UCID-20613

Remote Sensing of Rock Fractures by Shear Wave Reflections: A Progress Report

J. R. Hearst
N. R. Burkhard
R. C. Carlson
T. F. Hauk

Prepared for
Morgantown Energy Technology Center
Morgantown, WV

January, 1986

Lawrence Livermore National Laboratory

Unconventional Gas Program

Eastern Devonian Shales Research

INDEX

ABSTRACT

For stimulation of gas wells in the Devonian shales, it is desirable to be able to locate the natural rock fractures. These gas bearing fractures are vertical and usually do not intersect the wells. The objective of this project is to provide remote sensing of fractures which do not intercept wells, by using sonic reflection. A previous effort based on P-waves was not successful. This new effort concentrates on shear waves. Shear-wave transducers, 10 cm long, were built for us by Southwest Research Institute. They were designed to operate at 20 kHz, so that the wavelength, in hard rock, would be approximately the same as the transducer length. The transducers did indeed produce shear waves with a visible frequency of about 20 kHz. The transducers were designed to minimize strength of the direct wave. We tested the transducers on granite slabs, attempting to observe reflections from a free surface. We used common-depth-point stacking to enhance reflected signals. The direct wave was considerably shorter than that seen with the transducers used in the past, and we observed events at the times at which reflections would be expected. The success with the optimal reflectors needs to be confirmed with real in-situ conditions. Future proof-of-concept tests should take place at an actual rock site. This could be the granite quarry where the 1983 field tests were performed.

1. INTRODUCTION

This research is part of the Unconventional Gas Program at LLNL (Heuze, 1986). Geological evidence and production history indicates that much of the gas in the Devonian shales is contained in natural fracture systems. There is also evidence from cores and logs that a large fraction of these fractures are near vertical. Clearly, if the fracture system in a reservoir is near-vertical very few of the fractures will intersect a vertical borehole. It is common practice to increase production from the Devonian shales by stimulation; either explosive-induced or hydraulic fracturing. The artificial fractures connect the borehole to remote natural fractures, and thus provide access to much more gas. The natural fractures do not exist at all depths in the formation, and often one does not know at what depths they occur. Consequently, operators often stimulate throughout the entire depth range of the formations believed to contain gas. The cost of stimulation could be reduced, and much well damage prevented, if the natural fracture systems were located before the stimulation was started.

It has been difficult to locate the natural fractures. There is no accepted method for location of fractures that do not intersect the borehole, although Hanson et al (1979) have attempted to use a modification of the conventional full-wave acoustic logging technique. Even for fractures that do intersect the hole, conventional methods are not always reliable (Koerperich, 1978, Paillet, 1980, 1981). In particular, none of the methods in current use is designed for dry boreholes, and the holes in the Devonian shales are drilled dry since liquids can damage the formation.

In a previous report, we described tests of a dry-borehole P-wave seismic reflection system (Hearst and Burkhard, 1983). The system, acquired in 1978, was designed to locate natural near-vertical fractures that do not intersect boreholes. We tested the system on the surface in a granite quarry, and attempted to detect known horizontal fractures between 0.6 and 6 m below the surface. We could not detect reflected waves from any of the fractures. We proposed two possible explanations for the problem: either the reflection coefficient of the fractures was so small that no significant reflected wave was produced, or the signal going on a straight path from transmitter to receiver (the direct, or surface wave) was so large that it obscured the reflected wave.

We then tested the system on concrete blocks, where the reflector was the side of the block away from the system. In that case the reflection coefficient of the free surface was 1.0, so only the direct wave effect would be present. A very weak reflection was seen only when the reflected wave arrived before the surface wave, and the gain of the receiver was sufficiently high, but this gain caused the surface wave to saturate the electronics. It would have been impossible to observe the reflection if it were coincident with a surface wave, or even if one did not know when to expect it. Since even with a perfect reflector it was difficult to observe the reflection, we could reach no conclusion as to the effect of the small reflection coefficient of the fracture.

Meanwhile, we learned that Palmer et al (1981) had succeeded in locating fractures in the laboratory with shear waves. They had been unable to locate the fractures with compressional waves; the type used in our system. We therefore proposed to test shear wave transducers that might be suitable for our geometry. Palmer et al used transducers with energy fairly evenly distributed in a frequency band between 10 and 120 kHz, compared to the 2.5 kHz used in our system, and their transducers were larger than a wavelength in diameter. A transmitter whose size approximated a wavelength would be less likely to produce strong direct waves. Attenuation goes inversely with frequency; consequently the lower the frequency the greater the depth of penetration. We therefore proposed to build the largest plausible transducer that might be installed in our downhole system, and which could be vibrated at a frequency f such that $\ell = v/f$, where ℓ is the length of the transducer and v the sound velocity expected in the rock. We planned to build transducers with a resonant frequency of about 25 kHz and a size of about 14 cm. This report describes the design of the shear wave transducers, and the results of tests on granite blocks.

While construction of the transducers was in progress, Palmer (1982) published results of tests of his shear wave system in the same quarry, and was unable to locate fractures. He attributed the difficulty to variation in water content of the rock causing Love waves, which interfered with the reflection. We do not know if this explanation is correct.

2. THE TRANSDUCERS

Shear wave transducers were designed and built to our specifications by Southwest Research Institute. Figure 1 is a photograph of a typical transducer (transmitter and receivers are identical in appearance) and Fig. 2 is a drawing.

The 10-cm-long jagged edge of the transducer contacts the rock. It was hoped that such an edge would be better than a solid edge at being able to make contact with a rough surface, and would act as an array, which should help in reducing the direct wave. The vibration of the transmitter is horizontal, perpendicular to the long edge. Consequently, shear waves with vibrations transverse to the long edge are produced on the surface in the direction of the long edge, and going down into the rock. A compressional wave traveling parallel to the surface and perpendicular to the edge is also produced. The receiver is sensitive to the shear waves traveling on the surface, along its length, or coming up from below, and to the compressional waves parallel to the surface and perpendicular to its length.

The transmitter was excited by a single pulse about 80 microseconds long. On a granite block, we observed a direct wave with a frequency of approximately 20 kHz and a length of about 0.6 ms. This is contrasted to a length of about 3 ms for the direct waves observed with the original system. The wavelength of the signal was about 12 cm, approximately the same as the 10 cm length of the transmitter. It therefore appears that the transducers performed as designed, and that the direct wave, for wavelengths comparable to the transmitter length, was greatly reduced.

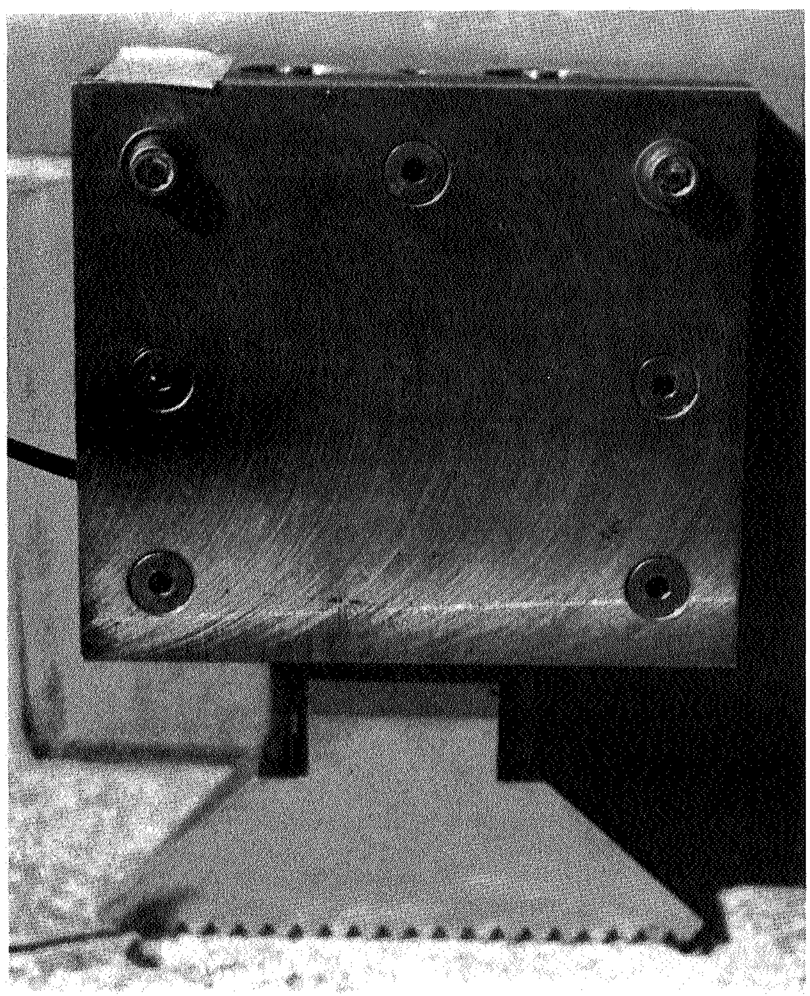

Figure 1. Shear Wave Transducer Designed and Built in Cooperation with Southwest Research Institute.

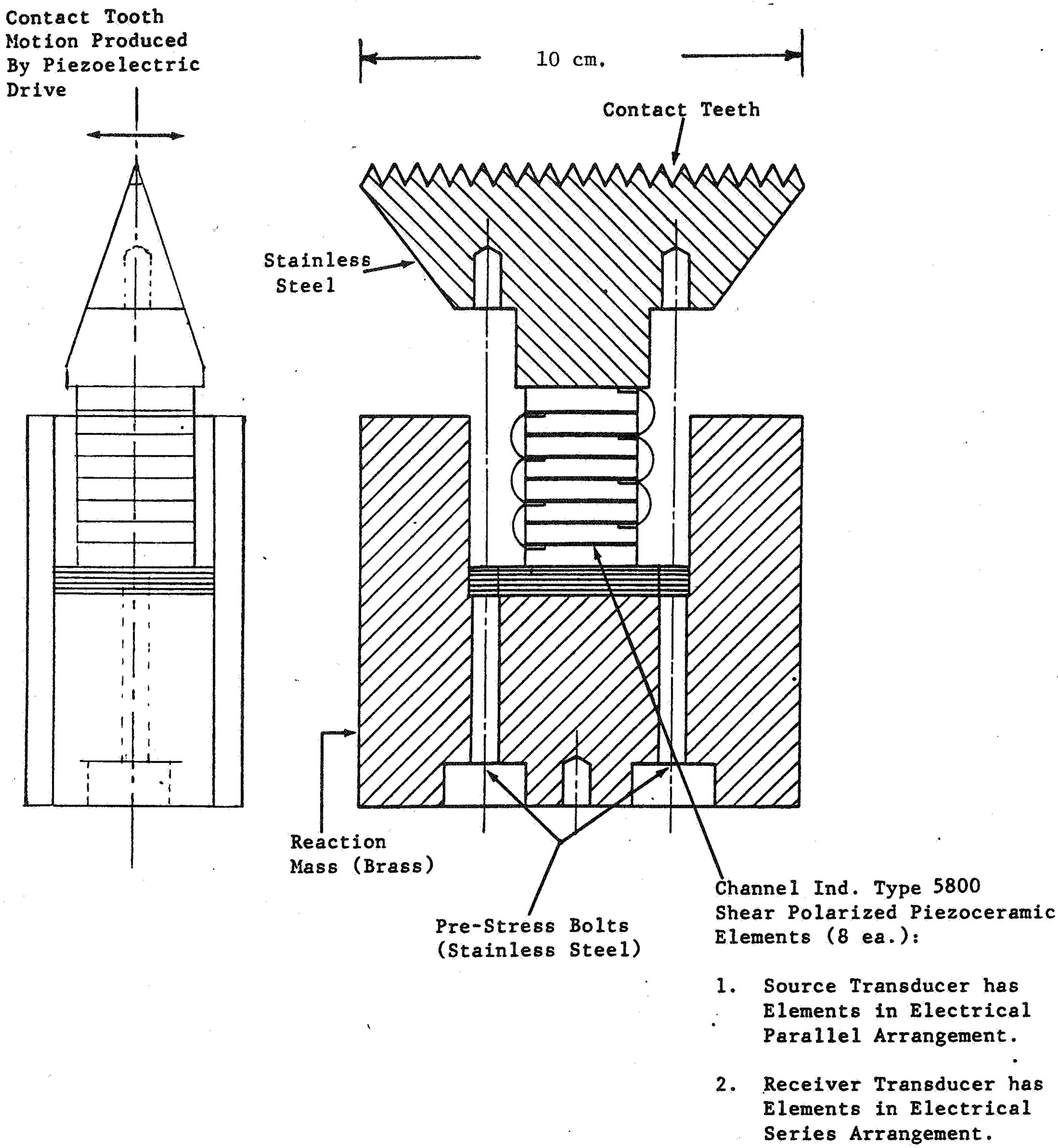

Figure 2. Shear Wave Transducer Design and Assembly
(Courtesy of Southwest Research Institute).

3. REFLECTION TESTS

The transducers were tested on two granite slabs (actually optical benches). Both were 3 m long and 1.5 m wide. One was 30 cm thick; the other was 62 cm thick. Shear wave velocity was measured by placing the transmitter on the top of each slab, and the receiver on the bottom, determining the transit time for each, and then taking the difference in transit times. This difference was 0.125 ms, giving a velocity of 2560 m/s. An instrument delay of 0.048 ms was observed.

The transducers were then aligned on each slab, with the long edge of the transducers collinear, as shown in Fig. 3 (they were, however, centered in the slab, parallel to the long axis). They were initially 25 cm apart, and the spacing was increased in 5 cm steps. The received signals were adjusted in time so that the leading edges of the first arrival of each signal were aligned.

Figure 3. S-Wave Transmitter and Receiver on a Granite Slab.

The results are shown on Figs. 4 and 5. On each record, the white line shows an event with arrival times appropriate to a reflection from the bottom of the slab.

It was, however, difficult to pick out the event. We therefore used a standard procedure called "common-depth-point stacking" or "CDP stacking" to enhance the results. The experiment was repeated, with spacings between 15 and 100 cm, and the signals recorded on tape. Then for each record, a new record was constructed, on which the amplitude at each time T_o on the new record was equal to the amplitude at time T_x on the original record, and

$$T_x^2 = T_o^2 + (x/v)^2$$

where x is the distance between transducers and v is the shear velocity, 2560 m/s. Then the amplitudes of all the new records were summed to produce a single stacked record.

4. RESULTS AND DISCUSSION

The stacked records are shown in Figures 6 and 7. A number of events are seen on each record. On Fig. 6, the event at 0.234 ms is at the time at which one would expect a reflection from the bottom of the slab, and the event at 0.465 ms is the time at which a double bounce between top and bottom would be expected. The event at 0.55 ms is consistent with a reflection from the side of the slab. The provenance of other events is not known. There are many possible paths in a slab. Note that the compressional arrivals will not be seen on the stacked record.

On Fig. 7, the event at 0.472 ms is very close to the expected time for the reflection from the bottom, that at 0.943 ms is close to the double bounce time, and that at 0.562 ms is right for a reflection from the side. Again, there are other, unexplained, events. Note that in Fig. 7 the first arrival energy seems to be decaying rapidly until the arrival of the reflection. This would not be seen in Fig. 6, because the reflection arrives before the decay.

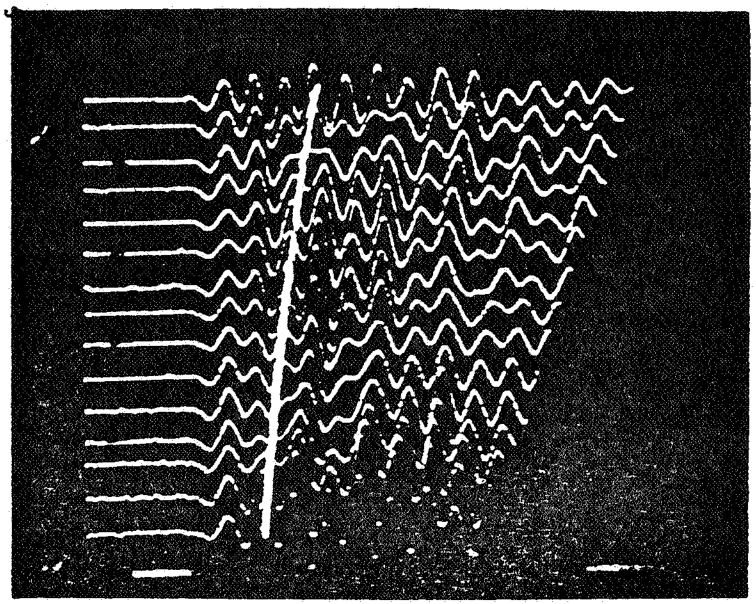

Figure 4. Aligned Traces on the 30-cm Block.

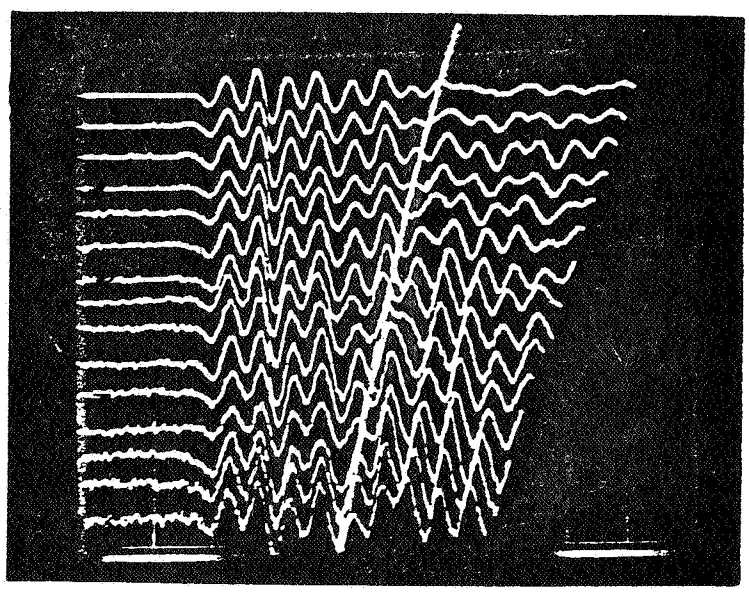

Figure 5. Aligned Traces on the 62-cm Block.

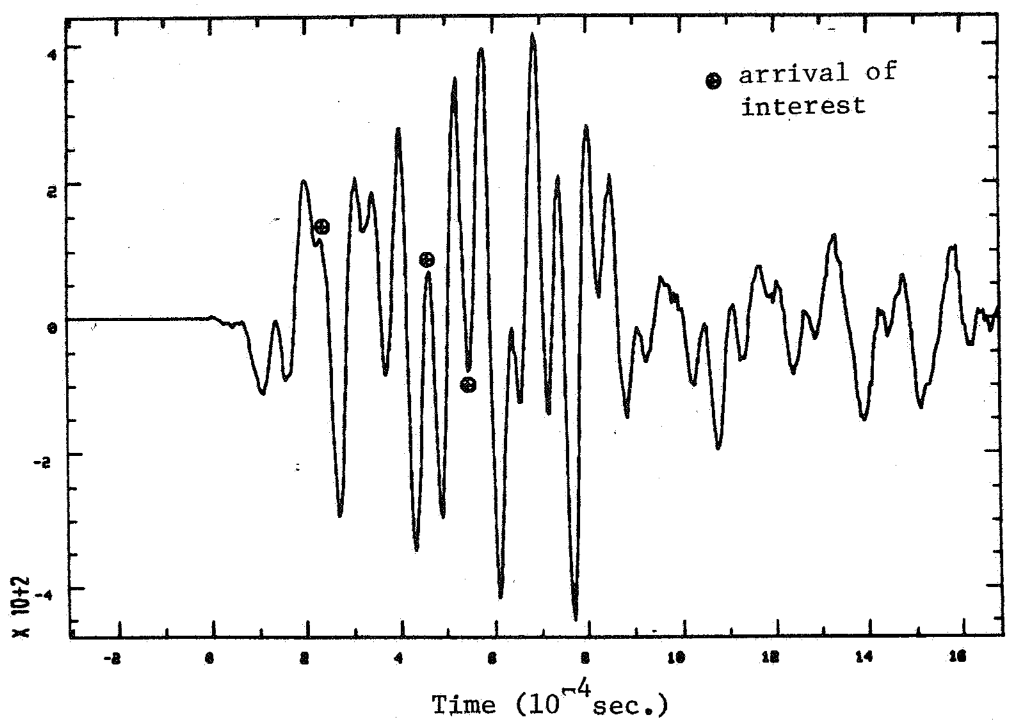

Fig. 6. Stacked Signals from the 30-cm Block.

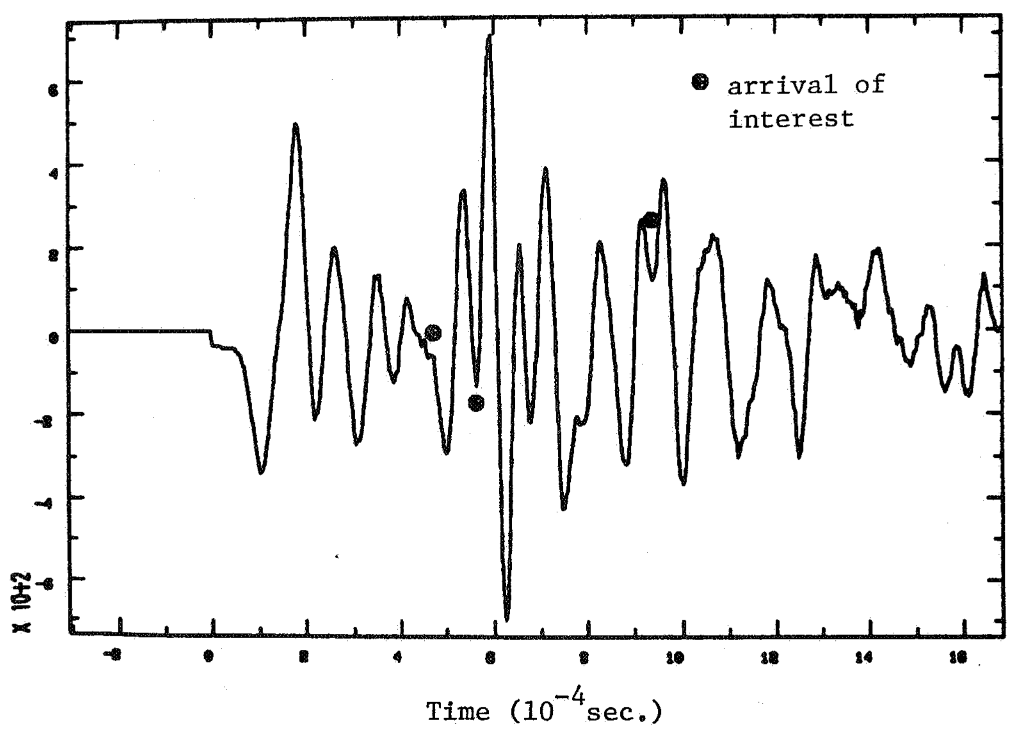

Fig. 7. Stacked Signals from the 62-cm Block.

Of course, we cannot be sure that the apparent events observed in the stacked records are in fact the reflections described. In fact, had we not known where to look, we would not have chosen those events as being particularly significant. If we are to detect fractures in real field situations, the reflections must arrive after most of the direct wave energy is gone. We see from the original records that the direct wave is no more than 0.6 ms long, and perhaps, looking at the stacked signal, only half of that. Consequently, strong reflections arriving after about 0.6 ms should, in the absence of earlier reflections, be visible in the stacked record. Evidently, reflections arriving after 1 ms should be visible in any case. This time corresponds to a distance of about 1.25 m. In reality, we are interested in reflectors at such distances and greater, so the restriction is not important. Finally, it must be recognized that this experiment used a perfect reflector, not a fracture.

5. CONCLUSIONS

These results raise two important questions:

- how well can we identify signals reflected from real rock fractures?
- how does the ability to identify the signals decrease with distance to the fractures?

These can best be answered by going to a site with fractures at known distances. The Raymond quarry used in the 1983 study is such a site. Future field work will depend on availability of funding.

6. REFERENCES

Hanson, M.E., Anderson, G.D., Shaffer, R.J., Towse, D.F., Hearst, J.R, Lin, W., and Cleary, M.P., ""LLL Gas Stimulation Program Quarterly Progress Report July through September 1979", UCRL-50036-79-3. 1980.

Hearst, J.R and Burkhard, N.R., "The LLNL Dry Borehole Seismic Reflection System: An Attempt at Remote Sensing of Natural Rock Fractures", Lawrence Livermore National Laboratory, UCID-19871, 1983.

Heuze, F.E., "The Unconventional Gas Program at Lawrence Livermore National Laboratory", UCID-20610, January, 1986.

Koerperich, E.A., "Investigation of Acoustic Boundary Waves and Interference Patterns as Techniques for Detecting Fractures", Jour. Pet. Tech., p 1199, 1978.

Paillet, F.L., "Acoustic Propagation in the Vicinity of Fractures which Intersect a Fluid-Filled Borehole", Trans. Soc. Prof. Well Log Analysts, 21st Logging Symposium Paper DD, July 8-11, 1980.

Paillet, F.L., Comparison of Fracture Characterization Techniques Applied to Near-Vertical Fractures in a Limestone Reservoir", Trans. Soc. Prof. Well Log Analysts, 22nd Logging Symposium Paper XX, June 23-26, 1981.

Palmer, S.P., "Fracture Detection in Crystalline Rock Using Ultrasonic Reflection Techniques", Lawrence Berkeley National Laboratory, LBL-16347 (2 vols), 1982.

Palmer, S.P., Smith, J.A. and Waters, K.H., Fracture Detection in Crystalline Rock Using Ultrasonic Reflection Techniques; Int. J. Rock Mech. Min. Sci. p. 403, 1981.

7. ACKNOWLEDGEMENTS

This report was prepared by the LLNL Unconventional Gas Program for Morgantown Energy Technology Center, Morgantown, WV, under Contract W-7405-ENG-48 with the U. S. Department of Energy.

The authors are grateful to F. Heuze, at LLNL, and A. Yost, at METC, for their helpful reviews, and to S. Spataro and G. Metzger, at LLNL, for electronic support.