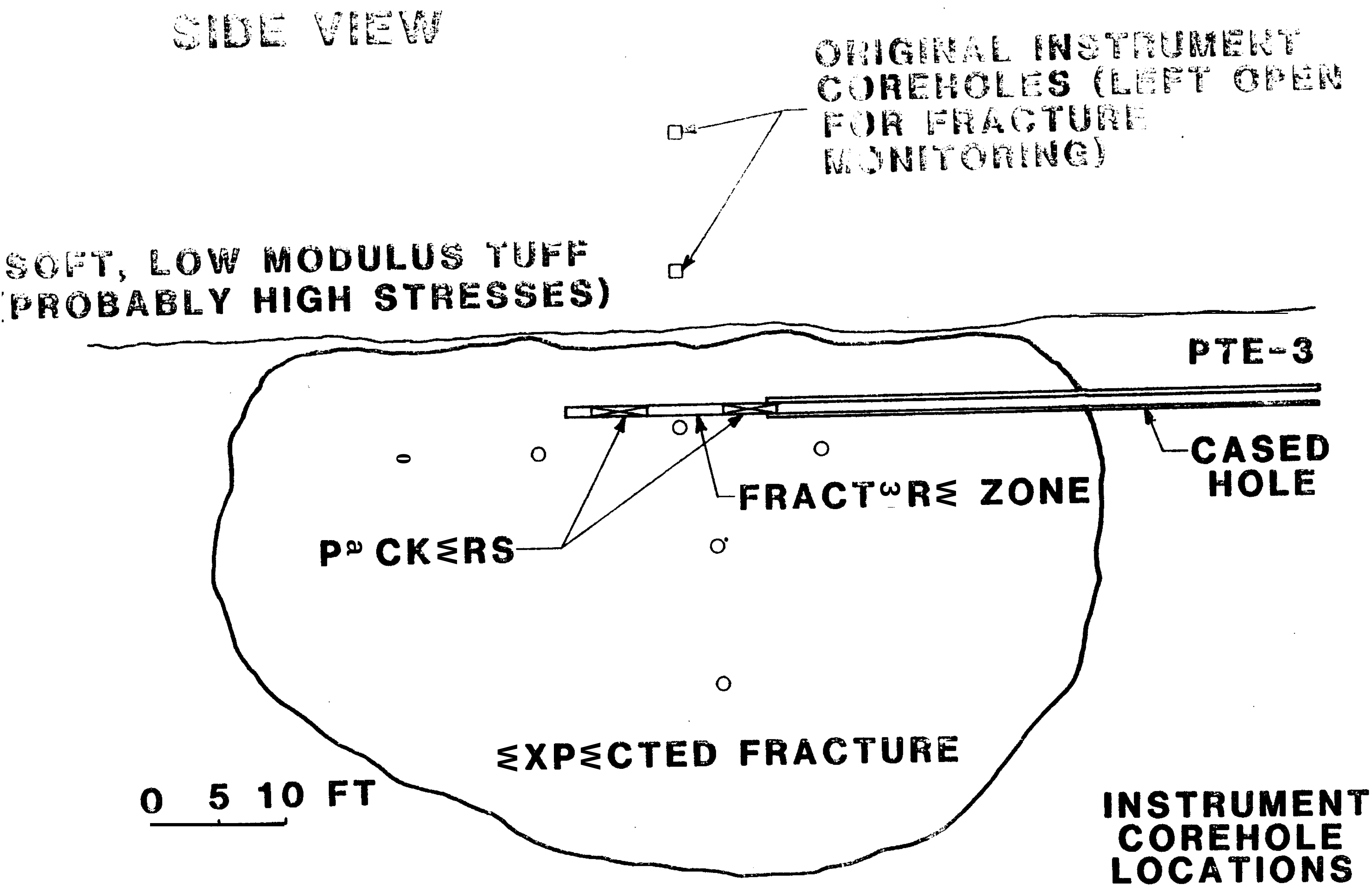

Figure 4. Side View of Revised Instrument Corehole Locations

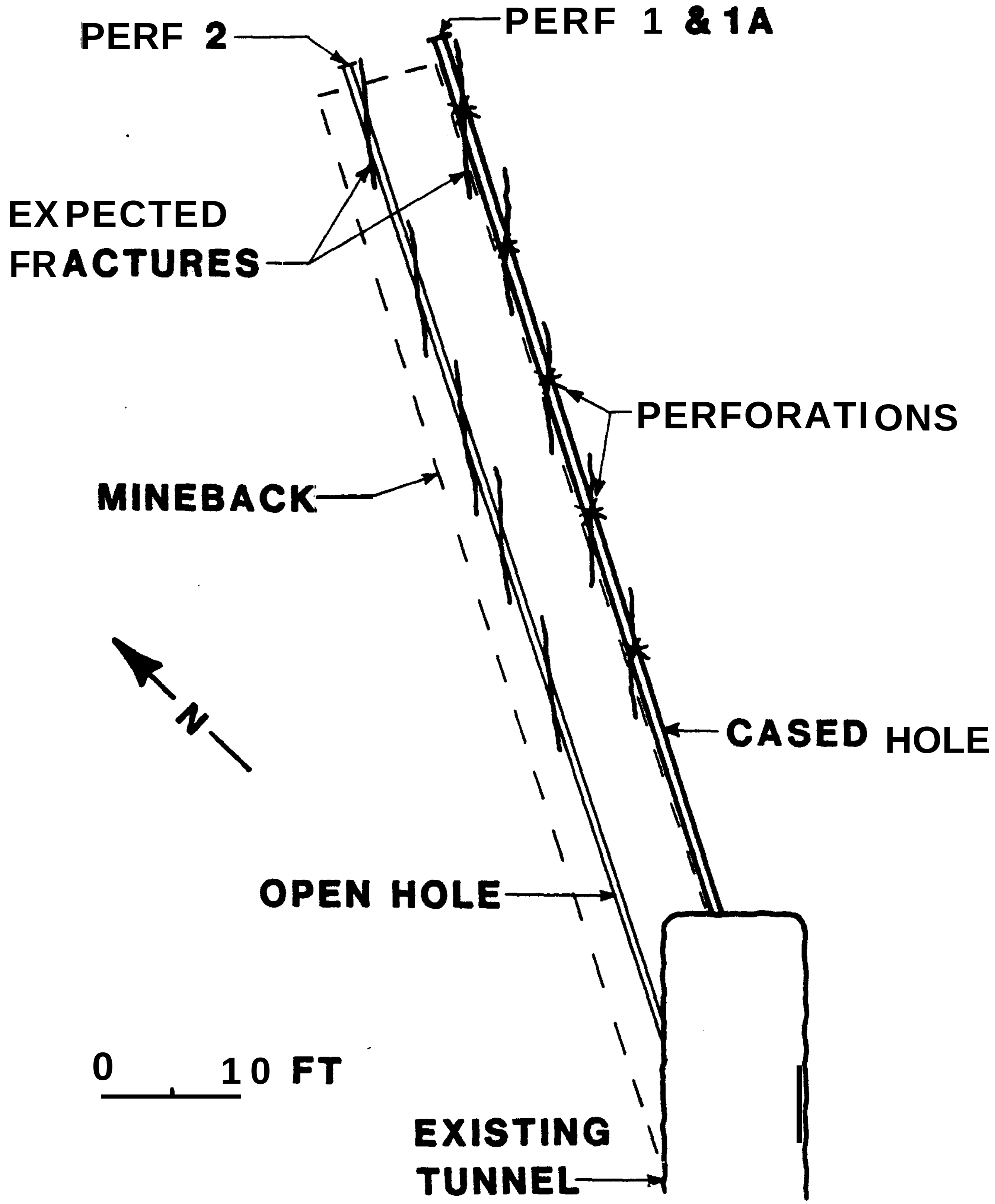

Figure 5. Perforation Experiment Plan View.

TABLE 1

Minimum Principal In Situ Stress Data
for the Perforation Experiments

Cased (poor cement job)				PERF 1A Cased				PERF 2 Open-Hole		
Zone (ft)	# of Perfs	P_f (PSI)	ISIP (PSI)	Zone (ft)	# of Perfs	P_f (PSI)	ISIP (PSI)	Zone (ft)	P_f (PSI)	ISIP (PSI)
60	4	1150	1000	60	4	1235	930	71	1100	935
50	3	2160	----	50	2	2350	1100	58	1100	910
40	2	----	----	40	2	2840	1100	48	1100	910
30	2	----	----	30	4	1845	1100	38	1125	845
20	2	----	----	20	4	2270	1050	28	975	845

zones. It appears that the shut-in pressures obtained through these perforations are about 200 psi too high.

The fractures initiated through perforations and in the open hole were then mined back, including detailed observation of fracture initiation near the perforations. The penetration of the perfs varied from just barely into the grout annulus to about 4 in into the ash-fall tuff. All perforations penetrated through the casing, leaving a hole of about 0.5 in diameter. In general, when perforations penetrated the rock, hydraulic fractures appeared to emanate directly from the perf into the tuff. Where the perforations terminated in the grout, the fractures were initially confined to the grout annulus or the grout-tuff interface. Eventually these annulus fractures propagated into the rock, but frequently at distances ranging from a few inches to several feet from the perforations. Fractures typically initiated parallel to the borehole but then turned somewhat to align with the in situ stress orientation which was 20-30° different from the borehole.

There are two major, unresolved questions about the results of these experiments. Why were the fracturing pressures so high and why were the shut-in pressures about 200 psi above that measured in the open hole? The high fracturing pressures were clearly not due to the size of the perforation in the casing. Perforations measuring 0.5 in in diameter provide a sizable flow path for the rates used here (4-8 gpm). Also, no clear correlation could be made with number of perfs or depth of penetration. Complicating this further was the fact that many of the perfs were partially to completely packed with crushed rock particles. The high shut-in pressures may in part be due to the turning of the fractures after emanating parallel to the borehole. Thus the ISIP observed may have been due to closure of the borehole which reflects a stress state greater than the minimum. Secondly, ISIP's were difficult to determine due to a lack of a well defined "knee" in the pressure decay curve. This problem may be due in part to the high fracturing pressures.

At the end of the quarter the mineback data was still being analyzed to correlate the fracturing results with observable fracture behavior. A plan is presently being formulated to repeat the experiment, possibly without mineback, under more controlled conditions. This proposed test should clarify many of the problems observed here.

D. Nature of In Situ Stress Variations Affecting Hydraulic Fracture Propagation

The results of mineback experiments showed that a high peak in the minimum horizontal stress within a low Young's modulus ash-fall tuff terminated the vertical propagation of hydraulic fractures. However, an overlying, high Young's modulus, welded tuff was not a containment feature. At that time, it was unclear why the stress peak existed. We have since conducted petrologic studies in conjunction with analytical and experimental rock mechanics studies to determine the nature and explain the cause of the stress peak which had such a profound effect upon hydraulic fracture propagation. Results indicate that elastic moduli changes within the ash-fall tuff are the dominant control of the stress peak and these changes reflect post-depositional geochemical alteration of the tuff as well as depositional inhomogeneities. It is thought that similar geochemical processes may also affect sandstone reservoirs.

Mineback of a small volume hydraulic fracture ($0.5 m^3$) initiated in ash-fall tuff 0.25 m below a high modulus welded tuff (Young's modulus, E = 28 GPa, Poisson's ratio v = 0.21), revealed that the hydraulic fracture terminated in the ash-fall tuff, but propagated upwards through the overlying welded tuff. The wall of the mineback tunnel is perpendicular to the plane of the fracture and, therefore, parallel to the orientation of the minimum horizontal in situ stress. Three overcoring strain relief measurements of the minimum horizontal in situ stress were done at each of three horizons on the tunnel wall. The average values for elastic moduli and calculated stresses are given in Table 2. Stresses determined within a single horizon varied by less than 10 percent. Near the contact with the welded tuff the ash-fall tuff is highly anisotropic with Young's modulus in the vertical direction almost twice that in the horizontal direction. Farther below the welded tuff, the material becomes less anisotropic with a much lower Young's modulus. Anisotropy near the welded tuff interface appears to be related to a strong horizontal planar fabric that becomes much less distinct at increased distances from the contact. The horizontal stresses calculated from the measured strains increased by 2.5 MPa over a distance of only one meter (see Table 2). Maximum stress occurs at the location of fracture termination, in the region of lowest Young's modulus and highest Poisson's ratio.

TABLE 2

Results of Overcoring Strain Relief Measurements

Distance Below Welded Tuff (m)	Young's Modulus (GPa) Vertical Ev	Horizontal Eh	Poisson's Ratio ν	Horizontal Stress (MPa)	Predicted Horizontal Stress (MPa)
-0.20	28		0.21	Not determined	2.02
0.15	6.73	3.51	0.18	1.05	0.87
0.45	3.11	2.27	0.24	1.59	1.75
0.85	1.84	1.58	0.34	3.44	3.36
1.05	58.1		0.15	Not Determined	1.34

This relationship between elastic moduli and stress suggests a uniaxial strain boundary condition. Stress predictions from a simple calculation, assuming uniaxial strain, anisotropy, and 7.6 MPa overburden stress, fit the measurements very well (see Table 2). However, this success might well be fortuitous because the effect of the tunnel upon the stress distribution was not included. A three-dimensional finite element calculation with appropriate tunnel geometry and anisotropic moduli variations is now underway.

Approximately 0.2 m below the stress peak is a narrow horizon that has elastic properties even greater than the welded tuff (E = 58.1 GPa, ν = 0.15). Strain relief measurements in this layer are planned. Similar horizons are not uncommon in the ash-fall tuff. These layers vary in thickness from approximately 1" to 6", are laterally continuous, and occur at regular intervals below the contact between the ash-fall tuff and welded tuffs. Samples were taken within, and adjacent to, these layers for examination by optical microscopy, scanning electron microscopy and x-ray diffraction. Petrographic results indicate that elastic moduli -changes are due to intense diagenetic alterations of the ash-fall tuff. Specifically, the altered layers are characterized by growth of large euhedral, authigenic crystals of zeolite and potash feldspar. Elsewhere, the ashfall tuff has a predominantly glassy appearance with relatively few phenocrysts and less intense authigenic re-crystallization. It is thought that the distribution of the altered layers is related to spatial and temporal changes in the location of the water table.

The primary difference in diagenetic alteration of the tuff appears to be that, within the altered layers, the authigenic crystals are larger and tend to occur as a pore-filling cement: elsewhere, authigenic recrystallization is much finer-grained and more dispersed throughout the matrix. Therefore, these observations suggest that in rocks of homogeneous composition, the mode of authigenesi can cause significant changes in mechanical properties.

The hydraulic fracture terminated in the lowest Young's modulus material because of a high minimum horizontal stress, but the fracture propagated through the highest Young's modulus material with the lowest stress state. Material moduli changes caused stress changes of at least 2.5 MPa over a one meter distance and such.stress changes, resulting in fracture containment, may also occur in gas reservoirs where modulus changes are common. Few data exist on minimum in situ stress variations as a function of depth in gas reservoirs. However, a recent paper (Wyman, Holditch and Randolph, JPT, 32, 1621, September, 1980), presents data showing variations of 3.5 MPa over 3 m. Furthermore, geochemical alteration of reservoir formations, precipitation of quartz or calcite by groundwater, and formation of authigenic clays may greatly affect elastic moduli, altering the in situ stress state caused by subsequent stress changes such as increased overburden. Geochemical alteration of gas reservoirs may thus result in important stress containment features as well as greatly affect permeability *or* gas evolution.

II. Rock Mechanics Investigations

A. Rock Mechanics Laboratory Experiments

No work was performed this quarter because the physical facilities were moved to a new location and the fracturing system is being upgraded. A new load frame which can produce a 20,000 psi overburden stress on our 8-in samples has been made available. Tests on the present system and the new load frame will resume in January.

B. Strain Relaxation Method for Predicting Hydraulic Fracture Azimuth from Oriented Core

In order to predict the azimuthal direction of a hydraulic fracture, it is necessary to know the direction of the minimum horizontal compressive stress, since a hydraulic fracture propagates perpendicular to this stress direction. In this study a strain relaxation technique for oriented core is presented as a simple and effective method to determine the direction of the maximum and minimum horizontal stresses and thus predict the fracture orientation. The essential idea for the technique is that when the ambient, in situ stress that exists at depth is reduced appreciably by coring a section of rock, there will be a relaxation of the locked-in strains.. The total strain relaxation will consist of two parts: (1) an instantaneous recovery of elastic strain, and (2) a continued time-dependent relaxation of the rock core that will tend asymptotically to a final, permanent strain. These relaxations, measured along known directions of an oriented core, are then used to calculate the principal directions of strain relief. If the rock behavior is linearly viscoelastic, then the strain relief along principal strain (stress) directions will be uniform with time, and the directions of the principal strain relief determined for a given time interval of strain relaxation will correspond to initial elastic strain relief and the in situ stress orientation.

The procedure for this method consists of two parts. First, field strain relaxation measurements are made on sealed, oriented core immediately after the core is extracted from the borehole. A set of disc gages (developed by K. Schuler at Sandia National Laboratories) are used to make the strain relaxation measurements. A set of disc gages are used rather than strain gage rosettes since they-can be more easily placed on the core within a considerably shorter time span (10 minutes), and more importantly measure changes in strain across the entire core instead of the small surface area beneath the strain gage rosettes. Sealed core is used to greatly reduce the effect of moisture evaporation. The second step is to determine if the core material is linearly viscoelastic by conducting strain relaxation experiments on the rock in the laboratory.

The method has been successfully tested on oriented core of ash-fall tuff from G-tunnel at the Nevada Test Site where the in situ stress directions and corresponding initial elastic strain relief directions were determined from hydraulic fracture tests and in situ overcoring strain measurements. A single horizon of ash-fall tuff was instrumented with strain gage rosettes for three in situ overcoring strain measurements. Immediately after overcoring, disc gages were mounted on the extracted cores. Time-dependent strain relaxation of the three cores occurred for 38 hours. Calculations of the minimum principal strain direction using the total time-dependent strain relaxation, as well as, individual, 3 hour strain relaxation time increments were consistently within 7° of the initial, minimum, elastic strain relief direction determined from overcoring and the hydraulic fracture azimuth. These results suggest that the strain relief method may be reliable in the prediction of a hydraulic fracture azimuth from oriented core, provided the rock is linear viscoelastic and with a relaxation period sufficiently long for measurements '(probably 24 hours for deep wells). The method is presently being applied to tight gas sands in the Green River Basin.

III. Fluid Mechanics Model of Fracturing

A preliminary model of the fluid mechanics of fracturing is under development. This model considers one-dimensional flow of flow through a fracture, but a "complete" width equation (the width is determined for any arbitrary pressure distribution) is employed and transient and convective terms in the continuity and momentum equations are not discarded. Although the model in its essence works, there are two major problems which must be resolved to make the model applicable for any arbitrary conditions. The first problem is to develop an efficient method to handle the equations at the crack tip. Since conditions change very rapidly over a short distance, the calculations of the tip can control the convergence of the system of equations. A second problem is the overall convergence of the system of equations. They do not readily converge to a solution matrix and techniques must be employed to force convergence. Finding a technique which efficiently does this has been a major obstacle. Work on these two problem-areas is continuing.

IV. Geochemistry and Petrology

A quantitative study of a set of forty thin sections of the Mesaverde sandstone from the Church Buttes field, Wyoming has been initiated.,. The significance of these samples is that they are the first set we have obtained that represent a core containing several fairly well-defined sand lenses. Thus far, the petrographic examination of one of these lenses has been nearly completed and the results are described herein. In general, the parameters of interest are grain size, shape, sorting, detrital and authigenic mineralogy, and cementation (amount, composition, and distribution). A complete mineralogical characterization of these samples is given in Table 3.

The abundance of quartz and rock fragments and the scarcity of detrital feldspars indicates the classification of this lens as a lithic arenite. Overall, these compositions are in good agreement with a mineralogical study conducted by the USGS[1] from samples collected elsehwere in the Piceance Creek Basin. For example, the chert:quartz ratios of 0.2-0.4 we have found support their interpretation of a supracrustal provenance for these sands. In addition, our identification of silicified microfossils (including coral), similar to observations made by the USGS, indicates the presence of re-worked earlier Cretaceous sediments. The composition diagram (Figure 6a) shows that, with the exception of one sample, all compositions based on the interrelationship of quartz, carbonate, and voids (pores) fall into one group. The exception is a sample taken close to the sandstone-shale contact at the top of this lens. However, if chert is substituted for the quartz component (Figure 6b), the samples may be considered to fall into two groups. This grouping also divides the samples into the upper and lower portions of the lens, suggesting that silica diagenesis is a significant parameter in distinguishing particular areas of lens mineralogy. The quartz grain measurements suggest a fining-upward cycle, consistent with that expected for a channel sand..

One of the more significant observations pertains to the mineralogy of the sandstone immediately adjacent to the lithologic contacts with over- or underlying shales. While the Mesaverde sands are dominantly cemented with calcite and/or dolomite (and less commonly, siderite or ankerite), sandstone adjacent to these

---

[1] Hansley, P. L., and Johnson, R. C., Preliminary results of mineralogic and diagenetic studies of low-permeability sandstones of late Cretaceous age, Piceance Creek Basin, northwestern Colorado. USGS Open-File Report 79-1702, 1979.

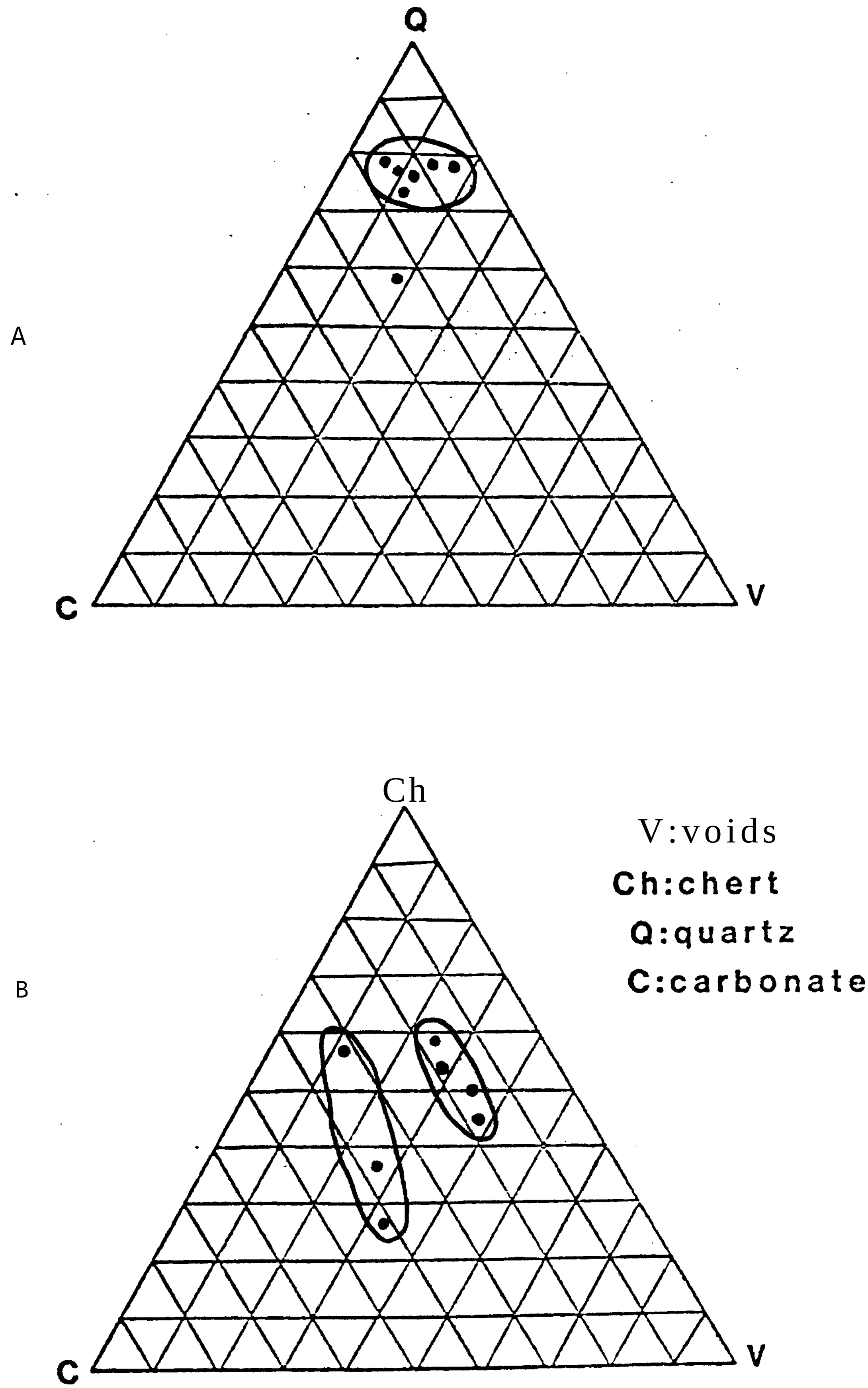

Figure 6. Composition of sand lens, Church Buttes Field, Wyoming; depth 8684-8704 ft.

TABLE 3

Mineralogical Analyses (%)*

Sample No.**	Quartz	Chert	Carbonate	Clays	Organics	Rock Frags.	Voids
7B	48.7	13.3	19.3	0.7	2.3	0.7	15
7c	56.2	21.8	12	4	0.6	1.2	4.2
7D	59.7	12.3	13	0.7	5.0	0.0	9.3
7E	62.7	16.3'	5.3	3.3	0.3	0.7	11.3
7F	48.5	22.5	7.5	8.5	1.5	2	9
7G	58	17	6	4	5	1	9
7H	55.7	11.7	4.7	4.3	2.3	11.3	9.7

*Average of 200-300 point-counts/thin-section
**Depths from 8684' to 8704'

shale contacts is frequently heavily silica-cemented, commonly with thick overgrowths on the quartz grains. This observation appears to confirm the hypothesis that the shales may act as permeability barriers to the movement of interstitial waters over geologic time, resulting in marked silica diagenesis at the boundaries. Consequently, deposition of silica at these interfaces may have a significant effect on fracture behavior.

On December 2 and 3, 1980, Sandia hosted a workshop on the geology and morphology of lenticular sands. Conversations with members of the USGS who attended suggest that the mineralogy of the Mesaverde sands may vary widely, based on preliminary observations of samples from the Green River, Uinta, and Piceance Creek Basins, but the dominant mineral components are similar. In particular, it was of interest to note that mineralogical composition within a basin varies slightly, suggesting localized diagenetic effects determined by differences in interstitial water compositions. Specifically, the occasional presence of barite and anhydrite implies the localized incursion of more saline waters. This workshop emphasized the importance of studying the sedimentological aspects of lenticular sands and several avenues of research along these lines are currently being-explored.

QUARTERLY INFORMATION LETTER - October, November, and December 1980

DISTRIBUTION:

M. R. Adams
a. G. DiBona
P. R. Wieber
J. B. Smith
Office of the Deputy Assistant
Secretary for Oil and Gas
Technology
U.S. Dept. of Energy
Mail S-top D-107
Washington, DC 20545

C. H. Atkinson
U.S. Dept. of Energy
Nevada Operations Office
P. 0. Box 14100
Las Vegas, NV 89114

R. T. Johansen
D. C. Ward
H. B. Carroll
A. B. Crawley
J. B. Jennings (6)
M. Loew
U.S. Dept. of Energy
Bartlesville Energy
Technology Center
Bartlesville, OK 74003

L. A. Schrider
C. D. Locke
A. E. Hunt
C. A. Komar
R. D. Manilla
U.S. Dept. of Energy
Morgantown Energy
Technology Center
Morgantown, WV 26505

R. L. Mann (3)
CER, Inc.
P. 0. Box 15090
Las Vegas, NV 89114

J. C. Sharer
Gas Research Institute
10 West 35th Street
Chicago, IL 60616

1110 J. D. Plimpton
1111 C. W. Smith
1112 C. R. Mehl
1130 H. E. Viney
Attn: B. G. Edwards, 1131
W. Vollendorf, 1133

4730 H. M. Stoller
4732 D. A. Northrop
4732 N. R. Warpinski
4732 R. A. Schmidt
4732 C. L. Stein
4732 J. A. Clark
4732 A. R. Sattler
4732 R. W. Ostensen
4733 C. L. Schuster
4733 T. L. Dobecki
4733 P. C. Lysne
4734 A. L. Stevens
5532 B. M. Butcher
Attn: L. W. Teufel
L. S. Costin