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Fracture detection using crosswell and single well surveys

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ABSTRACT

We recorded high-resolution (1 to 10 kHz), crosswell and single well seismic data in a shallow (15 to 35 m), water-saturated, fractured limestone sequence at Conoco's borehole test facility near Newkirk, Oklahoma. Our objective was to develop seismic methodologies for imaging gas-filled fractures in naturally fractured gas reservoirs. The crosswell (1/4 m receiver spacing, 50 to 100 m well separation) surveys used a piezoelectric source and hydrophones before, during, and after an air injection that we designed to displace water from a fracture zone. Our intent was to increase the visibility of the fracture zone to seismic imaging and to confirm previous hydrologic data that indicated a preferred pathway. For the single well seismic imaging (a piezoelectric source and an eight-element hydrophone array at 1/4 m spacing), we also recorded data before and after the air injection. The crosswell results indicate that the air did follow a preferred pathway that was predicted by hydrologic modeling. In addition, the single well seismic imaging using vertical common depth-point (CDP) gathers indicated an anomaly consistent with the anomaly location of crosswell and hydrologic inversion results. Following the field tests, a slant well was drilled and cored to confirm the existence and nature of the rock associated with the seismic anomalies. A vertical fracture was intersected within less than 1 m of where the seismic results had predicted.

INTRODUCTION

As part of its Department of Energy (DOE)/Industry cooperative program in oil and gas, Lawrence Berkeley Laboratory has an ongoing effort in cooperation with Conoco and Amoco to develop equipment, field techniques, and interpretational methods to further the practice of characterizing fractured heterogeneous reservoirs. The focus of the project is an integration of geology, rock physics, geophysics, and hydrology into a unified method for predicting fluid migration.

During the last five years, a series of joint Berkeley Lab/Conoco-Amoco seismic and well-test field experiments have been conducted at Conoco's Newkirk, Oklahoma Borehole Test Facility (Figure 1). The facility (Queen et al., 1992) contains six deep and five shallow wells used for geophysical and hydrological tests. The site occupied for the subject experiments consists of the five shallow groundwater wells (GW) in a "5-spot" pattern with the outside wells approximately 50 m from the center well (Figure 1). The shallow "GW" wells penetrate a fractured shale and limestone sequence of the Lower Permian Chase Group (Queen and Rizer, 1990). The regional dip of the formations is less than 1 degree west-southwest. As noted in Queen and Rizer (1990), two orthogonal sets of vertical fractures have been mapped from a near-surface exposure of the limestone: a systematic set striking N70°E and a nonsystematic set at N25°W. The velocity variations between the shale and the limestone at this site are sizable: contrasts of 2 to 1 exist (Harlan, 1990; Lines et al., 1992). Figure 2 shows a velocity log derived from well GW-3 which illustrates the strong velocity variation between the shale (low velocity) above and below the high-velocity Fort Riley limestone. The work described in this paper is focused on the Fort Riley limestone, a 10 to 15 m thick fractured formation approximately 15 m below the surface.

Prior to the work described here we had carried out several seismic crosswell and interference tests in the GW wells. The results of these initial crosswell seismic and hydrologic interpretations indicated that there is strong evidence for conductive fractures trending N70°E (Datta-Gupta et al., 1994). Specifically, the pump tests showed that wells GW-5 and GW-2 seemed to be connected by a "fast path"; however, wells GW-3, 2, and 1 were not as well connected to each other, or to wells GW-5 and 2. The initial seismic work (VSP and previous crosshole

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in the GW wells) also indicated seismic anisotropy consistent with the mapped fracture direction of N70°E.

In addition to the seismic and hydrologic evidence for a fast-path fracture system between GW-2 and GW-5, a single vertical fracture was observed in the core from GW-5 in the lower part of the Fort Riley limestone. The dominant fracture direction inferred from the initial seismic and hydrologic data collected by us was consistent with the stress and geologic data obtained in Queen and Rizer (1990). Preliminary crosshole work also indicated that there may be a reflector (possibly a vertical fracture striking NE?) in the subsurface a few meters north of GW-3. Considering the pump test data, the character of fractures mapped in the near by outcrops, and the seismic anisotropy together, we felt that there was strong evidence for a fracture controlled transport system. However, it was clear from the initial work that we had not unambiguously identified an individual "target" fracture or fracture system that was responsible for the hydrologic results that showed a "fast path" between GW-5 and GW-2.

To enhance the seismic visibility of the suspected fracture or fracture system, we decided to inject air into the formation. The assumption was that the air would travel in the permeable feature and hopefully increase the reflectivity and/or attenuation properties of the fractures. The plan was to inject air into GW-5 and draw down GW-2 below the Fort Riley formation, in an attempt to force air into the assumed fracture or fracture system. If there is a fast fracture path from GW-5 to GW-2, then

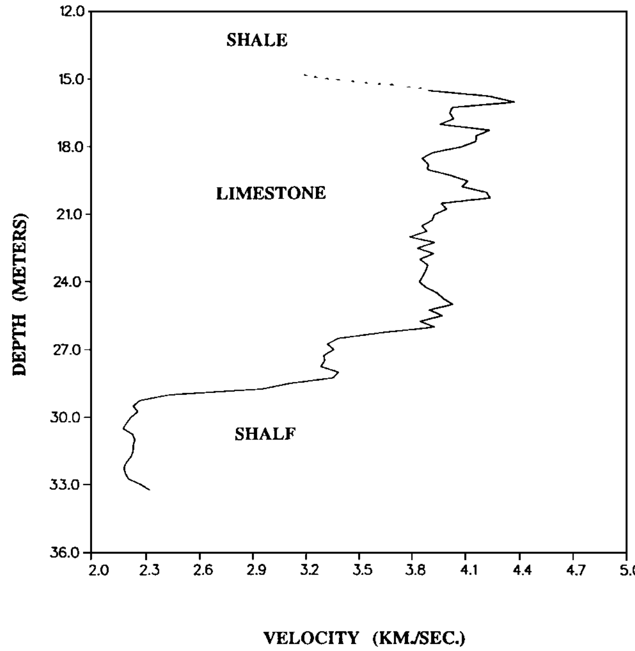

FIG. 2. P-wave velocity log as a function of depth in well GW-3 as derived from the near-offset data in the single well survey. The single well and crosswell measurements were carried out over the 15 to 30 m depth range.

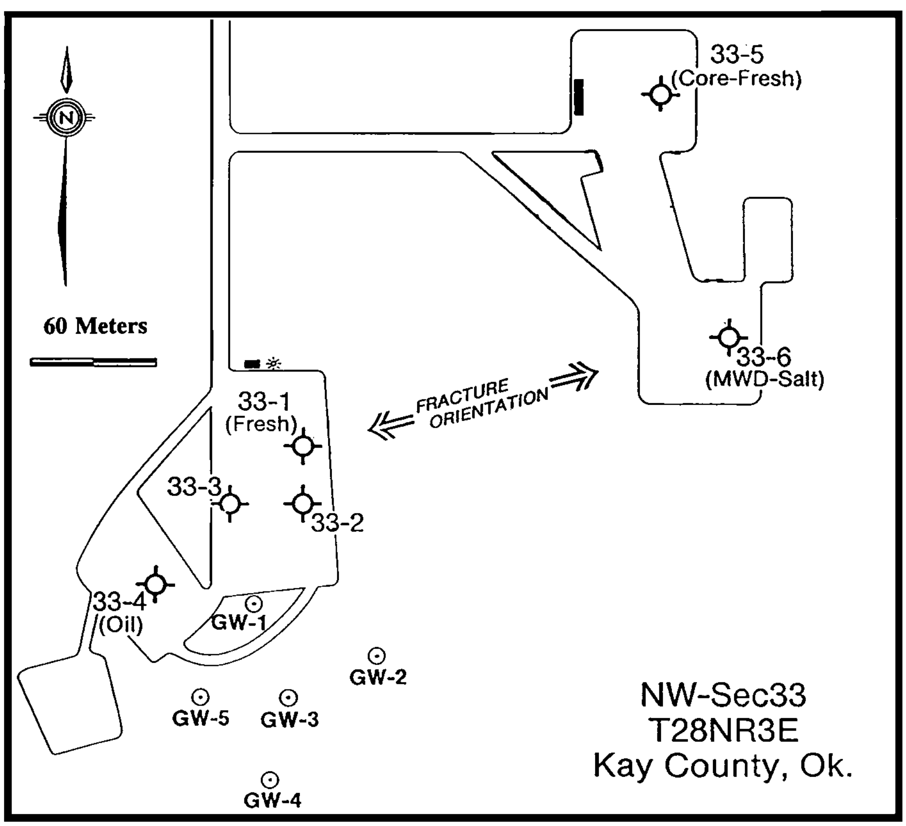

FIG. 1. Plan view of the Conoco borehole test facility located near Newkirk, Oklahoma, showing the geometry of the wells used (the GW wells) and the predominant fracture direction as inferred from mapping nearby outcrops of the limestone formation in which the seismic imaging was performed.

air would possibly follow that path and provide an improved seismic target.

FIELD EXPERIMENT

In June of 1994 the air injection experiment was carried out. The concept was to seismically image the "before," "during," and "after" experiment. The GW wells had been completed with slotted PVC casing and a sand backing through the Fort Riley limestone sequence. Above and below the limestone the wells were completed with unslotted PVC casing and bentonite behind the casing. Well GW-5 was isolated by putting packers at the top and bottom section of the slotted zone. A pipe extending through the packers and perforated over the length of the packed off zone was used to inject air uniformly over the region isolated by packers. An air compressor rated at 3.4 bars (50 psi) was used to inject the air. (We were, however, careful to keep the air injection pressure below the parting pressure of the formation, using a value of 1 psi/ft (0.07 bar/.3 m) as the parting pressure. The intent was to displace water with air rather than create new fractures or pathways.) This was a rather crude means of air injection, but this was not meant to be a precise injection of air for inferring transport behavior, but only to increase the seismic visibility of the conductive fractures. During the air injection a pump was placed in the bottom of GW-2 to keep the water level in GW-2 below the bottom of the limestone, in order to create a negative pressure gradient in GW-2 which would encourage flow of the air from GW-5 toward GW-2.

Before the air was injected, a series of crosswell seismic measurements were recorded between the center well and each of the outer GW wells. The procedure for the crosshole measurements was to move the transmitter (piezoelectric) and eight-channel receiver string (hydrophones) in 1/4 m increments up the holes concurrently. The starting and ending positions for the transmitter were at the bottom and top of the Fort Riley, respectively. The starting and ending positions of the center of the eight-element hydrophone array were the same as the transmitter. The transmitter was positioned directly across from the center of the receiver string, and both were moved up the holes at the same time. Such factors as the differences in well head height (relative to sea level) and cable stretch were accounted for when the equipment was deployed and the data were reduced. All surveys utilized a high-frequency imaging system (Majer et al., 1991), a 16-bit, 12-channel system with a sampling rate of 100 000/s per channel. The power electronics deliver up to 8000 volts peak-to-peak at 4 amps into a cable of up to 1 microfarad capacitance from 500 Hz to 15 000 Hz. The power system can deliver pulse, sweep, Barker code, or any other programmable signal code. In this experiment a piezoelectric source (cylindrical bender) was used with a swept sinusoid from 1000 to 10 000 Hz over a 50 ms time window and a recording time of 80 ms at 50 000 samples/s.

Single well reflection surveys were also performed in wells GW-1 and GW-3. The procedure for acquiring the single well data was to hang the eight-element hydrophone string with 1/4 m intervals in the same well as the source. With the string of receivers fixed, the source was moved from 1 m below the bottom receiver to the approximate bottom of the Fort Riley formation at 1/4 m intervals. The receiver string was then moved up 1/4 m and the procedure repeated until the entire Fort Riley was covered. This procedure was then repeated with the source above the receiver string. The result was a multifold imaging data set using a split spread.

After these "before" surveys were completed, we began injecting air into the formation at well GW-5. The effect of the air injection on the Fort Riley formation was continuously monitored between GW-1 and GW-4 by placing the piezoelectric transmitter at the center of the Fort Riley formation in GW-1 and centering the hydrophone receiver string in the formation in GW-4 with the eight elements at 1 m spacing. The transmitter and receiver string were not moved during this monitoring. Crosswell data were taken at various time intervals over the injection period. We began using a 30 s interval but, after observing little change, we increased the time interval. After the completion of the air injection, crosswell measurements were again taken between GW-3 and the other four wells with both the source and receiver at the same elevation, as described before. The single well reflection surveys in GW-3 and GW-1 were also repeated with the same recording strategy.

RESULTS OF SEISMIC MONITORING DURING AIR INJECTION

It was unknown whether the injected air would follow a path along a fracture or whether it could be seismically detected. There was also a chance that the fast path was the boundary between the shale and the limestone, i.e., not a vertical feature at all. Although we had strong evidence that our target was between GW-1 and GW-3, there was a slight chance that the fast path could lie between GW-3 and GW-4. We elected to monitor the injection between GW-1 and GW-4, a distance of about 100 m, to ensure that as many fractures as possible between the two wells were monitored and we would have the highest chance of detecting the effect of air injection.

The monitoring began 30 minutes before the start of the air injection and repeated at 2 minute intervals. After 1 hour there was no change in the data, and recording was increased to every 10 minutes. Figure 3 shows the effect of air injection on the crosswell seismic measurements during the injection. In Figure 3, time "zero" is at the bottom. We began monitoring 30 minutes prior to air injection, not expecting changes, but primarily to determine repeatability and stability of our system. Several different significant observations can be made from looking at Figure 3. It should be noted that all amplitudes are plotted at the same scale; the dipped signals are from plotting only. A general observation is that the amplitudes significantly dropped over time; however, there were also minor effects on traveltime. At first there was a very slight increase in traveltime, then after about 2 hours and 15 min of air injection there was a small, yet detectable decrease in traveltime. (Note the shift in traveltime between the group 1 and group 2 sets of traces in Figure 3.) This effect lasted about an hour, after which the traveltime returned to almost the original value (group 3). Another slight velocity increase followed group 3, then the amplitude dropped significantly. This temporary decrease in traveltime, velocity increase, was so small compared to later effects we do not consider it significant. After these episodes of small velocity change, the crosswell velocities then began a much larger decrease along with the amplitudes. Air was injected for about 6 hours, at which time because of a variety of logistical, operational, site access, and safety reasons, air injection was halted and well GW-5 was shut in to maintain pressure overnight. Although the air injection was terminated overnight, the seismic source and receivers were left in place to reduce any ambiguity upon continuation of monitoring the next day. The next day we continued air injection for about 5 1/2 hours. There was some reversal in the amplitude decrease overnight, because of the pressure drop in well GW-5 (the pressure had dropped from 3.4 bars to .68 bars (50 psi to 10 psi) overnight), but upon continuation of air injection the same effect quickly duplicated the results from the day before. We therefore believe that the break in the experiment had no effect on the final conclusions or results. We stopped the air injection when we saw no significant change in the crosswell data. It is obvious from the crosswell data in Figure 3 that the air injection had significant effects on the amplitude of the seismic data. It was clear that the air injection significantly reduced the signal amplitudes by an order of magnitude and decreased the traveltime of the initial arrival by several samples (difficult to see at this scale). The hypothesis was that, due to increased acoustic impedance contrasts, a reflection from the air-filled zone would also be observed.

RESULTS OF THE CROSSWELL IMAGING DATA AFTER INJECTION

Immediately following the air injection, we performed the crosswell experiment between the GW-3/GW-1 and GW-3/GW-4 well pairs. From the results of the monitoring

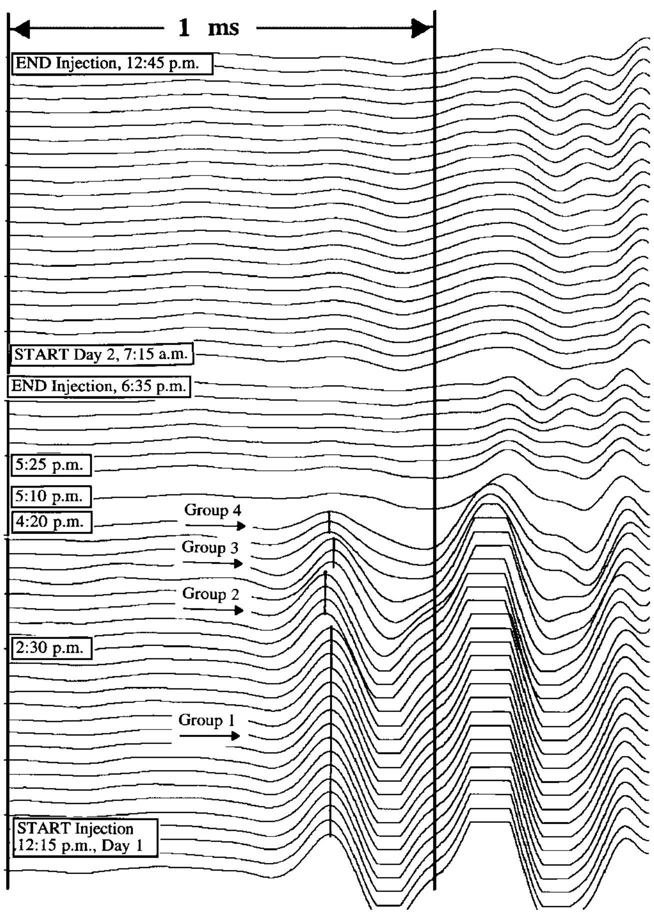

FIG. 3. Crosswell seismic data recorded during the air injection between wells GW-4 and GW-1. This figure shows the behavior (attenuation and delay) of the P-wave data as air is injected into the formation. The amplitude scale is the same for all traces.

during the air injection we expected a significant effect on the crosswell data if air had migrated in between any of the crosswell pairs. We quantified the crosswell results by calculating a summed spectral amplitude over the frequency band of 4000 to 6000 Hz in 0.08 ms time steps along each trace at each depth. This band was chosen because it had the maximum power. The result is a time-amplitude plot for each trace. Figure 4 compares the crosswell data between well pairs GW-3/GW-1 and GW-3/GW-4 before and after air injection. A sharp decrease in the amplitude of the first-arrival is observed for almost all traces. However, the GW-3 to GW-4 crosswell first-arrival signals look virtually identical before and after the air injection. This also shows the repeatability of the data. The only significant difference between the before and after data from the GW-3/GW-4 well pair is the increase in amplitude of a secondary arrival at 17 ms. The large decrease in seismic energy produced when introducing air into the fracture is easily seen in these plots. The crosswell pairs GW-3 to GW-5 and GW-3 to GW-2 are similar to GW-3 to GW-1. We assume this is due to effects of air being injected at GW-5 and the water being removed from GW-2.

Although very little effect was seen in the before and after results for the GW-3 to GW-4 P-wave arrivals, there is a difference in energy content at about 7 ms after the P-wave for traces in the 23 m depth range. This may be a reflection from a vertical fracture set. If the large drop in amplitude was caused by a fracture being filled with air, then it is likely that there would be reflected energy from this feature. The increase in energy at 7 ms after the P-wave in the GW-3 to GW-4 data could be caused by such reflected energy. At 4000 m/s velocity, this would put a vertical feature about 14 m from GW-3. Using the crosswell data alone, the strike of such a feature cannot be determined; the only conclusion that could be made from the crosswell data was that there is a feature between GW-3 and GW-1 causing an amplitude anomaly.

ANALYSIS OF SINGLE WELL CDP DATA

The single well surveys were designed with the intention of processing the data as a common CDP reflection survey. Single well surveys were acquired from wells GW-3 and GW-1 before and after the air injection. The “before” and “after” injection traces were each sorted into CDP gathers. The gathers indicated a low-amplitude P-wave arrival with a velocity of 4000 m/s, and very large secondary arrivals with a velocity of 2200 m/s. The radiation pattern of the piezoelectric source used is such that the P-wave energy is largest at 90° to the borehole and is quite small parallel to the borehole. The radiation pattern for the S-wave has maximum energy 45° to the borehole (Gibson, 1994). These radiation patterns are consistent with our data and, taken with the velocities, indicate that the secondary arrivals are S-waves. Shown in Figure 5 are several representative shot gathers from the single well data in GW-3. The strong secondary arrival is an S-wave, not a tube wave. The data are surprisingly free of tube waves which are commonly seen in borehole data. The absence of tube waves may be due to the sand packing that was used to pack the slotted PVC casing (a gradual acoustic impedance change from water to rock, rather than a water rock interface), but the high frequencies (shorter wavelengths) used were also a great advantage in tube-wave minimization. Our experience has been that strong tube waves are generated at lower frequencies (1000 Hz

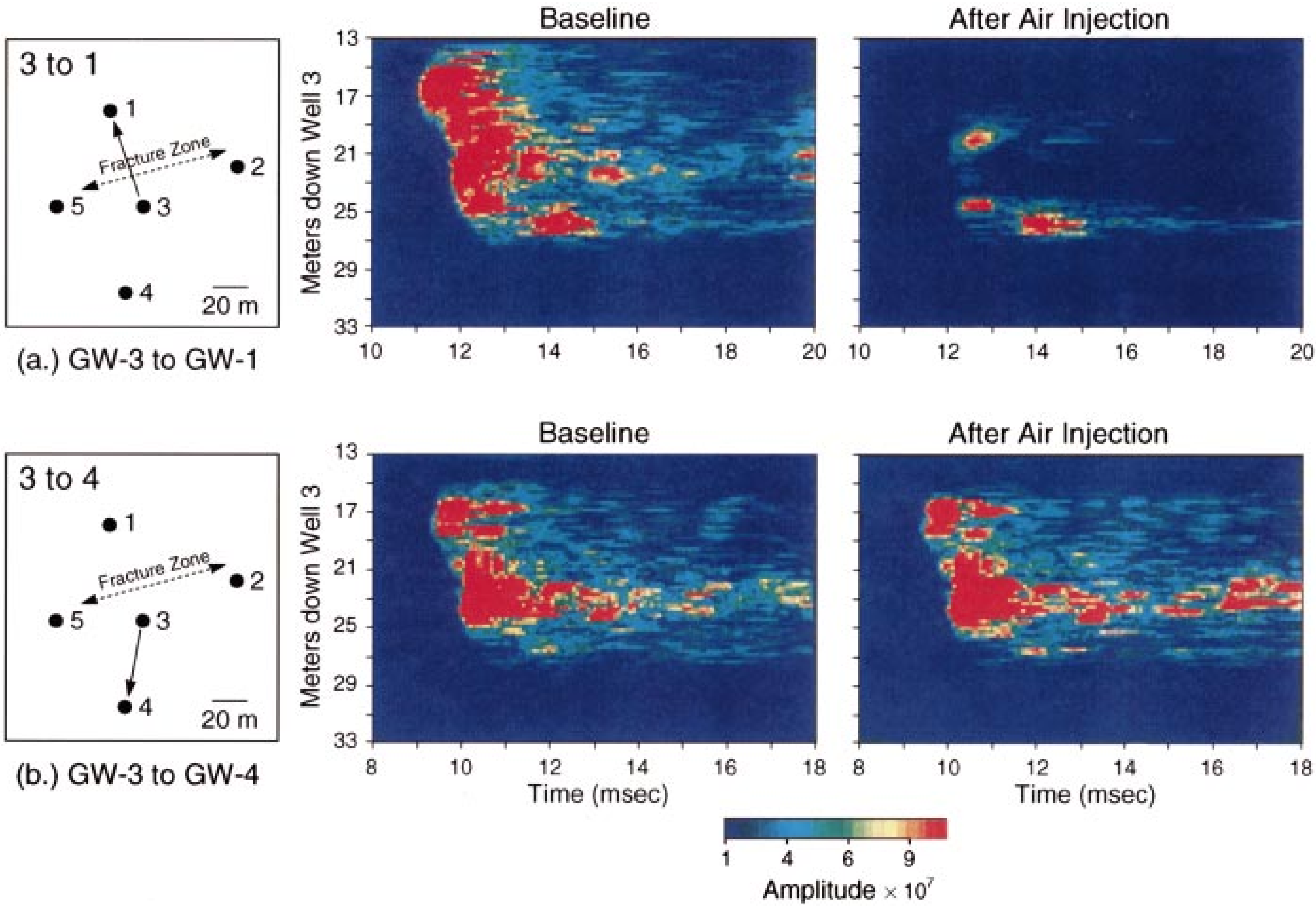

FIG. 4. Crosswell amplitude data as a function of depth and time between well pairs GW-3/GW-1 (a: top row) and GW-3/GW-4 (b: bottom row), before (left tomograms) and after (right tomograms) air injection.

and less) and/or in uncased wells in high-velocity (granite) rock.

The strong *S*-wave energy had to be removed from the data before stacking. Muting these arrivals is not advisable since reflectors are expected close to the well and as much energy as possible should be preserved in this time window. *f*-*k* filtering was performed instead of the mute on receiver gathers before sorting into CDP gathers. Velocities from 1000 m/s to 2500 m/s at all frequencies were removed using a fan filter. A simple stack was then performed with a constant stacking velocity of 4000 m/s, which was derived from the crosswell data and borehole logs. In this case the velocity logs represented a "horizontal" velocity variation with respect to the "downhole reflection line." The CDPs covered the interval from about 17 m to 28 m at 1/4 m increments, which extended the survey to the higher velocities at the top of the Fort Riley limestone formation, and into the lower velocities at the bottom of the formation. This "horizontal" velocity variation is difficult to remove and was ignored for this application; we were interested in the central part of the formation and not the edges.

The resulting CDP stacks before and after the air injection in GW-3 are shown in Figure 6. The two sections representing before and after injection are almost identical except for a strong reflector at 7 ms after injection. The reflection is strong from a depth of about 19 m to 26 m, which is a region of relatively high velocity (see Figure 2). The reflector appears to extend to a depth of 28 m, but is less detectable, possibly due to large velocity contrasts in this region. There is evidence of some reflected energy shallower than 19 m, but the large velocity contrasts at these depths produce poor stacks. The reflector is observed on the before-injection section, but it is not as strong and not as extensive. It is interesting to note that the reflector was observed at the same expanded time as the secondary arrive seen at 17 ms in the GW-3 to GW-4 crosswell data.

The same processing was performed on single well data acquired from GW-1 (Figure 7). The *P*-wave traveltime between GW-1 and GW-3 is about 12.5 ms. Therefore, the reflector seen in Figure 6 at 7 ms should be at 18 ms (two-way traveltime) from GW-1. Depending on the depth in the well, there does appear to be an increase in reflected energy between 15 to 18 ms comparing before injection to after injection (Figure 7). However, the reflector appears very weak, probably due to its distance from GW-1. Also the disadvantage of using a constant velocity stack is more pronounced at larger distances from the reflector.

RESULTS OF DRILLING

To verify our results, we designed a drilling program based on the combined results of the single well and crosswell surveys. We had seen a large decrease in amplitude of the crosswell seismic signal between GW-3 and GW-1. Therefore, we wanted to drill between GW-1 and GW-3. We had also observed a large reflector at approximately 7 ms in the CDP section from the GW-3 single well survey. The reflector seemed to be the strongest in the lower half of the Fort Riley. We therefore set our drilling target to be at a depth of maximum amplitude change and at a distance of half the 7 ms two-way traveltime times the average velocity. This turned out to be a target at a

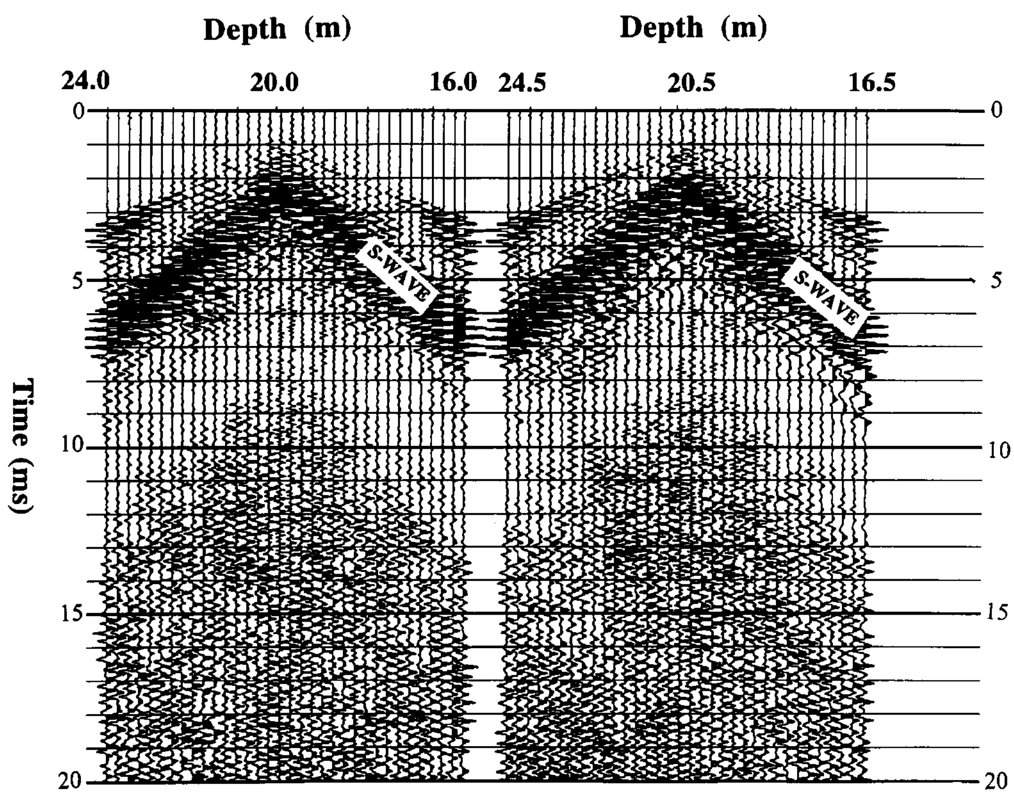

FIG. 5. Two typical shot gathers from the single well reflection profile in GW-3. Receiver spacing was 1/4 m. The location is approximately in the center of the limestone formation. The data are raw and have not been filtered. Note the lack of tube waves and the strong *S*-wave arrival.

depth of 24.25 m below the surface and 13.54 m from GW-3, on a line connecting GW-3 and GW-1.

A commercial slant well drilling rig was used to drill a hole (GW-6) at 30° from the vertical. This was the maximum angle the rig could handle safely. The hole was cored through the Fort Riley formation. NX size core [diameter = 84 mm (2.125 inches)] was taken in GW-6 from 24 m to 33 m core depth with a recovery of nearly 100%. Taking into account the angle of drilling, this was a depth of 20.8 m to 28.6 m below the surface. Only one natural fracture was intersected. It was encountered between the depths of 24.9 m and 25.1 m. This fracture was located less than 1 m from the target fracture depth of 24.25 m predicted by the single well and crosswell seismic experiments. A photograph of the core through the fracture is shown in Figure 8.

There are three pieces of evidence that suggest the fracture is natural and not drilling-induced. The fracture is planar and oriented 30° to the core axis (Figure 8). This orientation is consistent with an interpretation that the fracture is vertical. Natural vertical fractures are commonly observed in outcrops of Fort Riley limestone, and one was observed in the Fort Riley core from the GW-5 well. Second, we examined the fracture surface under an optical microscope and observed perfectly formed dog-tooth spar (calcite) and framboidal pyrite. Their occurrence indicates that the fracture was open in the subsurface enabling euhedral mineral crystals to form. Third, the driller noted significant water influx immediately after 24.9 m. This observation is the most compelling evidence that the fracture in the core is natural and the target fracture.

It was impossible to measure the aperture of the natural fracture in GW-6 because one side of the fracture was broken into rubble (Figure 8). However, based on our observations of the natural fracture in the GW-5 core, we estimate that the fracture in GW-6 has an aperture of approximately 1 mm in the subsurface. This estimate is also supported by the interpretation of a

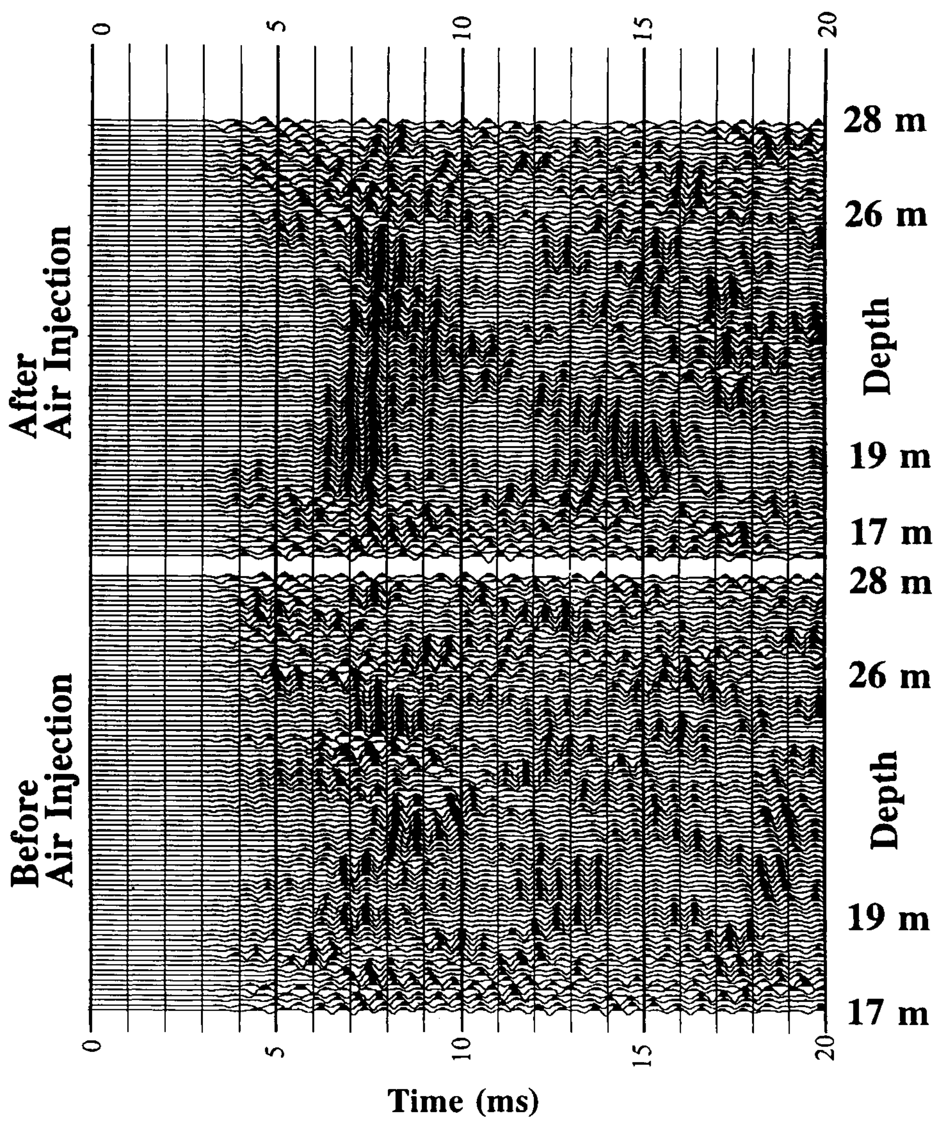

FIG. 6. A CDP stack of the single well reflection data from GW-3 before the air injection (bottom) and after the air injection (top). Note the increase in the reflected energy at 7 ms.

tracer survey conducted in the GW well array that suggested a fracture aperture between 0.7 and 1.2 mm (Sheely, 1991).

DISCUSSION AND CONCLUSIONS

Before this work began, we were uncertain that seismic methods could map fractures or heterogeneities at a fine enough scale to provide useful information for fluid transport models. Although we do not claim to have solved the problem, we feel that we have taken a small step toward providing an approach to characterizing fractured heterogeneous environments. Although the work was performed at shallow depths, the apertures of the fractures detected (1 mm) are representative of fractures. Therefore we feel that the results are significant in fracture detection at much greater depths. As usual there is no one magic method that can solve a difficult problem and one must resort to a combination of approaches. We guided the seismic work by interacting with geologists and reservoir engineers, with the primary goal being an effective method for imaging fractures important in controlling fluid transport. The high-frequency approach described in this paper is the end result of starting out with conventional low-resolution methods (VSP and surface reflection, which yielded little useful information) and ending up with a combination of seismic methods (crosswell and single well) to map conductive features.

We feel that there are several significant results from this work.

1) We have demonstrated that single well reflection surveys can provide useful information on vertical features at 10 s to possibly 100 s of meters from the well. Single well surveys hold great promise for characterizing fine-scale reservoir heterogeneity, but due to operational issues (tube waves, horizontal velocity gradients, lack of

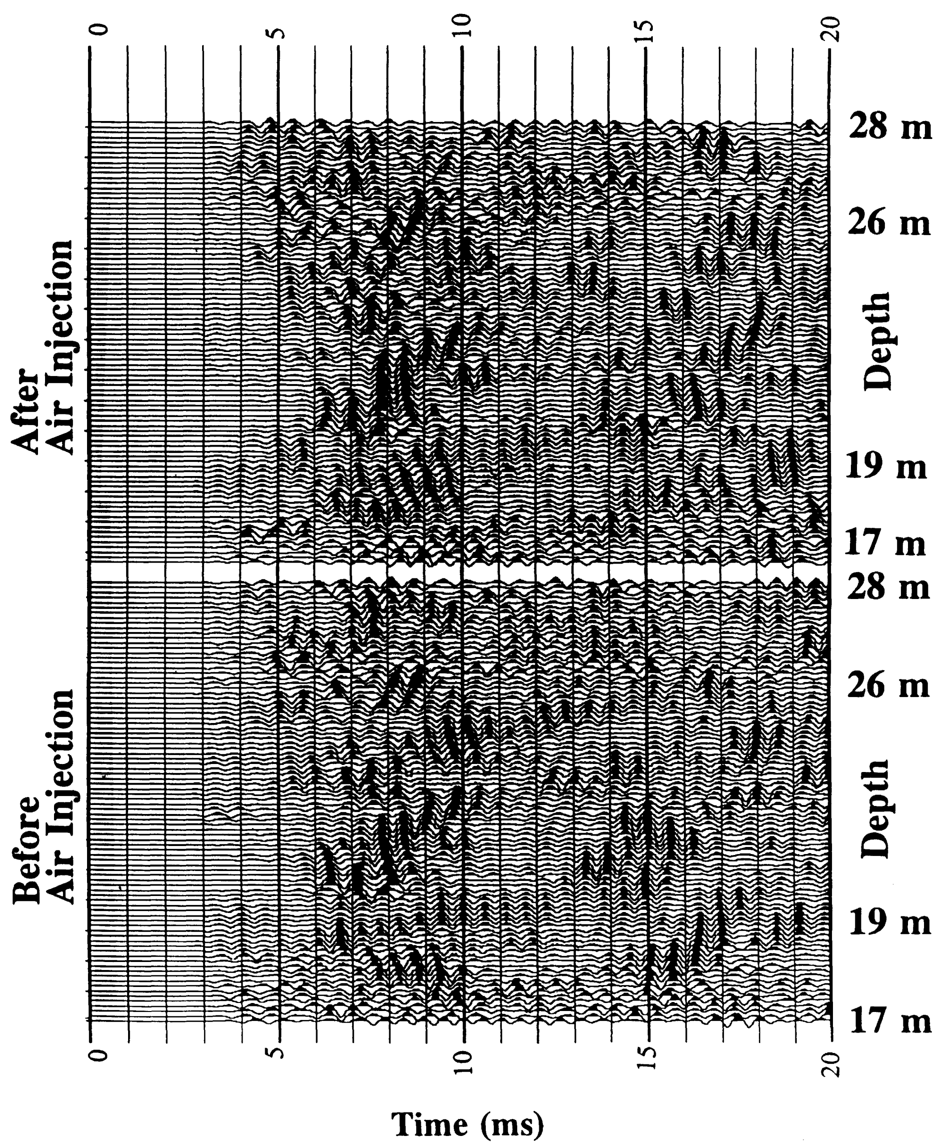

FIG. 7. A CDP stack of the single well reflection data from GW-1 before the air injection (bottom) and after the air injection (top). Although there is an increase in the reflected energy between 15 and 18 ms, the energy is weaker due to the larger distance the fracture is away from GW-1 than GW-3.

FIG. 8. Natural fracture in GW-6 core between 24.9 m and 25.1 m depth. The top of the core section is on the left. The core piece on the left has a planar, natural fracture surface oriented 30° to the core axis. The other side of the fracture has been broken into rubble because of coring. The scale is 10.16 cm (4 inches).

commercial systems) the method has not been used extensively. The single well data presented here were characterized by a lack of tube waves, but contained large shear-wave energy. The tube waves may have been attenuated by the sand packing around the boreholes, and it must be anticipated that strong tube waves could exist in other single well surveys. We feel that our success was a combination of careful attention to electronic noise reduction, the use of high-frequency data, and well bore conditions. Tube waves could have a strong complicating effect on the processing, but the shear-wave energy was easy to remove with f-k filtering so it can be assumed that the tube wave could just as easily be removed. In the worst case one would design the survey such that the arrival times of interest would not be in the same time window as the tube waves.

2) This experiment has shown that relatively small fractures can account for significant fluid flow. Methods such as VSP and surface reflection may provide clues to general fracture directions and anisotropy, but accurately locating and characterizing such features is a difficult task and requires high-resolution subsurface methods. Using standard processing techniques, fracture zones were located that could be detected, but not located, by other means. This was accomplished by using high-frequency energy in a combination of crosswell and single well approaches.
3) From a rock physics point of view, we have shown that displacement of water with a gas (in this case air) produces large changes in the P-wave signal, even in such small features as a fracture with a width on the order of a millimeter. This is significant because although our wavelengths were on the order of 1/2 to 1 m, we still "saw" the fracture. This lends field evidence support for the displacement discontinuity theories that predict such effects (Schoenberg, 1980; Pyrak-Nolte et al., 1990a, 1990b).

Future work will pursue field and laboratory scale experiments to explain why and how such small features cause such large seismic anomalies, using S-waves as well as P-waves. We also feel that to make single well imaging a practical method, we must develop arrays of sources using modern compact electronics combined with innovative beam steering methods so that the energy can be directed in any desired direction with greater bandwidth and strength. Just as important, we will also take the high-frequency crosshole and single well methods to larger scales with surveys in production environments. We feel that only in this joint basic/applied approach can we make true progress in developing useful methods for characterizing heterogeneous reservoirs.

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