FRAC MAPPING BY SURFACE ELECTRICAL TECHNIQUES

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ABSTRACT

Geophysical diagnostic techniques are being developed to characterize massive hydraulic fractures. The surface electrical potential technique has been used by Sandia Laboratories in cooperation with industry at several locations in the United States. Comparison of field data to model calculations shows that the electrical potential gradients produced by the direct electrical excitation of the fracture well and fracture fluid can be used to map and characterize massive hydraulic fractures. The direction and asymmetry of the fracture can be determined.

INTRODUCTION

In April 1973, a special Natural Gas Technology Task Force issued a preliminary report on gas resources in the United States that cannot be exploited with standard extraction techniques.[1]

The low permeability of the gas-bearing sands in some regions dictates that massive hydraulic fracturing (MHF) is required to provide adequate productivity. MHF consists of multi-stage sand and fluid injections that can create long fractures over a large gross pay interval. To assess the efficiency of the MHF process, characterization information is needed on the azimuthal, length and height of the permeable portion of the hydraulic fractures. Considering production applications of MHF, similar information is needed to affect optium well placement to achieve overall efficient drainage.[2,3]

Sandia Laboratories is currently developing geophysical diagnostic techniques to characterize and map massive hydraulic fractures. These techniques include the use of passive seismic signals created by the fracture and surface electrical potentials created by injecting current into the casing of the fracture well.

Early experiments with both techniques conducted in cooperation with the El Paso Natural Gas (EPNG) Company have previously been reported.[4] A more detailed description of the surface potential technique has been presented.[5] In this paper, a conspectus of the modeling and field results of recent tests for the surface potential technique will be given.

The surface electrical potential technique consists of measuring potential gradients at the surface of the earth. The well casing along with the associated fracture when filled with a conducting fluid acts as the induced current electrode and a remote well casing as the current return. As the fracture progresses, the potential gradient changes at the surface due to changes in the electrode geometry. The potential gradients are measured before, during, and after the fracturing and are compared to determine fracture orientation and asymmetries.

MATHEMATICAL ANALYSIS

To aid in the interpretation of the field data, mathematical modeling efforts were undertaken. The initial approach treated the well casings and the fluid filled fracture as perfectly conducting line sources in an infinite isotropic and homogeneous medium. For a nonhomogeneous medium a resistance ladder network was used to apportion the current densities on the fracture well casing and the fluid filled fracture. Because of limitations imposed by the initial model, a second modeling effort was undertaken that utilizes the Green's function integral approach where the so-called half-space Green's function is used. An extensive description of the Green's function model that has been developed is reported elsewhere;[5,6] consequently, this paper will only summarize some of the calculations which can be used to aid in the interpretation of the field data.

The schematic layout for the model is shown in Figure 1. The potential difference ($\Delta\phi$) that exists at the surface at radii R_1 and R_2 as a function of fracturing conditions are calculated on the basis of the model. $\Delta\phi_B$ is the potential difference calculated between R_1 and R_2 before the fracture and $\Delta\phi_A$ represents the calculation after fracturing. The change in potential gradient for various angles around the well is defined:

$$V(\theta) = \Delta\phi_A - \Delta\phi_B$$

A plot of $V(\theta)$ for selected R_1 and R_2 and fracture length ℓ' and ℓ'' are shown in Figure 2. For the calculations here the fracture is oriented in the 90^o to 270^o direction. The various curves in the figure represent the degree of asymmetry of the fracture. For the 0.50 curve, the fracture is symmetric and there are two cycles within the 360^o. The 1.00 curve denotes the total fracture in the 90^o direction. Also note that the asymmetric curves (.667, .75, 1.0) show a change in potential gradient to be one cycle for 360^o. For an asymmetric fracture the largest negative value of the cycle occurs in the direction of the major part of the fracture while the smallest negative value of the cycle is in the direction of the minor part. For these conditions the induced current was injected at the fracture well casing on the surface of the earth. Calculations have been made for the current injected into the fracture. The results for a down hole currents source are similar to those for the current injected at the surface.

EXPERIMENTAL TECHNIQUES

The potential field was created by inducing current flow through the earth. Pulsed DC current from a series of batteries was used where the pulse duration was three seconds and the direction of current flow was reversed during each measurement to eliminate polarization effects. The current pulse was induced directly into the wellhead at the surface of the earth for some of the tests, while for others the current was injected directly into the fracture zone with a down hole probe. The return line was attached to a well casing which varied from 1 - 2 miles in distance.

The surface potential data were taken by recording the potential differences between 24 pairs of voltage electrodes (probes) around the wellhead (Figure 3). The 24 pairs of probes were placed circumferentially around the well with an inner probe radius of R_1 and an outer probe radius of R_2. R_1 remained at approximately 1800 feet for most of the tests and R_2 varied from 2300 feet fo 4000 feet. In early tests, each probe consisted of a copper rod inserted into a saturated solution of copper sulphate. The solution was allowed to seep slowly through a ceramic filter into the ground to insure a good electrical contact. Because of poor control on the rate of seepage of the solution, this type of probe has been replaced by a simple metal stake.

The induced current and the data collection were controlled from the instrumentation van. The potential difference between the inner and outer stakes at each location was transmitted to the van where it was recorded and measured. The output for the stake-pair locations were frequency multiplexed sequentially and the data carried via coax cable into the instrumentation van.

A mini-computer initiated the entire sequence of one complete set of data measurements. The three second current pulse was initiated, and after a one second delay each data channel was sampled 20 times at 25 millisecond intervals. This sampling was repeated for the reverse current flow. A large number of potential measurements were made before, during, and after the fractures to obtain good averages. The potential for each position was taken as the difference between the sampled positive pulse and the negative pulse. The voltage and the current used to create the potential field were measured in the same manner. The output data are the normalized potentials which are the potential differences divided by the current.

EXPERIMENTAL RESULTS

Field data have been obtained on six fracturing operations in three locations. The fractures were conducted by EPNG at the Pinedale field in Wyoming, by Amoco at the Wattenberg field in Colorado, and by Columbia Gas south of Huntington, West Virginia.

Conclusions have been drawn concerning the fracture characteristics in the earlier tests (EPNG) from the surface potential gradient technique, however interpretation of the data was made more difficult because the early diagnostic technique was less sophisticated. Although the data from the Wattenberg field tests are also developmental in nature, they were obtained with an improved measurement system. Consequently, only the Wattenberg field data from the Well C test will be discussed to illustrate the capabilities of the surface potential gradient technique.

The potential probe placement has been described. The probe radii for the Well C were 1800 feet and 4000 feet. The current was injected at the open hole fracture depth of approximately 8000 feet. A sinker bar was electrically connected to the center conductor of a standard wire line and in turn, connected to the current pulser. The return current line was attached at two wells -- one located approximatley 1.5 miles to the northwest and the second located approximately 1.5 miles to the southeast.

Figure 4 shows the change in potential gradient, pre-test to post-test. The data clearly shows a one cycle change, indicating an asymmetrical fracture was formed. The minima in the cycle (major fracture length) occurs in the NW quadrant while the cycle maxima (minor fracture length) lies in the SE direction.

A further analysis of the data was made in order to determine the progressive growth of the fracture as a function of the fracturing fluid injected into the formation. Figure 5 shows the plot of the fracture fluid volume versus time of day. Five groups of data were averaged in the same manner as the previous plot. The first group is used as the reference (before-fracture) measurement. Subsequent groups of data are taken in approximately 75,000 gallon increments. A plot of these groups is clearly shown and this represents the major frac length being in the northwest direction. The reversal in the northwest quadrant is not clearly understood, but could be caused by the total length being increased while the degree of asymmetry is changing.

CONCLUSIONS

Although the modeling is based on a homogeneous and isotropic earth, the results are expected to describe the behavior of the surface potentials for mapping and characterization of massive hydraulic fractures. Comparison of the model calculations and field data has shown that the surface potential gradient technique can be used to determine the orientation of hydraulically-created fractures as well as the ability to indicate degree and direction of asymmetrical fractures. Further refinements in the diagnostic system, continues numerical modeling studies, and utilization of calibration field experiments should allow the surface potential gradient technique to quantiatively characterize the dimensions of fracture systems.

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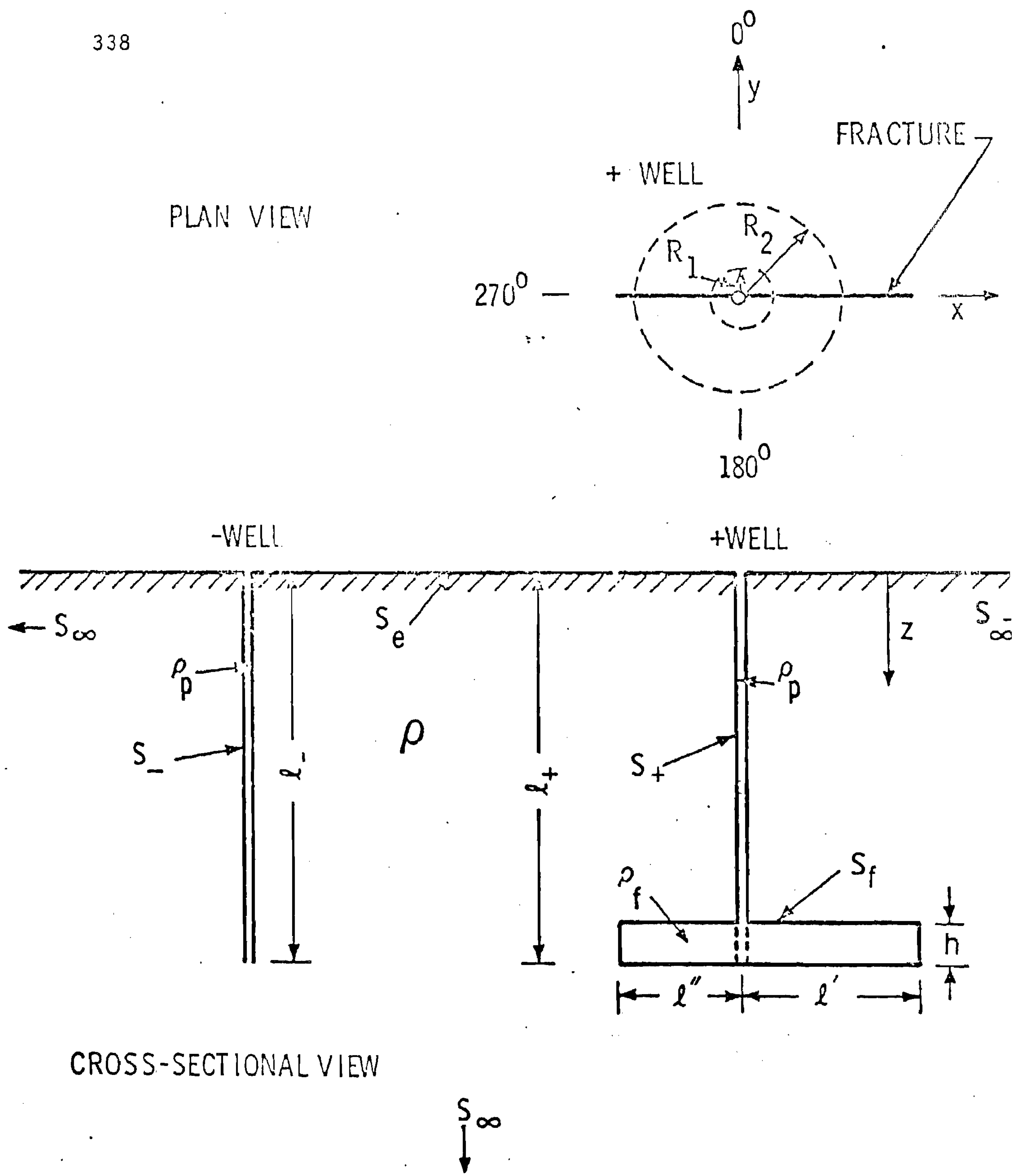

Fig. 1 - Schematic Layout of the Model Calculations.

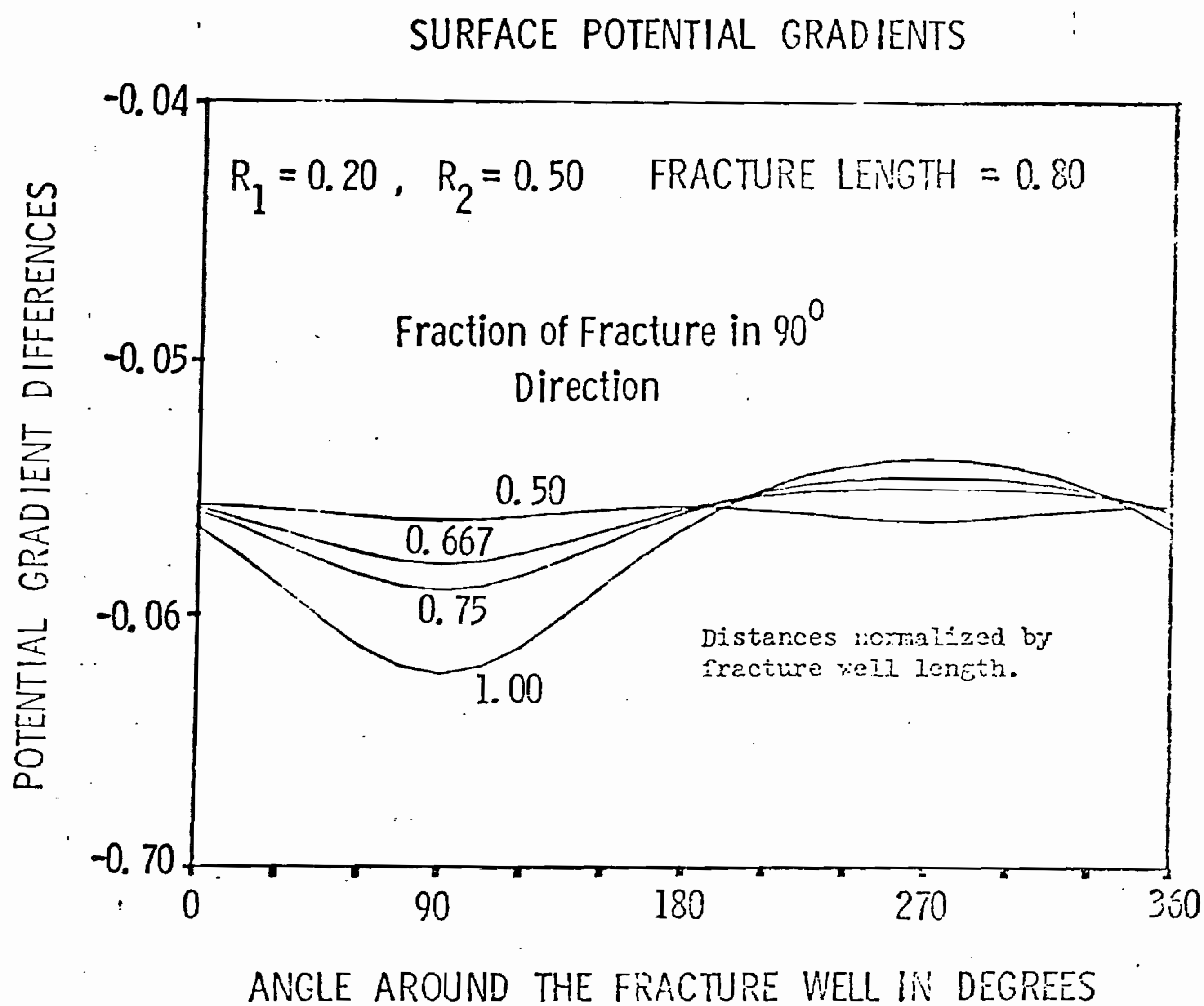

Fig. 2 - Difference in Potential Gradient V(Θ) (after fracture minus before fracture) as a Function of Angle Around Fracture Well.

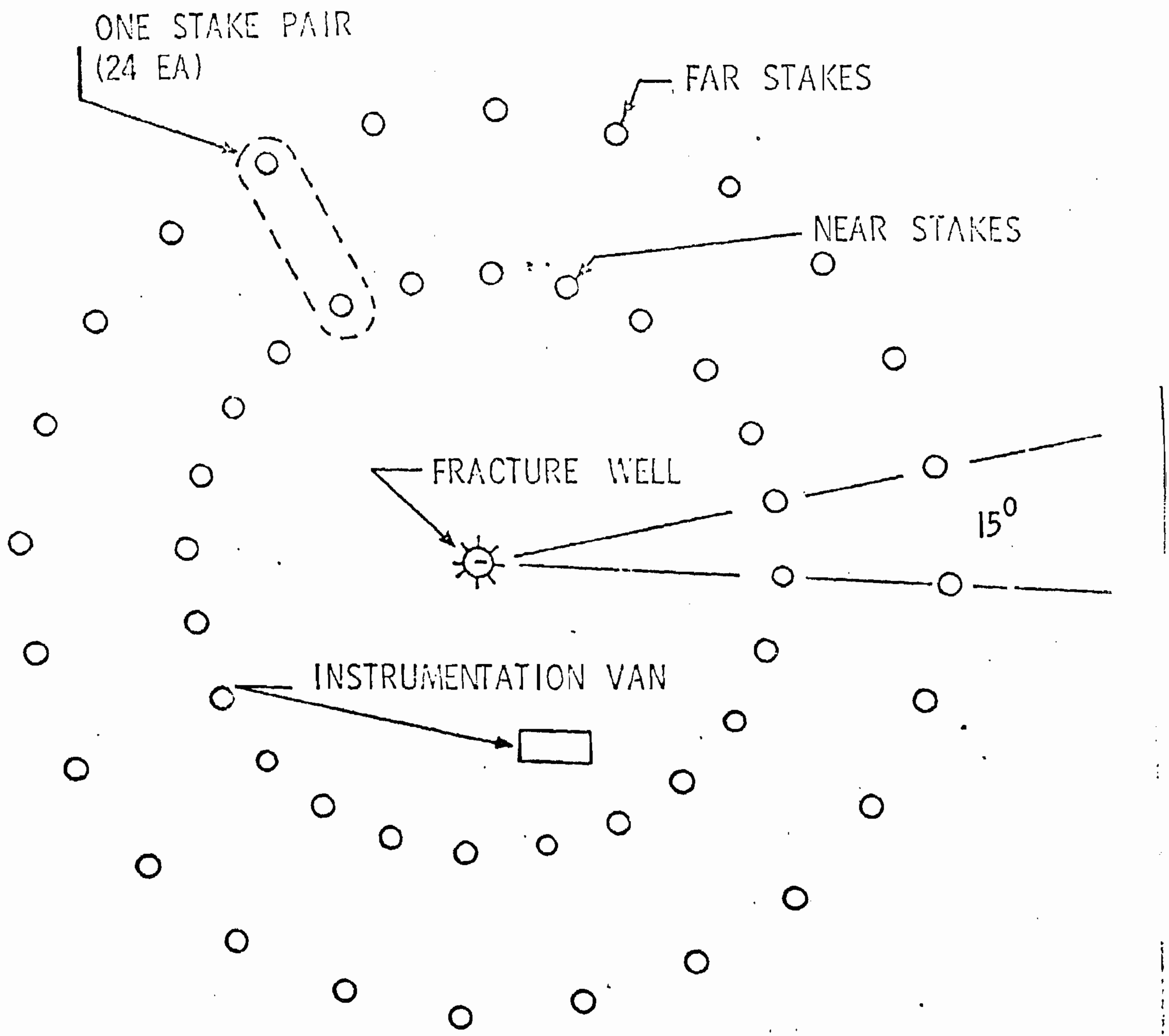

Fig. 3 - Layout of the Surface Potential Instrumentation.

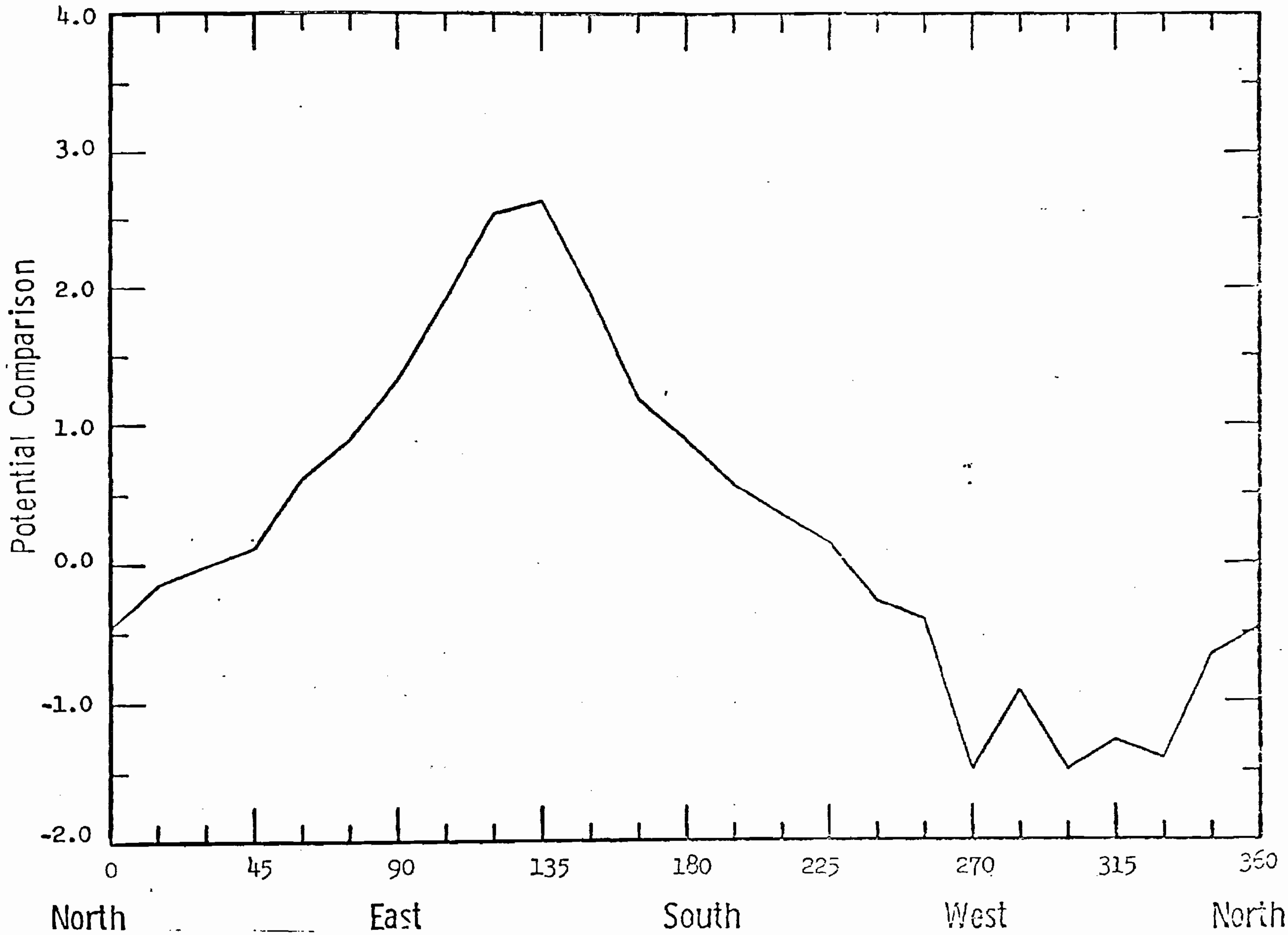

Fig. 4 - Potential Comparison as a Function of Direction for the Wattenberg Well C Fracture, January 27, 1976.

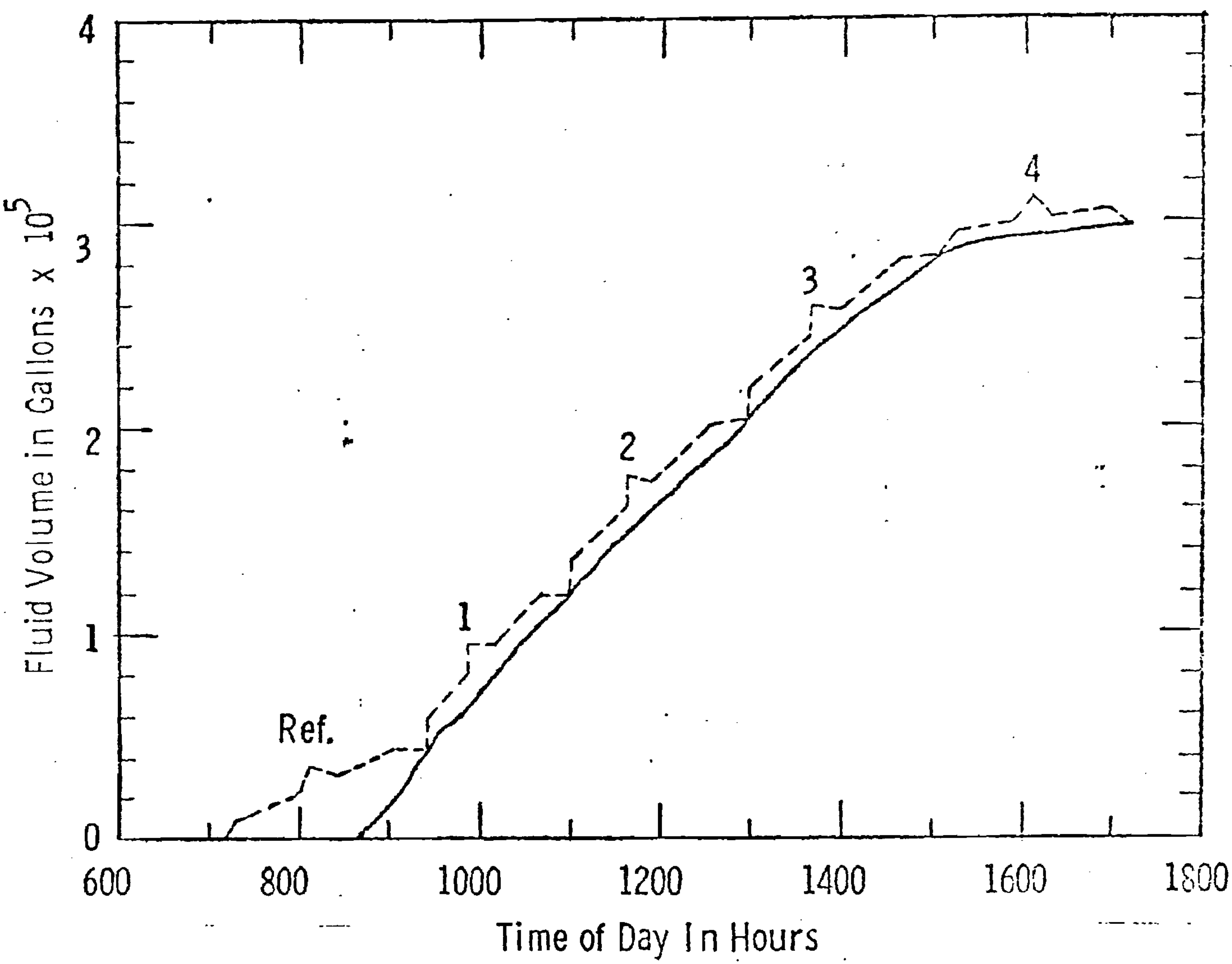

Fig. 5 - Fluid Volume vs. Time of Day for the Wattenberg Well C Fracture, January 27, 1976.

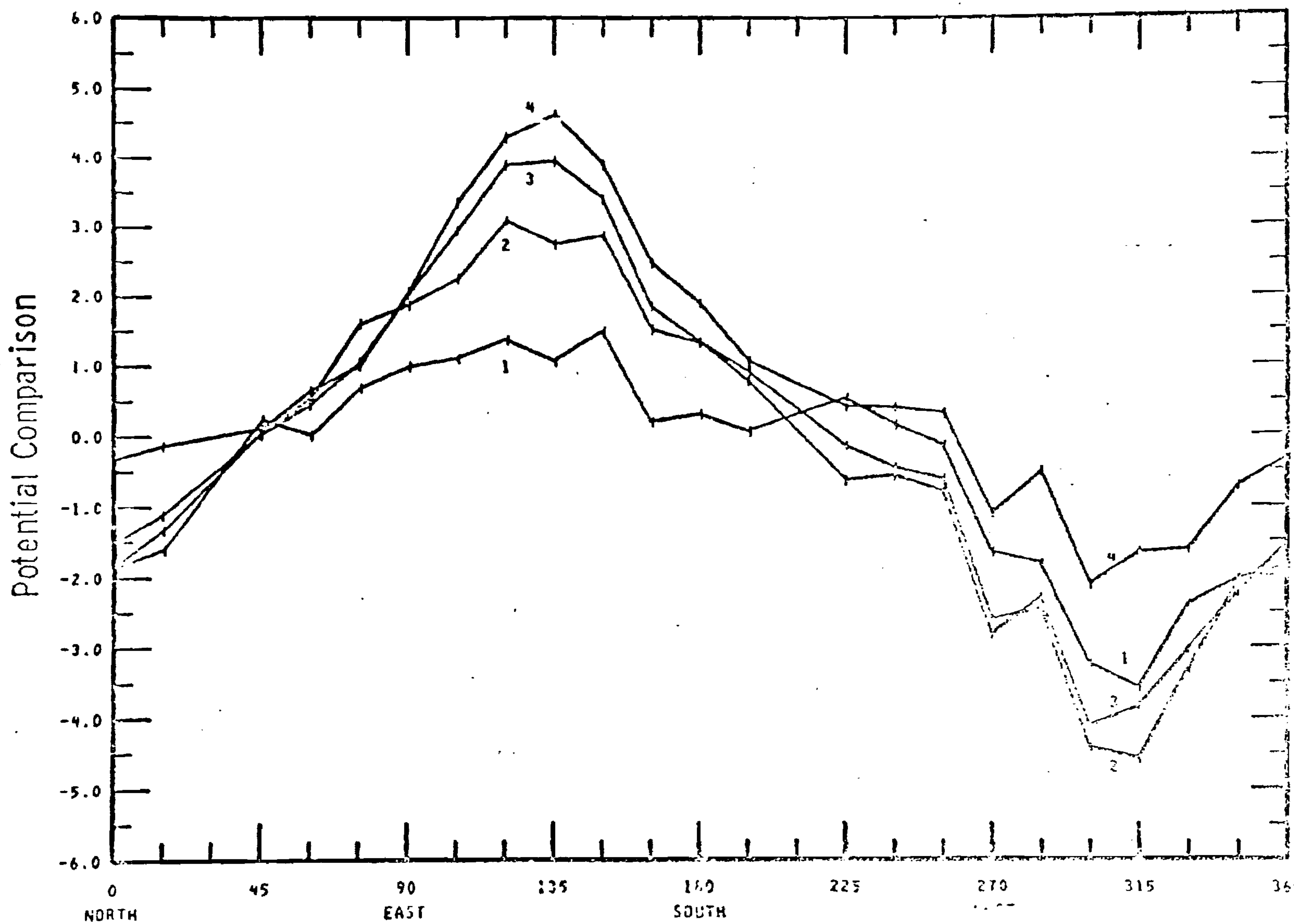

Fig. 6 - Progressive Growth of Fracture as a Function of Direction for the Wattenberg Well C Fracture, January 27, 1976.

OPEN DISCUSSION OF:
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GIDLEY EXXON	What is the source of potential difference in the well prior to its being fractured? Are you imposing an electrical potential on the well so that you can measure that.
ANSWER	Yes.
GIDLEY EXXON	It requires no placement of a different fluid in the well or anything of that sort.
ANSWER	We recommend the fluid being conductive to see the change after the fracture. Of course, if the fracture fluid contains a few percent KCl water then it is a very conductive fluid. We are looking for that change in current-electrode geometry as reflected by the conductive fluid being there.
GIDLEY EXXON	You do have a conductive fluid in there to observe these changes.
ANSWER	Yes.
SCHONFELDT OCCIDENTAL	How deep can you go with this method. What is the limiting depths?
ANSWER	We really don't know. We do not have enough experimental data to tell us yet and our model just isn't big enough to tell us what

kind of signal/noise ratio we might expect and at what depth. It is a function of the depth versus the length of the fracture. Of course, if the fracture is really short you won't see it. However, if the length is a sizeable portion of the depth then you probably have a good chance of seeing it at the surface.

SCHONFELDT OCCIDENTAL How deep was the hole that you got this data from?

ANSWER This data came in an 8000' hole. This is a Wattenberg Muddy J.

SCHONFELDT OCCIDENTAL One more question. Can you differentiate between a horizontal crack and a vertical crack.

ANSWER I don't think so.

QUESTION I have a question about the continuation or the propagation of the fracture after pumping is ceased. Do you see any evidence of this?

ANSWER We really haven't looked for it.

QUESTION Do you mean the next day or the day after? A shorter period of time afterwards, one or two hours before the well has been flowed back.

ANSWER I really haven't seen it. We haven't been able to dig it out of the noise.

COMMENT One observation will help clarify the next question a little bit. When Carl started this work we had the fortuitous situation of where we started the research and he has been able to continue the research in areas where you do not have brine aquifers between the surface and the fracture. When you have a brine aquifer with a conductivity higher than the electrical conductivity of your fracture fluid, then you really get shorted out. I think that the existence of a brine aquifer with a salinity of overlying aquifers is of overwhelming importance. It is not the depth itself. One of the reasons why we really need to get this layered model done is to find out answers to this kind of question. Can it work? How well would it work? How does this brine aquifer affect it?