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IN-SITU FRACTURE MAPPING USING GEOTOMOGRAPHY AND BRINE TRACERS*

by

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Summary

The Lawrence Livermore National Laboratory is currently assessing the capabilities of high resolution geophysical methods to characterize geologic sites for the disposal of high level nuclear waste. A successful experiment has recently been performed in which salt water tracers and high frequency electromagnetic waves were utilized to map rock mass fracture zones in-situ. Multiple cross-borehole EM transmissions were used to generate a tomographic image of the fractured rock region between two boreholes. The tomographs obtained correlate well with conventional wireline geophysical logs which can be used to infer the location of fractured zones in the rock mass. This indirect data suggests that the geotomography and brine tracer technique may have merit in mapping fractured zones between boreholes.

Introduction

Geologic storage of high-level nuclear waste requires a careful and well planned site selection process in order to ensure that the waste material will be safely isolated from the neighboring environment. Of particular importance in the site selection and characterization process is a thorough understanding of the geology and hydrology which make up the host media, as well as a thorough characterization of the rock mass fracture systems which could ultimately channel waste material back to the biosphere.

There are numerous geophysical techniques available to assess repository sites. In general terms, current geophysical tecniques can be used effectively to establish the average properties of a site, however, variations from the average properties created by geological heterogeneities are more difficult to detect and recognize. The current state-of-the-art is not adequately developed to characterize and detect fractures not intersected by a free surface such as an exploratory borehole. Techniques that offer sufficient resolution to detect fractures at depth lack penetration into the rock mass and vice versa. The application of geophysical techniques to the detection and characterization of fractures is one of the prime research areas in geophysical exploration technology.

The Lawrence Livermore National Laboratory is currently involved in research which is aimed at improving some of the current limitations associated with geophysical site characterization. LLNL is assessing, both theoretically and experimentally, those high resolution, remote probing geophysical techniques which can be used to assure that site characterization is effectively performed. We have recently performed a geotomographic experiment in which a salt water tracer and high frequency electromagnetic waves were used to map fracture zones remotely. This paper describes the techniques used and the results obtained, and relates our results to other geophysical measurements obtained on site.

Cross-Borehole Electromagnetic Tomography

The use of electromagnetic tomography for site characterization provides a new tool which can penetrate and probe a region beyond a borehole surface and, in fact, form an electromagnetic image of a region between boreholes.

The principle behind the use of electromagnetic tomography is quite simple. In general, two or more boreholes are drilled in the ground to span a subsurface region under investigation. (The distance used between the boreholes is dependent upon the subsurface media and the frequency of the electromagnetic signal used to probe the region, but can be as great as a few hundred feet.) A small radio transmitter antenna is placed down one of the boreholes, and a small receiver antenna is lowered down a second borehole.

By measuring the magnitude of the signal loss encountered along the path between the transmitter antenna and the receiver antenna, it is possible to obtain a measure of the electromagnetic attenuation between the two boreholes. To reduce the data it is assumed that the displacement currents dominate the conduction currents, and that straight line ray-optics hold. Different regions of the rock mass will attenuate the electromagnetic signal differently. If a fluid which attenuates an electromagnetic signal such as a brine solution is introduced into the fracture system in the rock mass, then the locations of the fractured zones may be determined if the brine penetrates the fractures but not the intact rock matrix.

Geotomography is a technique adapted from the field of medical tomography in which many x-rays are propagated through a body and used to form a sectioned slice of the measured region.[1] To obtain a tomograph of the underground (geotomograph) a similar procedure is followed. First, many ray paths or views of the region between the boreholes are obtained as illustrated in Figure 1. To reduce the data, the region between the boreholes is divided into many cells, and for each cell we attempt to solve for the differential attenuation of the signal which satisfies all the ray paths which pass through the cells in a consistent, rigorous manner. Typically, an iterative solution is followed, and the general solution procedure used in our study is referred to as a modified back projection method.[2]

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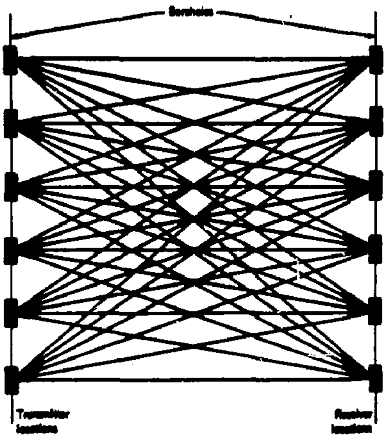

Figure 1 A region can be electromagnetically probed using many source and receiver locations. The attenuation of the signal along a ray path is used to compute a geotomograph of the region.

Once the attenuation in each of the cells is evaluated, a visual image of the region may be graphically displayed. Here we have used a graylevel television display to show the attenuation constant for each of the cells in a two-dimensional format. Darker shades of gray are used to indicate larger values of attenuation, while lighter shades indicate less attenuation. In this experiment, the brine in the fractures would be expected to show up as darker regions when compared with the lower loss unfractured granite regions.

Electromagnetic Geotomography Instrumentation

A block diagram of the instrumentation system used to obtain the electromagnetic geotomographic data is shown in Figure 2. The radio frequency spectrum analyzer used to measure the amplitude of the cross-borehole EM signal is the key element in the instrumentation system. Typically, measurements are made in the 10 MHz to 100 MHz region with signal levels ranging from -120 dbm to -20 dbm.

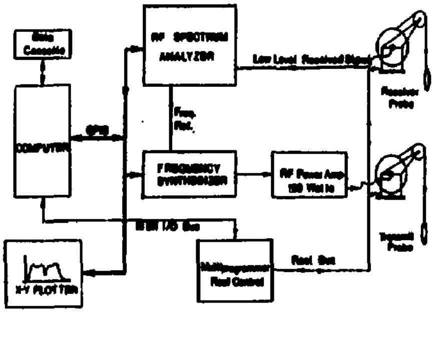

Figure 2 Block diagram of the electromagnetic cross-borehole measurement system.

The radio frequency signal used to excite the transmitter antenna is generated by a frequency synthesizer. The output of the synthesizer is amplified by a broadband power amplifier which supplies up to 100 watts of power to the transmitter antenna. A reference signal from the synthesizer is also coupled to the spectrum analyzer so that the two instruments may be frequency locked, allowing the use of narrow spectrum analyzer bandwidths for low-noise signal reception.

Both the transmitter and receiver antenna probes are automatically positioned in the boreholes. Coaxial cables are used to transfer the sginals up and down the boreholes. The transmitter antenna is an electrically short sleeve dipole 1 m in length, while the receiver antenna is a 0.45 m long monopole with an active element amplifier to transform the high impedance of the antenna to the 50 ohm impedance of the coaxial transmission line.

All of the measurement instruments are digitally controlled by a small desktop computer. Instrument control is via the IEEE-488 GPIB while the cable reel depth control is handleo by a separate data bus.

The desktop computer also controls the entire operation of the measurement process. Data from the spectrum analyzer is smoothed and averaged and then stored on a data cassette for later off-line processing. The raw data is also plotted on a small x-y plotter to provide an online validity check. Currently, the tomographic data is reduced and displayed back at the Laboratory, but design is currently underway to provide an in-the-field image display system.

Oracle Fracture Mapping Experiment

In order to assess the capabilities of crossborehole electromagnetic geotomography to map fractures, an experiment was performed at a granitic field test site located near the town of Oracle, Arizona, 45 miles north of Tucson. This site, developed by the University of Arizona for the NRC, is being used to test and evaluate various techniques for fracture characterization.

Three different types of earth materials underlay the site. An overburden layer consisting of highly weathered and decomposed granite outcrops throughout the area. On the average, the overburden is approximately 50 feet thick. This unit is underlaid by a granitic rock mass which contains an extensive network of fractures. The granite is intruded by dikes which are also extensively fractured.

Four coplanar boreholes (300 foot deep) are available at Oracle, and they are separated by 30, 20, and 50 feet respectively, as illustrated in Figure 3. For the fracture mapping experiments, we used the M-1 and H-2 boreholes, and gravity fed the attenuating brine solution into the M-1 borehole. A submersible pump was placed at the bottom of the H-3 borehole, to create a hydraulic gradient that forced the brine flow from M-1 to H-2 through the fractured rock mass. The brine was circulated for several days before the final geotomographs were obtained.

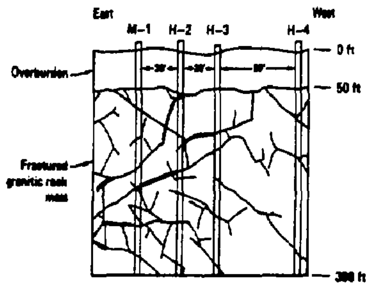

Figure 3 Four coplanar boreholes were available at the Oracle Site. Brine was injected in the M-1 borehole.

The EM geotomograph measurements were chosen to cover three overlapping zones. The upper zone covered depths of 26 m to 51 m. The middle zone covered 45 m to 73 m, while the lower zone extended from 66 m to 91 m. The transmitter antenna was located in the H-2 borehole and moved at 40 cm increments, while the receiver antenna was located in borehole M-1 and moved on 1 meter increments. The total process of positioning the antennas and measuring the signal levels picked up by the receiver antenna was automatically controlled by a small desktop computer system. A total of 1690 ray paths through the rock mass were obtained for the lower zone. The next section shows the results obtained at the Oracle site.

Oracle Test Results

Figure 4 shows an example of a geotomograph obtained for the lower zone at the Oracle test site. The gray-scale image in the center of the illustration shows three predominant fracture zones. In this figure, the dark regions represent zones of inferred fracturing.

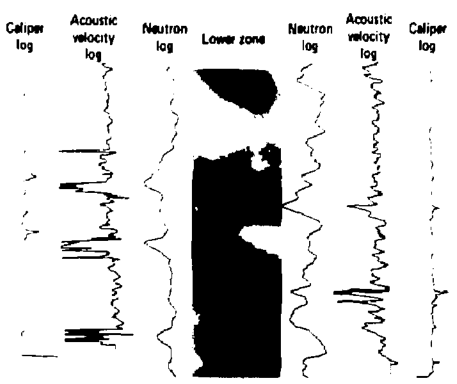

Figure 4 The gray level geotomograph in the center shows fractured regions in the lower zone. Shown beside the geotomograph are the bore-hole geophysical logs for the same region.

Shown beside the geotomograph are some of the more conventional single borehole wireline logs as obtained by the W. Scott Keys of the U.S. Geological Survey. The neutron log provides a measure of the hydrogen content in the rock which, in turn, can be used to infer the water content in the region surrounding the borehole wall. In this case, fractured regions would have much more water per volume than would an unfractured region. As can be seen, the perturbations in the neutron logs for the two boreholes correlate well with the dark regions shown in the geotomograph.

The acoustic velocity log is diagnostic of fractured regions, where the acoustic velocity diminishes markedly when passing through fractured zones. Again, good correlations can be seen between the geotomograph and the velocity logs.

Finally, the caliper logs provide a measure of borehole diameter, and the hole diameter frequently increases in fractured regions. Note that individual fractures apparently are not shown by this technique, but only clusters of fractures or fractured zones correlate with the geophysical logs.

While these logs do not provide "ground truth" (i.e., direct evidence) by which to assess the capabilities of the geotomography technique, they do provide indirect corroborative data which tends to support the geotomograph. A point which is significant about the tomographs is that they provide information of the region between the boreholes, not simply a measure very near the borehole wall.

Conclusions

Indirect data suggest that the cross-borehole EM geotomography and brine tracer method to map brine filled fractures provides a new technique for site characterization. The results obtained from these tests generally correlate with other borehole measurements near the borehole walls, and provide additional information for the regions between boreholes.

Core samples will be taken of the region between boreholes M-1 and H-2 to obtain ground truth data (i.e., direct data) which will allow us to evaluate the accuracy and resolution of the geotomographic technique and compare our results with other available techniques.

Further testing in other media, however, will be required before any generalizations can be made about the applicability to the nuclear waste site characterization problem.

Acknowledgments

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