Geothermal Resources Council, TRANSACTIONS, Vol. 13, October 1989

FIELD TEST RESULTS OF A BOREHOLE DIRECTIONAL RADAR

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ABSTRACT

The Borehole Directional Radar System is a high-power, high-resolution tool that is being developed to locate lithologic layers of fractures away from a wellbore. The prototype is a 50-kW peak-power pulsed directional radar system that determines fracture location by transmitting powerful radar pulses, 8 nanoseconds in length, in a known direction from a borehole. The frequency spectrum of the pulses ranges up to the VHF band, which is between 30 and 300 MHz. The transmitter and receiver rotate in place, permitting the tool to scan for fractures in all directions from the borehole. Because discontinuities in the rock interrupt and reflect radar signals, signals that return to the tool's receiving antenna indicate fractures. The distance of the fracture from the borehole is determined by the time delay of the return signal. The radio frequency signal is sampled and transmitted to the surface by wireline at audio frequencies, and then reconstructed at the surface using a personal computer. The key to the tool's potential is its ability to accurately measure distance and direction of a lithologic discontinuity underground.

This paper presents field test results that show the capabilities of the tool for locating lithological discontinuities up to 10.5 m (34.5 ft) away from a wellbore. Unique features of the system are discussed. Potential applications of the system are described, such as locating gas and oil reservoirs below a salt dome and possibly detecting a blow-out well with or without casing. In the area of national security, this system might be used to evaluate the integrity of underground structures, such as the Strategic Petroleum Reserve and Nuclear Waste Repository Site. It might also be used to locate underground tunnels and is being considered for underground nuclear test verification.

INTRODUCTION

In the 70's, drilling in the Valles Caldera, New Mexico, geothermal resource area yielded dry holes not far from producing wells. Although a fracture system apparently existed in the area, efforts to commercially exploit the geothermal resources in the region were abandoned, in part because of the failure to locate and intercept the fractures from the dry holes. Because characterizing fractures in the vicinity of boreholes (but not intersecting the boreholes) offers the potential to convert a dry hole to a producing well or to increase production from geothermal wells, the U.S. Department of Energy (DOE) solicited research proposals in 1984 that were aimed at developing fracture detection technology from a single wellbore.

In 1984, in response to DOE's request for fracture detection technology, Sandia National Laboratories (SNL) proposed a radar fracture detection technique based on theoretical analyses (Statton, 1941; Hartenbaum and Rawson, 1983). To demonstrate the feasibility of such a concept, a simple field experiment at a granite quarry in Marble Falls, Texas, was conducted. A section of granite was selected that had an existing flame-cut slot, and the slot was filled with salt water to simulate a brine-filled fracture. A transmitter consisting of two dipole antennas, which were arranged to provide a directional signal toward the fracture, was installed in several boreholes at various distances from the fracture. A receiver was also located in the same borehole as the transmitter. The transmitting antenna's excitation signal was an impulse that contained the frequency spectrum up to the VHF band (30 to 300 MHz). The radar returns from the simulated fracture were detectable in boreholes located at distances of up to 12 m (39 ft) from the fracture. The results indicated for the first time that it was feasible to use a downhole VHF radar in a single borehole to detect fractures located away from the borehole (Chang, 1984).

Similar experiments were conducted using acoustic techniques at 5 kHz. A high-energy piezoelectric transmitter was located in a borehole 8 m (26.1 ft) from the water-filled slot, and a commercial piezoelectric transducer was used as a receiver in a borehole 4 m (13.2 ft) from the slot. Both transducers could be rotated for maximum transmission or reception for either the compressional wave or the shear wave. During the experiment, reflections from the simulated fracture were obtained with the transducers oriented only for shear wave illumination and detection. These test results suggest that a high-frequency shear wave can also be used to detect fractures located away from a borehole (Chang, 1985).

The radar technique was finally selected for further development, instead of the acoustic technique, because a directional antenna that fit into a small wellbore at the frequencies of interest (VHF), using a corner reflector (Kraus, 1951) and an eccentric antenna (King and Smith, 1981), was developed in a short time. In addition, conductivity measurements on rocks that were obtained from existing geothermal sites indicated that for both dry and wet conditions these formations behave at VHF frequencies as a low-loss dielectric, thus allowing an electromagnetic wave to propagate to a reasonable distance (Chang, 1986).

The prototype borehole directional radar (BDR) system that was designed and fabricated is the first downhole radar system to use a corner reflector concept to provide directional capability (Chang, 1987). The impulse generated by the circuit (50 kW peak power with 2-ns rise time) is by far the highest power used in any downhole radar tool today. The BDR system uses a special sampling technique to transmit the high-frequency signal uphole and thus provides high-resolution data. The minimum detectable sensitivity (MDS) of the system is as low as -100 dbm, which makes it possible to detect very weak signals.

Because the first step in understanding a new instrument is to operate the instrument under known or controlled conditions, a series of tests of the radar probe using a known target was conducted in a man-made lake known as the Water Impact Facility, located at Sandia Labs. In the tests, which are described in Duda, Chang, Uhl, and Gabaldon (1987), signals reflected from the target were observed when the target was 1.5 m (5 ft) and 2.7 m (9 ft) from the probe; in the latter case, the returned signal was greatly attenuated by the water. The measured 3-dB beamwidth of the system to the target was 70°. The effect of target size was also studied by moving the probe across the face of the target.

The next step in understanding the radar tool was to characterize it in a rock formation. A dry travertine quarry site near Belen, New Mexico was selected for the field test. The electromagnetic attenuation is small in such a formation, which represents a close to ideal case for the radar probe. The quarry also has numerous natural and man-made small-scale fractures that create noise typical of actual reservoir rock. To ensure that the reflected signal was detectable, we selected a target 4.3 m (14 ft) away from the wellbore. The target was a rock-air interface (i.e., cliff). We put a large metal target against the rock wall to ensure maximum reflection coefficient. To avoid any unnecessary attenuation, there was no water inside the wellbore. As discussed in Duda, Uhl, Gabaldon, and Chang (1988), the target was clearly detected by our borehole radar system in these tests. The time of the reflection was about 105 ns. The direction of the target as seen by the radar system also agreed with that measured by compass.

FIELD TEST RESULTS AT THE QUARRY AND NEVADA TEST SITE (NTS)

The tests described above demonstrated that the prototype borehole radar was operational with directional capability and was able to detect targets away from a wellbore both in water and in a rock formation. To determine the ultimate capability of the current prototype, additional field tests were conducted. These tests included different, more realistic field tests at the travertine quarry and a separate field test at NTS.

New Mexico Travertine Quarry Field Tests

At the travertine quarry, a borehole was drilled 18.3 m (60 ft) deep and 8.5 m (28 ft) away from a cliff wall. The cliff wall is about 9.1 m (30 ft) to the base. The relative location of the cliff to the borehole is shown in Figure 1. To determine the effect of water on the radar probe, the wellbore was filled with water.

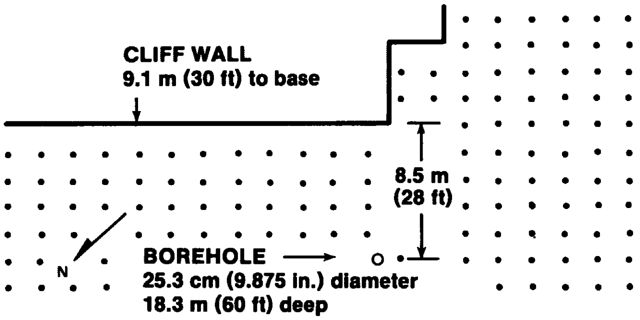


Figure 1. Schematic Diagram of Target and Borehole at the Travertine Quarry in Belen, New Mexico (Plan View).

Typical test results are shown in Figure 2. The second column of numbers on the left side of the graphs indicates the location (depth) of the tool; the numbers shown on the right side indicate the direction of the antenna. The number of waveforms averaged in this experiment is shown at the bottom of the graph along with the radio frequency (RF) attenuation, post-sampler gain (PS Gain), and the uphole gain (UH Gain).

As shown in Figure 2, the waveforms from different antenna directions were almost identical. The reason for the similarity is that the direct wave from the transmitter to the receiver is much more dominant than the reflected waves from the target. Fortunately, these direct waves are angle independent; the reflected waves are angle specific. Thus, if we subtract one waveform from the other, the identical direct waves should be eliminated, leaving only the reflected waves, which stand out at specific angles. Using the waveform at 344° as the reference for subtraction, the residual waveforms are demonstrated in Figure 3. Strong reflected signals are shown at about 240 ns. The reflection time observed in this experiment is more than double the reflection time of the earlier test (i.e., 105 ns), which took place 4.3 m (14 ft)

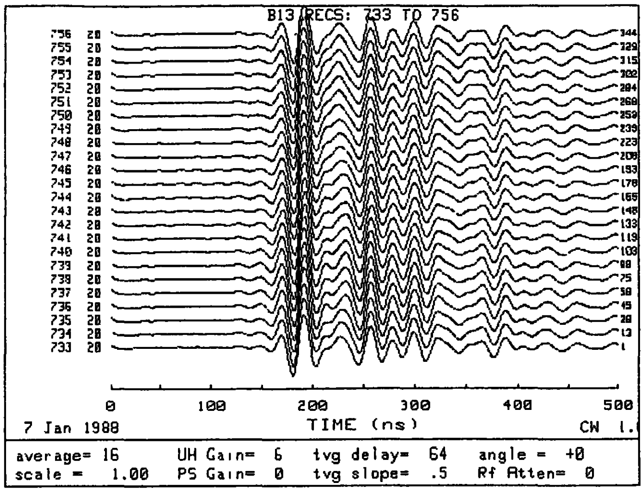


Figure 2. Raw Test Data with Target 8.5 m (28 ft) from the Wellbore.

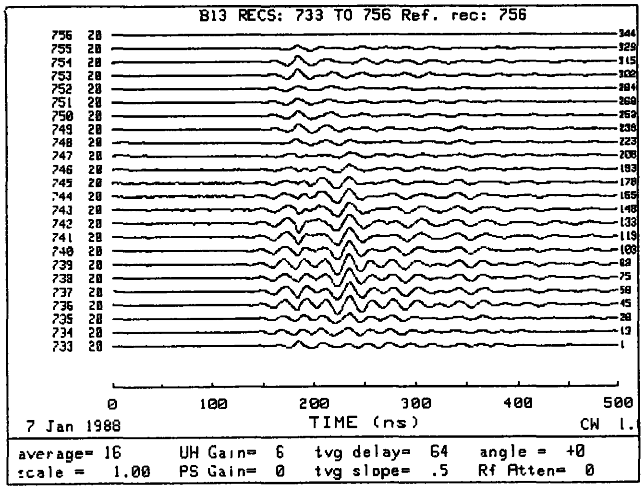


Figure 3. Residual Data with Target 8.5 m (28 ft) from the Wellbore.

from the target. The difference is caused by the wellbore being dry in the earlier test and filled with water in the later test. Water in the 8.5-m (28-ft) test not only filled the borehole, but also penetrated into the formation, which slowed down the velocity of the electromagnetic wave propagation.

In this experiment, the receiver data were attenuated by 63 dB in the first 64 ns in order to reduce the field strength of the direct waves from the transmitter to the receiver. The attenuation is indicated by setting Time Varying Gain (tvg delay) equal to 64. After the delay, the attenuation was slowly reduced by 0.5 dB/ns (tvg slope = 0.5). Therefore, 126 ns after the delay (or 190 ns after t = 0), the receiver circuit was fully open to record incoming data, just in time to record the reflected signals. The t = 0 is the time at which the transmitter fires.

The maximum PS Gain capability for the system is 40 dB; the maximum UH Gain capability is 20 dB. This particular experiment did not fully utilize the system's capability. In theory, targets farther away than the distance of 8.5 m (28 ft) that was used in this experiment should be detectable.

Nevada Test Site (NTS) Field Tests

The next experiment was conducted in a partially water-saturated formation in Area 15 of the NTS, a DOE test site near Las Vegas, Nevada. A 30-cm (12-in.) diameter radar test hole (RTH) was drilled about 10.5 m (34.5 ft) from an existing shaft to a depth of 61 m (200 ft) as shown in Figure 4. The shaft is 2.6 m x 1.8 m (8.5 ft x 6 ft) (cross-section) and more than 213.4 m (700 ft) deep. A 2-m x 2.8-m (6.5-ft x 9.3-ft) metal target was hung in the shaft against the wall, with a few inches separating the target from the wall. The formation in the upper portion of the test site appeared to be a mixture of clay and rubbled granite. Water was continuously running from nearby elevations through the near-surface layers and into the hole. The water level in the hole was at 33.5 m (110 ft).

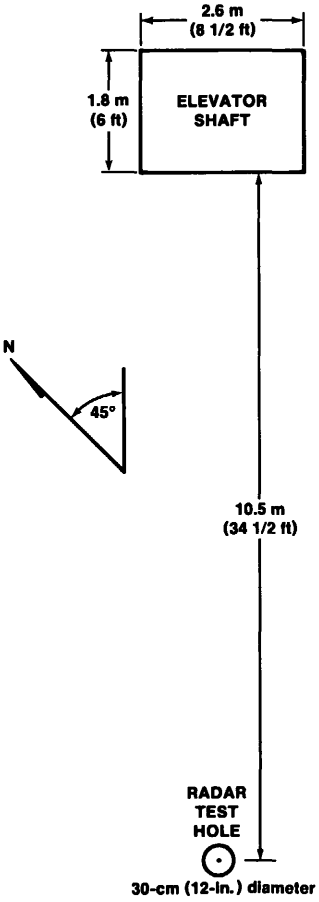
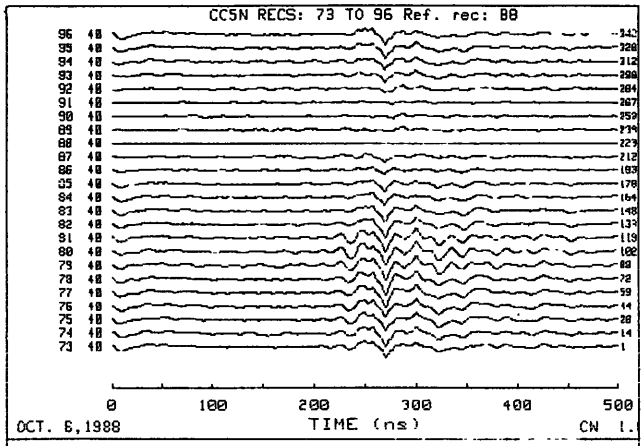


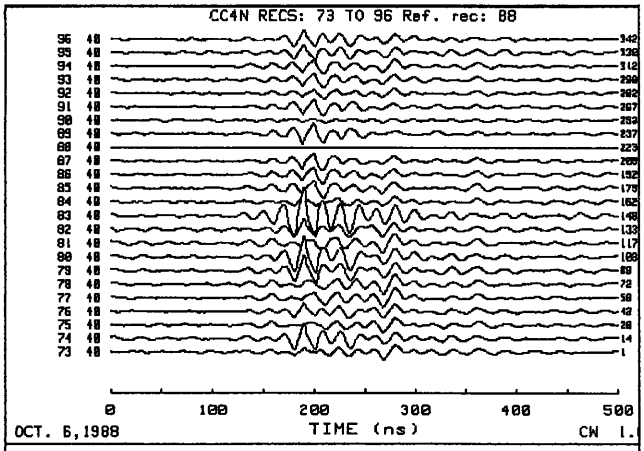
Figure 4. NTS Test Configuration.

When the tool was first located 15.2 m (50 ft) below the surface, we did not observe any detectable reflections. When we raised the tool to the 12.2-m (40-ft) level, reflections appeared at 270 ns, using the settings, tvg delay = 128 ns and tvg slope = 0.5 dB/ns, as shown in Figure 5. The values in Figure 5 are residual data, using the data at 223° as reference. (As described above, the residual data eliminate the direct waves from the transmitter to the receiver and leave only the reflected signals.) With the above tvg settings, the receiver circuit is fully open 254 ns after the transmitter fires, just in time to record reflected signals.



average= 16 UH Gain= 20 tvg delay= 128 angle = +0
scale = .50 PS Gain= 20 tvg slope= .5 Rf Atten= 10

Figure 5. Data Returns at 12.2-m (40-ft) Depth with TVG of 128 ns in NTS Area 15 Radar Test Hole.



average=256 UH Gain= 20 tvg delay= 64 angle = +0
scale = .50 PS Gain= 40 tvg slope= .5 Rf Atten= 30

Figure 6. Data Returns at 12.2-m (40-ft) Depth with TVG of 64 ns in NTS Area 15 Radar Test Hole.

To confirm these test results, we opened the receiver window by an additional 64 ns. (TVG delay was reduced from 128 ns to 64 ns.) Because strong direct waves from the transmitter to the receiver might saturate the receiver circuit, we attenuated the incoming signal by an additional 20 dB in the RF attenuator immediately after the receiving antenna and then added the 20 dB back at the post-sampler circuit. Although the net gain of the system in this arrangement is similar to that shown in Figure 5, the higher attenuation of input signal (to the receiver circuit) increases the noise level. We had to take the average of 256 waveforms to reduce the noise, as shown in Figure 6. This figure shows that other radar returns, possibly from existing underground structures, occurred during that additional 64-ns window. Nevertheless, reflections from the shaft consistently occurred in the 270-ns range, similar to those shown in Figure 5. Figure 6 used the full capability of our current prototype system. In such a partially water-saturated formation, the maximum depth of penetration of the current system is about 10.5 m (34.5 ft).

Because we were not able to test the results at more than one depth location, the data presented for the NTS test are not conclusive for target identification at 10.5 m (34.5 ft). As mentioned above, we did not observe any detectable reflections when the tool was located 15.2 m (50 ft) below the surface because of high water saturation, which increased the signal attenuation. Test locations above 12.2 m (40 ft) were unacceptable because the well was cased down to 6.1 m (20 ft). The tool itself is 6 m (19 ft) long, and the depth of the test is measured at the midpoint of the tool's length. Therefore, at a test location of approximately 9.2 m (30 ft), the receiving antenna would be either close to the casing, which would distort the electromagnetic wave signal, or inside the casing, which would shield the signal from the antenna. We would like to repeat the NTS test in the future.

APPLICATIONS

Although the borehole directional radar (BDR) system was developed to provide the direction and distance of the faults or fractures in geothermal reservoirs (Figure 7), it also has the potential for oil and gas applications, if the electrical property of the formation is low loss. Its directional capability distinguishes it from other subsurface imaging techniques, which are unable to determine the direction of fractures from a borehole.

Because of this unique feature, the BDR System has the potential to positively affect the oil, gas, and geothermal industries. For example, as an exploration tool, its detailed radar mapping of strata and structures surrounding a borehole would enable it to locate potential producing zones. In addition, the tool could be used commercially within the construction industry. For example, the tool could be used to detect dangerous fractures or faults at construction sites that include tunnels or other underground excavations.

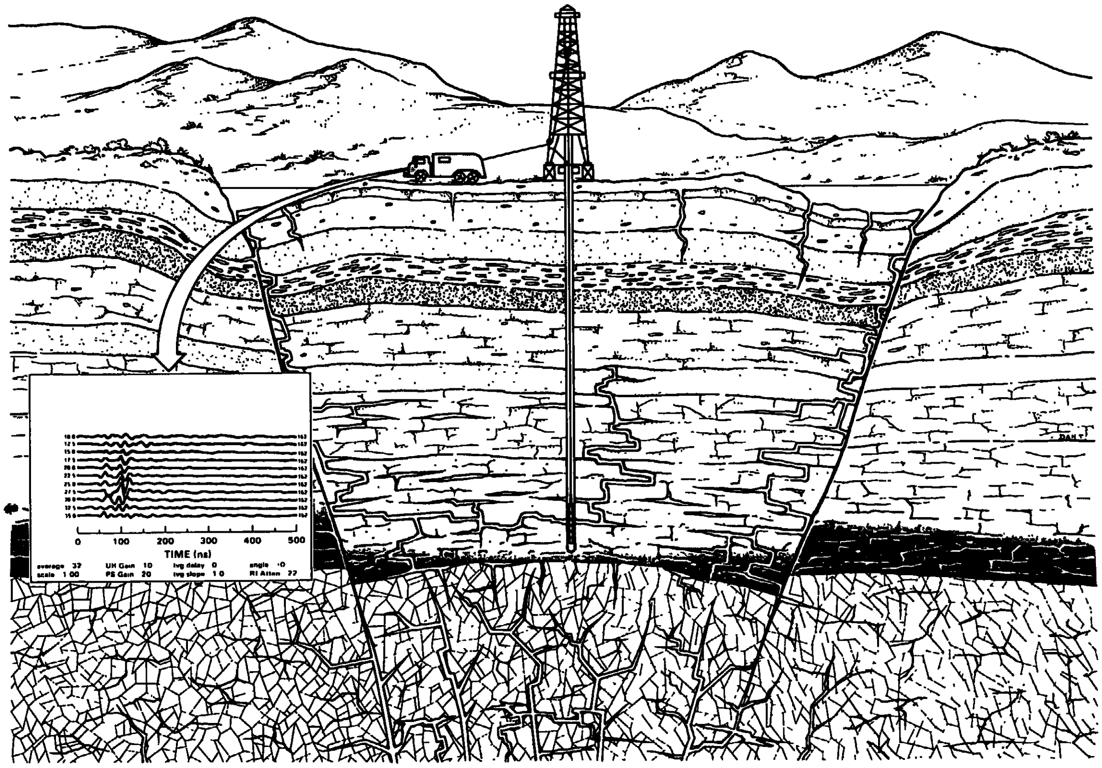


Figure 7. BDR System is Designed To Locate Fractures and Faults.

Other applications for which the BDR System might be used include: (1) determining the integrity of underground structures such as mines; (2) estimating the thickness of a coal seam; (3) investigating whether significant fracturing exists near proposed underground radioactive waste disposal sites or a strategic petroleum reservoir; and (4) locating gas or oil reservoirs below a salt dome (Figure 8).

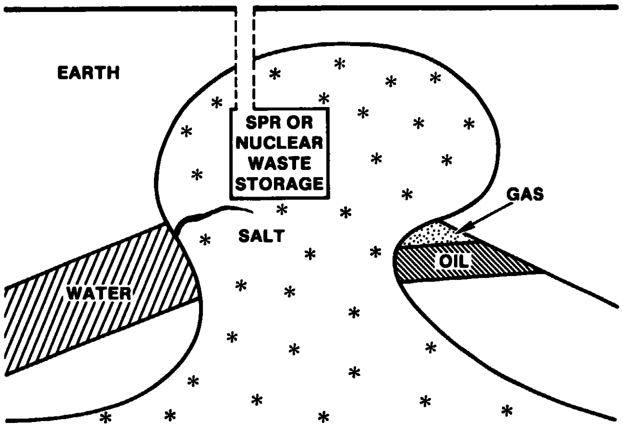


Figure 8. Salt Dome is an Ideal Medium for Radar Scanning.

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This work is supported by the U.S. Department of Energy under contract DE-AC04-76DP00789.