NUREG/CR-3758
UCID-20060

Crosshole Geophysical Methods Used to Investigate the Near Vicinity of High Level Waste Repositories

A. L. Ramirez, R. J. Lytle, P. Harben

Prepared for
U.S. Nuclear Regulatory Commission

Lawrence
Livermore
National
Laboratory

NOTICE

Availability of Reference Materials Cited in NRC Publications

Most documents cited in NRC publications will be available from one of the following sources:

1. The NRC Public Document Room, 1717 H Street, N.W.
   Washington, DC 20555

2. The NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission,
   Washington, DC 20555

3. The National Technical Information Service, Springfield, VA 22161

Although the listing that follows represents the majority of documents cited in NRC publications, it is not intended to be exhaustive.

Referenced documents available for inspection and copying for a fee from the NRC Public Document Room include NRC correspondence and internal NRC memoranda; NRC Office of Inspection and Enforcement bulletins, circulars, information notices, inspection and investigation notices; Licensee Event Reports; vendor reports and correspondence; Commission papers; and applicant and licensee documents and correspondence.

The following documents in the NUREG series are available for purchase from the NRC/GPO Sales Program: formal NRC staff and contractor reports, NRC-sponsored conference proceedings, and NRC booklets and brochures. Also available are Regulatory Guides, NRC regulations in the *Code of Federal Regulations*, and *Nuclear Regulatory Commission Issuances*.

Documents available from the National Technical Information Service include NUREG series reports and technical reports prepared by other federal agencies and reports prepared by the Atomic Energy Commission, forerunner agency to the Nuclear Regulatory Commission.

Documents available from public and special technical libraries include all open literature items, such as books, journal and periodical articles, and transactions. *Federal Register* notices, federal and state legislation, and congressional reports can usually be obtained from these libraries.

Documents such as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings are available for purchase from the organization sponsoring the publication cited.

Single copies of NRC draft reports are available free, to the extent of supply, upon written request to the Division of Technical Information and Document Control, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, 7920 Norfolk Avenue, Bethesda, Maryland, and are available there for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

GPO Printed copy price: $4.50

NUREG/CR-3758
UCID-20060
RW

Crosshole Geophysical Methods Used to Investigate the Near Vicinity of High Level Waste Repositories

Manuscript Completed: March 1984
Date Published: August 1984

Prepared by
A. L. Ramirez, R. J. Lytle, P. Harben

Lawrence Livermore National Laboratory
7000 East Avenue
Livermore, CA 94550

Prepared for
Division of Radiation Programs and Earth Sciences
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
NRC FIN A0367

ABSTRACT

An evaluation is given of remote-probing geophysical techniques likely to be used to investigate the near vicinity of geologic repositories for nuclear waste. The sensors to be used would be placed inside the boreholes, shafts and tunnels of the repository to provide high resolution information of the rock near the repository. The geophysical methods evaluated are known as active methods because they make use of artificial seismic, electric or electromagnetic fields to probe the rock mass. Techniques involving through transmission measurements are emphasized. These techniques show merit for remote detection of geological heterogeneities such as fracture zones which influence the containment capacity of repository sites. The report discusses the results obtained with exploration methods used at a site near Oracle, Arizona.

CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

This report presents an evaluation of remote probing geophysical techniques likely to be useful in investigating geologic repositories for nuclear waste. In particular, this report focuses on remote probing the region between exposed surfaces and locations up to a hundred meters away. This region is herein designated as the near vicinity of the repository. The objective of this document is to provide the Nuclear Regulatory Commission (NRC) with a technical basis with which to judge the reliability of the methods discussed and the degree of confidence with which the results can be used.

Since the signal to noise ratio decreases with the distance to features of interest, the more useful techniques are those which can be applied close to the repository. Consequently, our discussion focuses on methods for which the sensors are placed inside boreholes, shafts and tunnels in the near proximity of high level waste (HLW) repositories.

The remote probing methods which are discussed include methods used to probe the rock mass between a source and receiver located in tunnels, shafts, or boreholes. Through transmission crosshole methods which use seismic, electrical and electromagnetic fields are described.

Various applications of the methods are discussed including detection of discontinuities and the monitoring of changes in rock behavior. Particular emphasis is placed on the detection of geological discontinuities such as fractures zones. The discussion focuses on methods used routinely to explore rock masses as well as on relatively new developments likely to be useful.

The information presented in this report is derived from published reports and from field experiments performed by the authors. The field experiments evaluated the capabilties to map fractures of various remote probing methods. The experiments were performed in a fractured granite rock site near Oracle, Arizona developed for the NRC by the University of Arizona.

I. INTRODUCTION

This report provides an assessment of selected remote-probing geophysical techniques that are likely to be used to investigate the near vicinity of geologic repositories for nuclear waste. The major focus of the report is on methods giving the high resolution needed to assure that a geologic repository has suitable characteristics.

In this section we review the general need for using geophysical methods at geological repositories and briefly describe the methods discussed in the body of the report.

The Nuclear Regulatory Commission needs a framework on which to base judgements about the characterization and monitoring activities to be performed by the Department of Energy at geologic repositories. The effectiveness of the various exploratory and monitoring methods available needs to be understood to adequately review DOE plans. This report contributes to the technical framework by discussing applications and limitations of selected remote-probing methods likely to be useful in exploring or monitoring high level waste (HLW) sites.

On the scale of a mined repository, no rock mass is completely homogeneous, and the inhomogeneities will influence rock behavior. Experts agree that during site characterization investigations, rock discontinuities such as lithological boundaries, fractures, brine pockets or dissolution voids must be mapped so that their impact on rock mass behavior can be correctly assessed.

Most surface geophysical techniques (i.e., those where the probing sensors are placed at the ground surface) are well suited for reconnaissance exploration, in which large areas are explored and the targets of interest are major geologic features such as faults, deformed strata, and changes in rock type. Candidate reconnaissance techniques for exploring repository sites include methods using gravity, magnetism, electrical resistivity, seismic refraction and seismic reflection.

The data provided by surface techniques is useful but insufficient to provide a high level of confidence in the projected performance of a site. Surface techniques are limited in their usefulness because the distance between the repository and the ground surface is expected to be very large; i.e., on the order of 1 km. The resolution of surface techniques is degraded because noise increases as a function of distance between the source/receiver and targets of interest. As a result, these techniques lack the resolution to detect geological heterogeneities such as fracture zones, brine pockets and small scale faults that will affect a repository's performance.

Useful techniques can also be applied close to the repository. Close-in techniques, known as underground geophysical techniques, are those where the probing sensors are placed inside boreholes, shafts and tunnels in the near proximity of HLW repositories. Although the volume of rock explored is smaller, better resolution is obtained.

The most direct means of sampling the subsurface environment is by taking rock cores from boreholes. This yields excellent information for the rock properties along the line of the borehole. However, assuming these properties are representative of the whole volume of rock is misleading. Rock features can change significantly within short distances. Thus, core samples may not be representative of the overall rock character.

Geophysical logs of boreholes (i.e., well logs) provide a continuous record of certain physical properties of subsurface rocks and their fluid content. These are particularly useful in establishing correlations between beds. Since geophysical borehole logging techniques provide localized information of the subsurface, most variations in rock properties that exist one or two meters from the borehole wall are generally not detected in the well logs. As a first approximation, the fracture intercepts at the borehole can be extrapolated away from the borehole. However, extrapolations of fractures from borehole logs laterally for more than a few meters are very uncertain. Conventional logs are not adequate to map unexposed fractures (Hartenbaum and Rawson, 1980). Very few boreholes will be drilled at a repository site. Thus the characteristics of large volumes of rock will not be adequately tested if only core samples and geophysical borehole logging techniques are used.

This report focuses on a subset of underground geophysical methods that provide better resolution capabilities to detect geologic discontinuities than surface techniques. These methods also have greater probing range than geophysical borehole logging techniques. The high-resolution remote-probing geophysical methods to be discussed complement data obtained using surface and geophysical borehole logging techniques by filling information gaps created by lack of resolution or short probing ranges.

Methods used to map geological discontinuities in the rock mass between a source and receiver are carried out in tunnels, shafts, or boreholes. For descriptive purposes, all such techniques are classified herein as crosshole methods.

The information presented in this report is derived from published reports and from field experiments performed by the authors to evaluate the capabilities of various remote probing methods to map fractures. The experiments were performed in a fractured granite rock mass near Oracle, Arizona, a site developed for the U.S. Nuclear Regulatory Commission by the University of Arizona. Sections II - V of this report contain general remarks on geophysical tomography; Section VI and parts of Sections II - V discuss geophysical tomography experiments.

The subset of geophysical tomography methods described in this report fall into three groups:

(1) Crosshole scanning methods. These methods generally involve transmission of energy between two boreholes in rock. The source and receiver are generally moved such that the ray paths are defined by a fixed orientation between each source-receiver pair (Fig. 1). Data is presented as a one-dimensional scan of variations of certain physical properties of subsurface rocks and fluids versus borehole length. This report contains examples of seismic, electromagnetic, and electrical resistivity crosshole scans. We use the term "scan" to refer to one-dimensional data collection and presentation formats to distinguish them from two-dimensional formats, historically referred to as "profiles".

(2) Crosshole transmission tomography methods. These methods make use of ray paths having many different orientations (Fig. 2). The data collected is mathematically analyzed to reconstruct an image presented as a two-dimensional representation of the variations of some physical property of a rock mass. This report contains examples of seismic and electromagnetic crosshole transmission tomographs.

PROFILING CROSSHOLE SCANNING METHOD

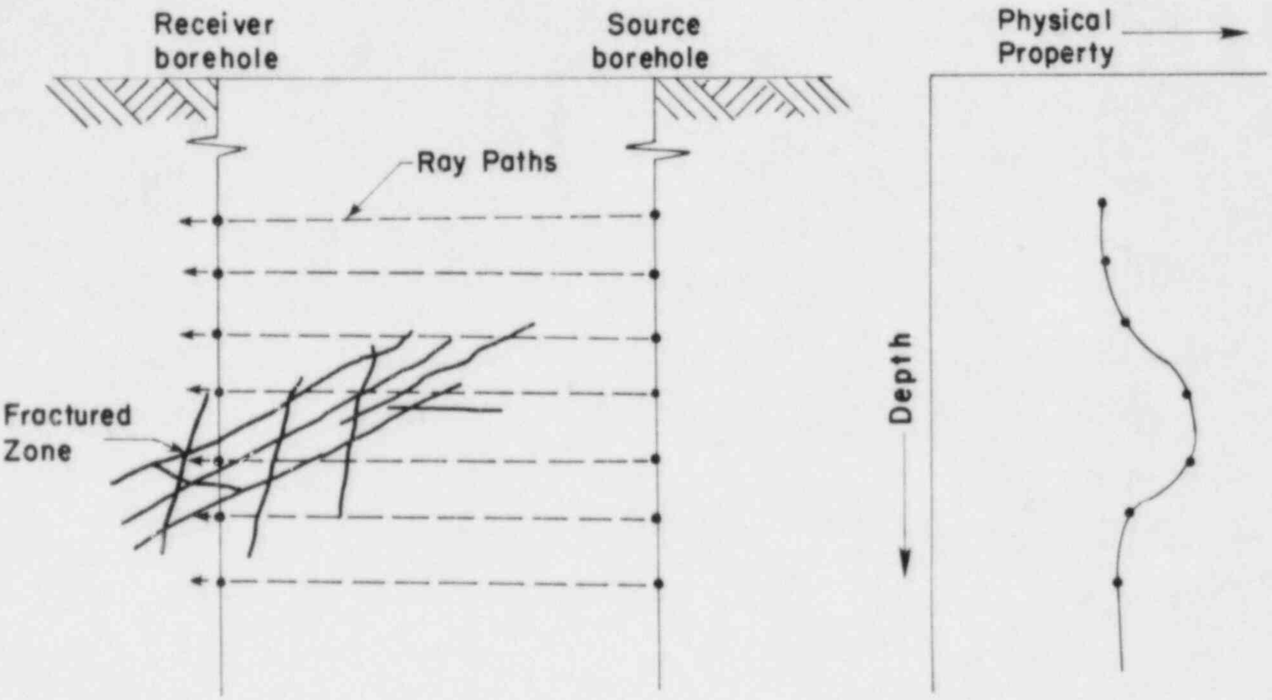

Figure 1

Artificial force fields are transmitted between two cr more boreholes in the crosshole scanning methods. Variations of a geophysical parameter with depth are obtained. A fixed orientation between the source and the receiver is maintained throughout the scan.

CROSSHOLE TRANSMISSION TOMOGRAPHY METHOD

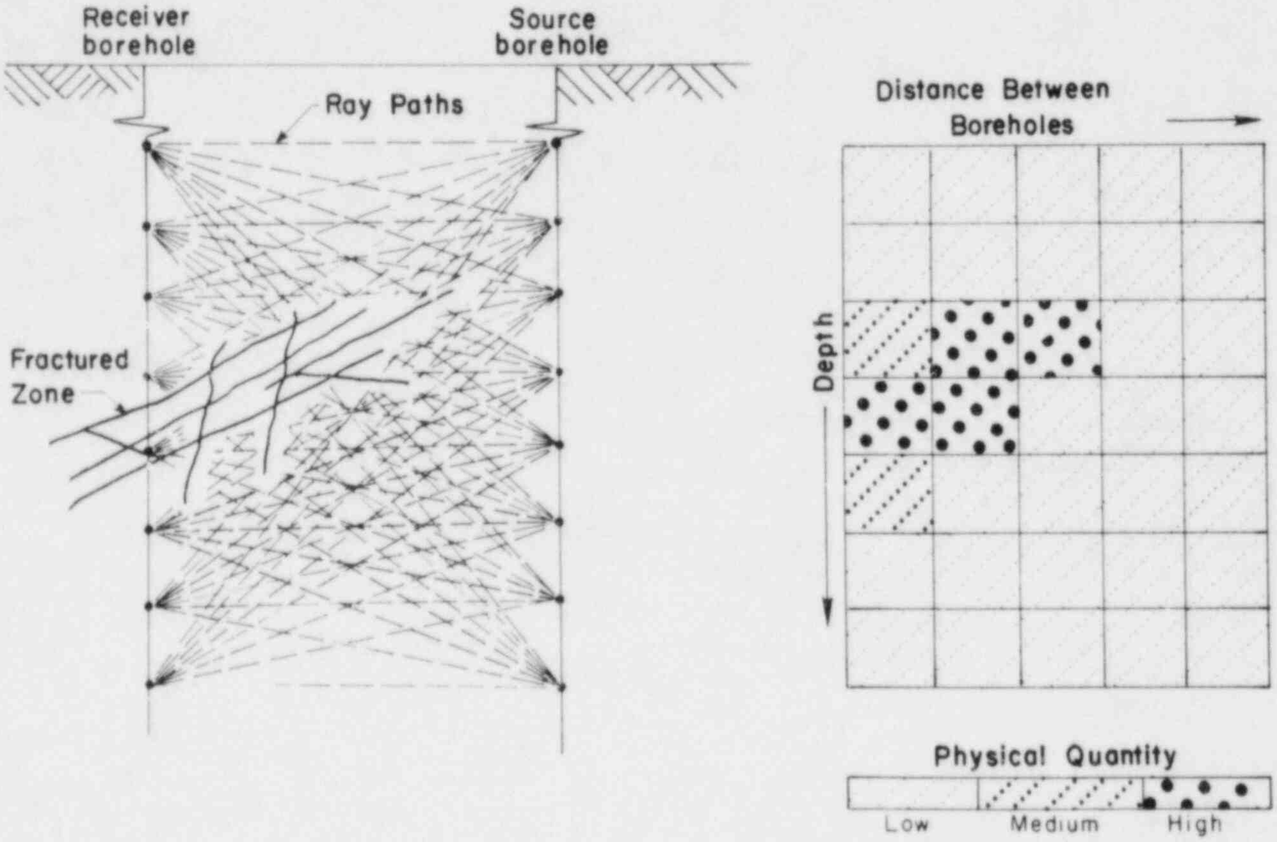

Figure 2

Geophysical tomography methods make use of ray paths with multiple orientations. Variations of a given parameter can be resolved versus depth and lateral position.

(3) Reflection tomography methods. These methods sample reflected ray paths rather than the direct transmission ray paths sampled by the two previous methods. The distance to the point of reflection can be calculated using the transit times of reflected rays. This method can lead to a two-dimensional representation of the variation of site properties. This report discusses scale model and computer synthesized acoustic reflection tomographs.

II. SEISMIC METHODS

A. CROSSHOLE SCANNING

Seismic, acoustic and ultrasonic geophysical methods are based on the fact that earth materials affect the propagation of elastic waves through the materials. Measurements of travel time are used to calculate the velocity of propagation of waves through rock. Measurements of wave amplitude are used to calculate the attenuation coefficient (a measure of the decrease in signal level per unit length of distance traveled) of rock masses. Anomalies such as fractured zones, which affect the elastic properties of rock masses, can be detected with seismic methods because the propagation of seismic waves is controlled by the elastic properties.

The seismic crosshole scanning method, with predominant frequencies from 0-200 Hz, has been used to obtain various engineering parameters such as seismic Young's Modulus and seismic Poisson's ratio (Darracot and Orr, 1976). In recent years, the seismic or acoustic crosshole scanning method has also been used to detect structures within rock masses such as fractured zones (McKenzie et al., 1982) and cavities (Buettner, 1984). Recent experiments suggest that acoustic waves, with predominant frequencies from 0.2-100 KHz, and ultrasonic waves, with predominant frequencies greater than 100 KHz, propagating between boreholes can be used to monitor conditions such as stress changes in the rock (Paulsson and King, 1980; Gladwin, 1982). These methods have many practical applications for investigating the rock mass surrounding a repository. In this section we discuss selected applications relevant to HLW site investigations and the limitations of these methods.

1. Determination of Rock Deformation Moduli

The seismic crosshole scanning method has been used routinely to determine the strength and deformational properties of rock masses. The propagation velocities of compressional (P) waves with velocity V_p, and shear (S) waves with velocity V_s, are used to calculate the seismic modulus of deformation, shear modulus, and seismic Poisson's ratio of a rock mass (Glass and Higgs, 1979).

The limitations of this approach should be considered. The seismic modulus of deformation cannot be used directly as the modulus of the rock mass for engineering design purposes. Seismic moduli of deformation are determined dynamically and are often considerably higher than the static moduli generally used for design of rock structures. There is no clear relationship between the seismic modulus and the modulus of deformation measured by static tests such as plate jacking (Stacey, 1974; Darracot and Orr, 1976). Thus, seismic moduli can not be used with a high degree of confidence to design repository structures.

The main use of the seismic crosshole scanning technique in the repository environment could be to investigate qualitative differences between the various zones of rock around the repository. For example, Sjogren et al. (1979) indicate that dispersion in Poisson's ratio and elastic moduli determined on the basis of seismic crosshole scanning measurements can be used successfully to establish the degree of homogeneity of a rock mass. They also indicate that by plotting elastic moduli versus Poisson's ratio one can reliably establish the location of optimum rock conditions.

2. Crosshole Velocity Scanning Used for Fracture Detection

Compressional (P) and shear (S) waves can be propagated between boreholes to detect structural discontinuities. Generally, propagation velocity anomalies are used as the diagnostic response. Figure 3 shows crosshole scans of V_p and V_s obtained near Oracle, Arizona. Note that the deflections in the curves roughly parallel each other, suggesting that both measurements were equally sensitive to the fractured zones in the rock. Note also that the correlation is relatively good between the crosshole scans and the well log information which is indicative of fracturing.

Results shown in Fig. 3 indicate that seismic velocity can be used successfully to detect fractured regions; however, limitations should be recognized. One problem that can affect the resolving power of this method arises when significant seismic energy travels along a path other than in a straight line linking source and receiver. When the geologic unit above or below the source and receiver has a higher velocity, refraction can occur. The refracted ray path can preclude obtaining the velocity for the material on a straight line path between source and receiver. This phenomenon is particularly problematic when fractured zones with thicknesses smaller than the distance between measurement stations are being investigated.

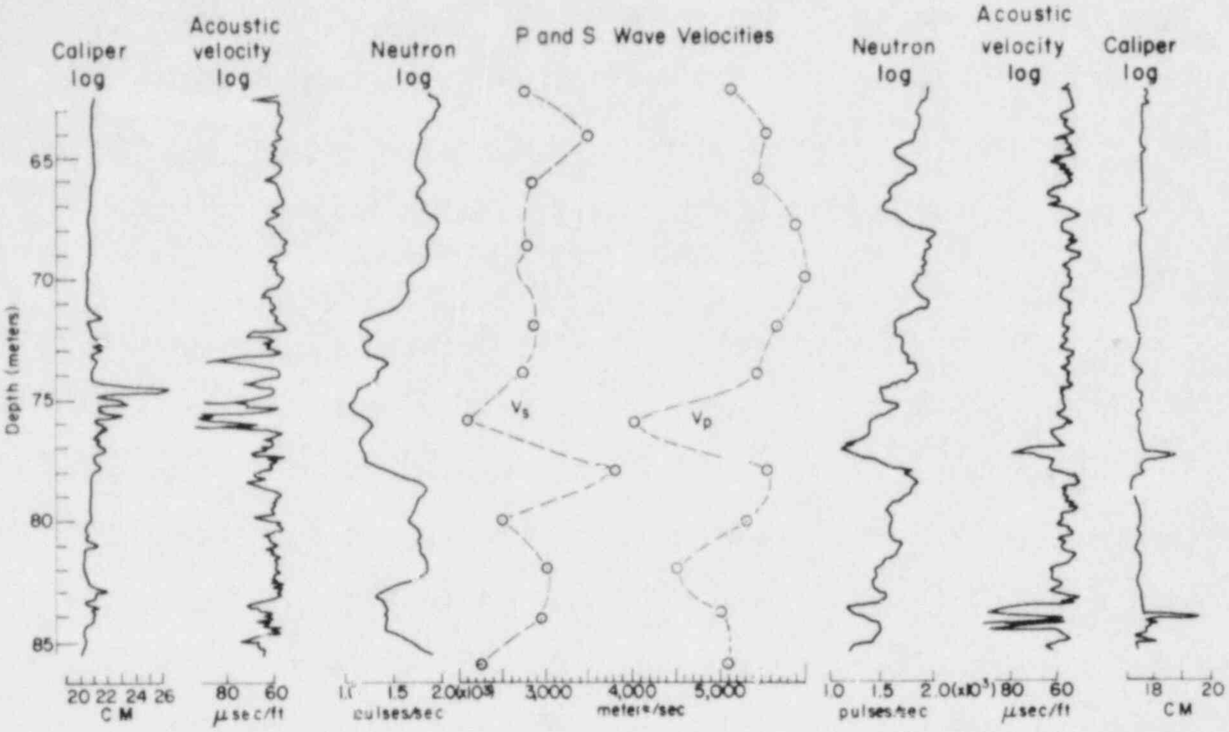

Figure 3

Seismic velocity scans of a fractured rock mass. Geophysical logs (from Keys, 1981) of the two boreholes used for crosshole scans are also shown.

Velocities calculated on the basis of refracted ray paths will be greater than velocities calculated for direct ray paths. Refracted ray paths can reduce the apparent contrast between intact rock and fractured zones when the true velocity of the fractured region cannot be measured. This reduction in apparent contrast may be sufficient to make the fractured zones undetectable. The minimum detectable thickness will depend on the velocity contrast between intact rock and fractured zones, the distance between source and receiver and the depth interval between source/receiver pairs.

Measurements of seismic propagation velocity appear to be sensitive to fractures at shallow depths, where confining stresses are low. However, as confining stresses increase, the effect of fractures on seismic wave propagation, particularly compressional wave propagation, decreases. Laboratory results from Stacey (1976) suggest that P- and S-wave propagation velocities are relatively insensitive to the number of joints when the confining stresses are larger than 2 MPa, the vertical stress expected when the depth is approximately 75m. Laboratory and field measurements performed by New and West (1980) indicate that the stress imposed even by shallow overburden can render P-wave velocity measurements insensitive to the frequency of fractures in a rock mass. On the other hand, Paulsson and King (1980) indicate that velocity measurements using a frequency of 20 KHz were sensitive to the presence of fractures at depths of 340 m. However, this may be due to their measurements being performed in the stress relief region about tunnel drifts at these depths. Given these results, the sensitivity of seismic velocity measurements to detect changes in frequency of joints should not be assumed.

3. Crosshole Seismic Investigations Using Other Wave Properties

Most seismic crosshole surveys are used to measure the travel time of seismic waves so that velocity of propagation can be calculated. In recent years, increasing numbers of researchers have studied other wave properties as potential indicators of fracturing in rock masses.

Laboratory studies (Stacey 1974, 1976) suggest that amplitude of compressional waves and shear wave frequencies appear to be good indicators of fracture conditions such as fracture frequency and fracture infilling materials. Furthermore, the studies suggest that shear waves in general are better detectors of fracture conditions than the generally used compressional waves.

The attenuation (or amplitude) of P-waves propagating through fractured media has also received increased attention in recent years. Mavko and Nur (1979) have indicated that seismic wave attenuation is very sensitive to pore aspect ratios (ratio of length to width). Flatter pores such as those associated with fractures affect the attenuation of seismic waves much more strongly than other pores. They also found that attenuation is very sensitive to the degree of saturation of fracture porosity rather than to total rock saturation. Stacey (1974, 1976) has indicated that compressional wave amplitude is sensitive to the number of fractures in the rocks. McKenzie *et al*. (1982) have also indicated that compressional wave amplitude is a good indicator of the presence of fractures in rock.

These studies suggest that the attenuation of seismic waves is a function of many variables. However, there appears to be agreement among investigators that attenuation can be an indicator of fracturing.

Results obtained at Oracle, Arizona appear to coincide with this observation. Figure 4 shows a scan of amplitude ratio. The amplitude is plotted in ratio form A_1/A_2, where A_1 and A_2 are the amplitudes measured at hydrophones positioned along a line defined by the source and the two hydrophones. Hydrophone 1 is located along the straight line between the source and hydrophone 2. This method normalizes all measurements so that inconsistencies in the wave amplitude generated at the source will not affect the results.

Note that the amplitude ratio and deflections in the well logs suggest zones of fracturing which roughly correlate. Frequent log deflections at the shallower depths correlate with zones of low amplitude ratio. The less frequent deflections occurring at deeper depths correlate with zones of high amptitude ratio. Note that individual log deflections and individual deflections in the amplitude scan do not always match.

The work of the various researchers previously listed indicates that wave attenuation is a function of multiple variables, such as fracture frequency, fracture geometry, and degree of saturation. The rough correlation shown in Fig. 4 may be due to this fact. Many poorly understood variables affect the attenuation measurements such that, at present, without in situ data at specific sites of interest, the measurement cannot be used with confidence for assessing overall rock fracture characteristics.

The attenuation scanning method may be a useful tool for monitoring time varying fluid saturation, fracture density and stress changes in the rock. The limited research performed in this area makes a weak case for the attenuation scanning method as a definitive monitoring tool for

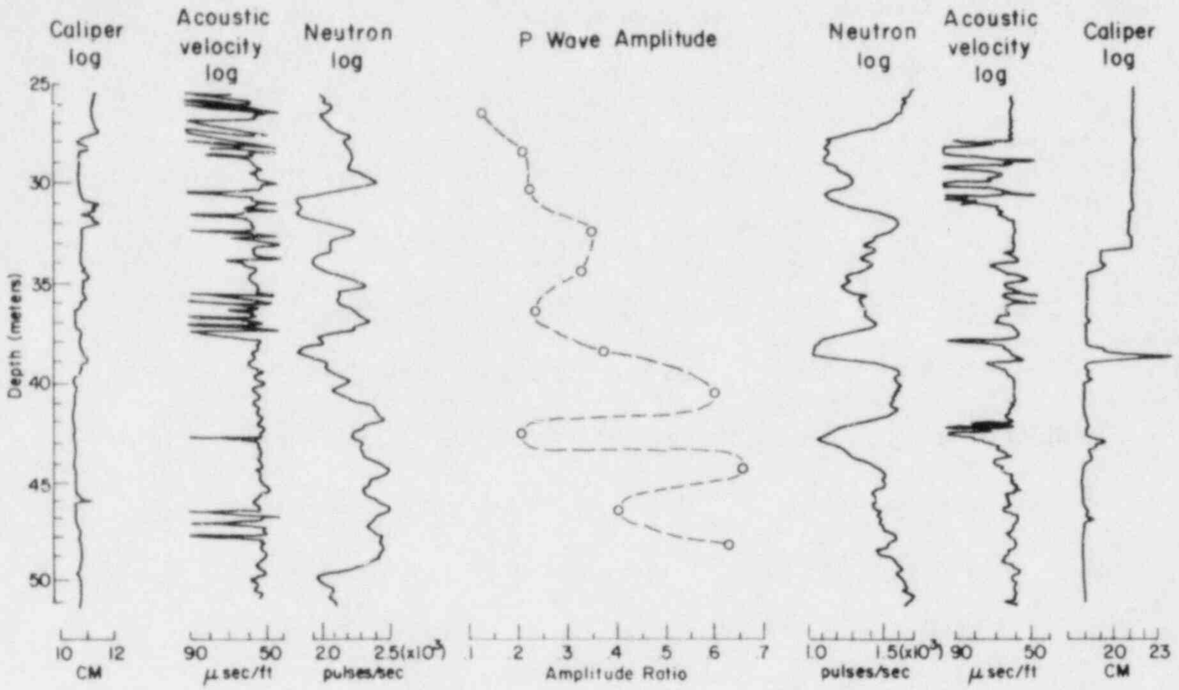

Figure 4

Crosshole scan of P-wave amplitude ratio of a fractured rock mass. Geophysical logs (from Keys, 1981) of the boreholes used for probing are also shown.

repository investigations. Additional research may eliminate many of the uncertainties associated with attenuation measurements and make such measurements reliable indicators of rock mass characteristics.

4. Factors Affecting the Accuracy of Seismic Scanning Methods

The accuracy of all seismic crosshole data is directly dependent on knowledge of the distance between boreholes where the sensors are placed. In many applications where the length of the boreholes is relatively short, there is a tendency to assume that the boreholes are straight. In fractured rock masses, this assumption is dangerous because fractured regions can cause significant borehole deviations. Consequently, accurate borehole surveys should be used when analyzing crosshole data.

The separation between boreholes also plays an important role when fractures are to be detected. Thin fractured zones with lower propagation velocities than the surrounding intact rock may not be detected if borehole spacing is excessive. When borehole separations are large, the first arrivals detected may be rays that refracted through adjacent zones of higher velocity. To minimize this problem, Snell's law can be used to calculate optimum borehole spacing, given the expected subsurface velocity contrast and minimum fractured zone thickness (Department of the Army, Corps of Engineers, 1979).

Most applications of seismic crosshole scanning involve measuring travel time between source and receiver. Various sources of error can affect travel time measurements. When explosive charges or blasting caps are used as sources some time delay may occur between the application of current to the cap and the begining of detonation. There is disagreement about the magnitude of this delay. It may be on the order of 0.5 milliseconds (Mc Lamore et al., 1978) or seven milliseconds. (Department of the Army Corps of Engineers, 1979). Consequently, it is important to use equipment which detects the actual moment of detonation and not the moment at which the electric current is applied.

Other errors in travel time data are caused by filters used to process the waveforms. Filtered waveforms are shifted in time and this shift introduces an error in the measured travel time (Hall et al., 1981). Filtered waveforms result from filters built-into the seismographs used to measure travel time, or from filters used subsequently to process the waveforms. Filtering-induced time-lags are a function of the predominant frequency of the waveform and of the cut-off frequencies of the filters, and can be easily calculated.

Such time lags are most important when they are more than several percent of the total travel time. Filtering-induced time lags can be important when the borehole separation is small (several meters) and yet, they are commonly disregarded. Since the induced time lags are a function of predominant frequency of the waveform, they are also a function of the ray path length because the higher frequencies are selectively attenuated with distance. Consequently, time-lags also become important in applications where ray paths of variable length are used (e.g., velocity scans along curved boreholes or in seismic transmission tomography.)

The travel time of S-waves can be in error because the arrival of shear waves can be difficult to recognize. S-waves arrive later than P-waves and, as a result, may be obscured by the P-wave train. Various strategies are available to highlight the arrival of the S-waves. Sources which produce polarized waves and can reverse wave polarity can be used successfully. Three-component geophones are very helpful because they sample waveform along three orthogonal orientations. Depending upon the orientation, one or two of the geophones will be more sensitive to S-wave motion than to P-wave motion. Low-pass filtering can be used to eliminate the higher frequencies in the P-wave train. Stacking of waveforms for which source polarity is reversed will also highlight S-wave arrival.

When wave amplitude measurements are performed, other factors affect the accuracy of the data. Several seismic sources used for crosshole surveys produce waves with inconsistent amplitudes (Department of the Army Corps, of Engineers, 1979). When explosives, air guns, or borehole hammers are used as sources, their lack of repeatability should be accounted for. One approach that accounts for lack of repeatability uses two geophones along each ray path to be sampled. In this case, the geophone farthest from the source is referenced to the geophone closest to source. Any inconsistencies in the wave amplitude at the source are thereby eliminated.

Erroneous wave amplitudes can be measured when seismic waves are reflected by various subsurface features such as the walls of tunnels and bedding. When reflections occur, the amplitude measured is affected by the interference (constructive or destructive) of the reflected ray path on the direct ray path. Significant reflections occur when there are relatively large variations in wave propagation velocity throughout the rock mass.

Seismic wave amplitudes are strongly affected by the coupling of the source and receiver to the rock. Since all excavations in the repository will be dewatered, coupling will have to be accomplished by pressing the sensors against the rock. To obtain meaningful measurements of amplitude, the coupling at each measurement station will have to be consistent.

B. SEISMIC TRANSMISSION TOMOGRAPHY

1. Seismic Transmission Tomography Applied to the Mapping of Fractures

The velocity scanning method discussed previously is generally interpreted in terms of a layered structure, i.e., the velocity measured along a given ray path is the average velocity of the layer of rock sampled. This information is sufficient to establish the depth to fractured zones but is insufficient to establish the orientation, extent, or interconnection between fractured zones. This information will be needed to fully understand the behaviors of in situ tests at the repository site and to predict the behavior of the repository system. To obtain this information, methods with higher resolution capabilities are required.

The seismic transmission tomography method was evaluated at Oracle as a method which could potentially offer better resolution to map fractures. Measurements of travel time for both P- and S-waves were obtained. Maps of the variation in propagation velocity were reconstructed using a reconstruction algorithm similar to that described by Dines and Lytle (1979). The result of a reconstructions of P-wave propagation velocity is shown in Fig. 5. S-wave results and additional P-wave results are discussed later. These figures pictorially show the variations in propagation velocity throughout the rock between the two boreholes used for probing. Dark regions represent rock having relatively low P-wave velocities and lighter regions represent rock with relatively high velocities. Note the correlation between the darker colored regions and the deflections in the well logs shown (log deflections indicate possible zones of fracturing around the boreholes). The patterns created by the variations in velocity can be used to infer the orientation, extent and interconnection of fractured zones in this region.

The geotomography method requires that ray paths with many different orientations be propagated through the rock. It is more time consuming than the seismic scanning method since more data is usually collected. The resolving capability of this method is better than that offered by the seismic scanning method because it provides a two-dimensional representation of variations within the rock instead of the one-dimensional representation of the crosshole scanning method.

2. Factors Affecting the Resolution of the Seismic Transmission Tomography Method

The same factors which affect the accuracy of the seismic scanning methods (section II.A.4) also affect the accuracy of the seismic transmission tomography method. This section discusses additional factors which should be accounted for to produce accurate results with this method. The resolution of the seismic transmission tomography method

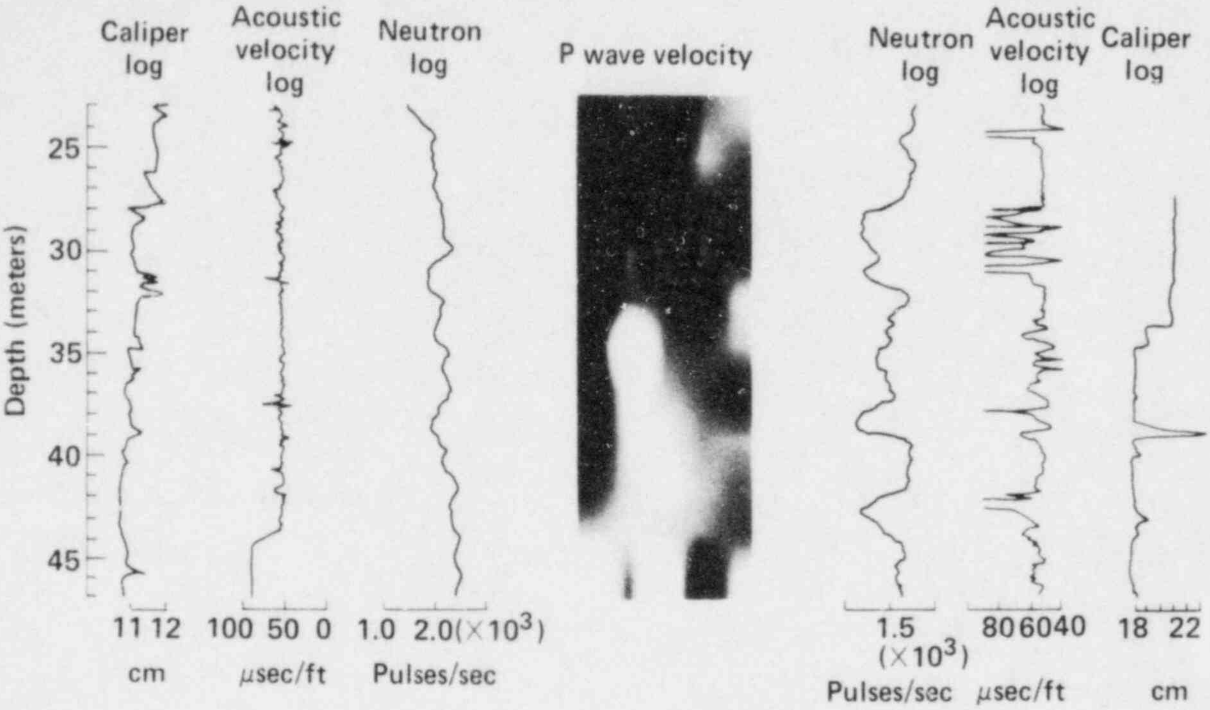

Figure 5

Geophysical transmission tomograph (geotomograph) showing velocity variations of a fractured rock mass. Geophysical logs (from Keys, 1981) of the boreholes used for probing are also shown.

decreases when refraction of ray paths occur, a phenomenon similar to the refraction-induced decrease in resolution in the crosshole scanning method. Since the reconstruction algorithm generally used in transmission tomography assumes straight ray paths, the resolution from this method decreases when significant ray bending occurs. Dines and Lytle (1979) performed modelling studies which indicated that refractions induced by velocity contrasts of up to 16% can be successfully interpreted although the resolution of the reconstruction was substantially degraded at that level.

Lytle and Dines (1980) developed a reconstruction method which can take into account significant ray bending. The method improves the accuracy of the reconstruction when rays are bent significantly by velocity contrasts in the rock. Their technique works well when the data has low levels of noise. This method is computationally time-consuming and expensive; it may limit the number of ray paths which can reasonably be analyzed to a few hundred.

The combined source-receiver radiation pattern affects the measured amplitude of the waves when ray paths of varying orientations are used. Inaccuracies in the radiation pattern used can cause errors in the reconstruction of the image. The radiation pattern can be obtained by modeling (Lee and Balch, 1982) or it can be measured in the field using a method similar to that proposed by Daily (1982). Field measurement is preferred because site-specific geologic conditions influence the radiation pattern. However, it is difficult to obtain accurate field measurements because the presence of geological heterogeneities causes data scatter. The radiation pattern effect is negligible when two geophones are sampled along each ray path.

The boreholes used to implement the seismic transmission tomography method place restrictions on the length and orientations of ray paths used for probing. The area of interest can seldom be surrounded entirely and therefore, the ray paths used provide biased information in terms of orientation. This biased probing geometry affect the accuracy of the reconstructed image. Dines and Lytle (1979) discuss strategies which minimize these reconstruction errors.

III. ELECTROMAGNETIC METHODS

A. CROSSHOLE SCANNING

Electromagnetic prospecting techniques have been used in mineral exploration (Telford et al. 1976). Low frequency methods are routinely used to detect good electrical conductors at shallow depth. However, these methods generally lack sufficient sensitivity and resolution to map geological heterogeneities in the near vicinity of HLW sites.

In recent years, electromagnetic crosshole scanning methods which use radio frequency waves have received increased attention for their ability to provide an increased level of resolution over the low frequency electromagnetic methods (Lytle, 1979, Lytle et al. 1981). Both signal velocity and amplitude measurements are used.

Methods of determining the velocity of propagation of electromagnetic waves through rock are performed by measuring the arrival time of pulses and by using swept-frequency measurements (Lytle et al., 1976). In the swept-frequency measurements, phase shifts are used to calculate the dielectric constant of the rock, which is then used to calculate the velocity of propagation of electromagnetic waves.

Signal level measurements are used to calculate the electromagnetic attenuation factor of rocks. The attenuation factor is a measure of the degree of attenuation an electromagnetic signal suffers when traveling through a unit length of rock.

Fluids such as water and air have electromagnetic properties substantially different from those of rock. Anomalies such as fractured zones or brine pockets may be fluid-filled. Since brine, and sometimes groundwater, have a much larger high-frequency electromagnetic attenuation factor than dry rock, anomalies may be detected with high frequency electromagnetic methods. High-frequency methods are especially useful in rocks which have relatively low water content (e.g. salt, crystalline rocks) because their probing range is large. For example, the electromagnetic probing range in salt can be of the order of hundreds of meters for frequencies of 100 MHz or greater.

Crosshole electromagnetic methods are similar to the seismic methods previously discussed. Scans of wave propagation velocity or attenuation can be obtained by the scanning method.

1. Electromagnetic Scanning Method Applied to the Detection of Fractured Zones

The electromagnetic crosshole scanning method has been used successfully to investigate prospective sites for the disposal of radioactive wastes (Nickel *et al.*, 1983). Representative crosshole scanning data has also been obtained for the fractured granite near Oracle, Arizona, as shown in Fig. 6. This figure shows scans of the ratio of change in phase to change in frequency (used to calculate dielectric constant and wave propagation velocity) and scans of received power levels (used to calculate attenuation factor). The formulas used for these calculations are given by Lytle *et al.* (1976). Note that increases in phase changes generally coincide with decreases in received power levels.

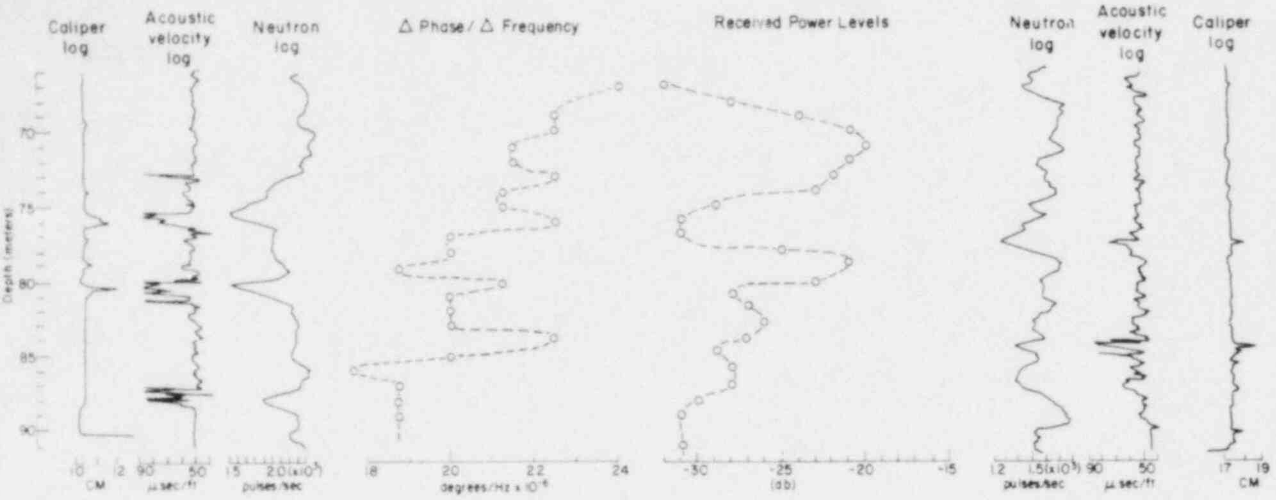

Figure 6

Crosshole scans of electromagnetic measurements of a fractured rock mass. Geophysical logs (from Keys, 1981) of the boreholes are also shown.

Also note that the increases in phase change and decreases in the power level correlate with deflections in the well logs which are indicative of fractured regions. The results of Figure 6 suggest that both sets of electromagnetic measurements are sensitive to fractured zones.

In a repository constructed below the water table, parts of the rock mass may be partially dewatered after the waste emplacement rooms are constructed. Olhoeft (1974) indicates that the electrical properties of rocks are dominated by pore fluid conduction when more than seven molecular layers of fluid are adsorbed onto a dielectric surface. Thus, rock fractures around the repository are likely to contain sufficient water to create contrasting electrical properties which are detectable. The degree of electromagnetic contrast between intact rock and fractured rock is difficult to predict, since it is governed by site-specific conditions. The degree of contrast is expected to be larger for a saturated fractured rock mass than for an unsaturated fractured rock mass. However, contrast may be eliminated if the rock is heated beyond the evaporation point of water.

2. Factors Affecting Accuracy of Electromagnetic Scanning Methods

Many of the factors controlling the accuracy of electromagnetic scanning methods are the same as those of the seismic scanning methods. Inaccurate knowledge of borehole deviations as well as ray path reflections or refractions, compromise the accuracy of electromagnetic results. However, there are a few important differences between seismic and electromagnetic scanning methods which will be discussed below.

The usefulness of electromagnetic methods is dependent on the ability to infer the geologic characteristics which cause the contrast in the electromagnetic properties measured. In repository applications subsurface water will be responsible for the bulk of the contrast in electromagnetic properties in the radio frequency range. The subsurface water can be detected along important hydrological pathways such as fractured zones or trapped in the matrix of the geologic materials. Thus, various alternative interpretations will have to be considered. To be able to differentiate between these requires some knowledge of the characteristics of the rock mass being investigated.

In a way similar to seismic scanning measurements, electromagnetic signal level measurements can be affected by interference between direct and reflected ray paths. To establish whether this interference will compromise the accuracy of the measurements, swept frequency measurements have been used (Lytle *et al*. 1976). Pulse measurements, not discussed here in detail, can also be used. Both pulse and swept frequency measurements may detect the presence of any reflecting boundaries as well as the distance to them.

B. ELECTROMAGNETIC TRANSMISSION TOMOGRAPHY APPLICATIONS

Results from electromagnetic transmission tomography experiments performed at Oracle, Arizona are described in Section VI of this report. General remarks pertinent to electromagnetic transmission tomography have been addressed previously in Section III A (Electromagnetic Crosshole Scanning) and Section II B (Seismic Transmission Tomography).

1. Factors Affecting the Accuracy of the Electromagnetic Transmission Tomography Method

The accuracy of the electromagnetic transmission tomography method is affected by the factors previously listed for electromagnetic scanning technique and the seismic transmission tomography method. Consequently, the same strategies used to minimize inaccuracies in both of these methods can also be used to improve the accuracy of the electromagnetic transmission tomography technique. However, there are also a few differences which need to be discussed.

When measurements of received signal level are used, it is important to measure accurately the power radiated by the transmitting antenna. Inaccurate knowledge of the transmitted power results in error measured along ray paths. However, since ray paths have variable lengths, the error affects each ray path to varying degrees and errors in the reconstruction are created. These errors are negligible if the power radiated by the transmitting antenna is measured accurately and taken into account.

One strategy which can significantly improve the accuracy and resolution of the electromagnetic transmission tomography method involves the use of tracers which change the electromagnetic properties of fluids in rock (Ramirez and Lytle, 1983). When this strategy is effectively used, it has been our experience that neither the power transmitted by the antenna nor the antenna radiation patterns are needed to perform accurate reconstructions. This strategy requires that measurements be taken before and after the tracer is forced into the rock mass. The difference in these two sets of measurements are used to reconstruct an image. Since changes in electromagnetic properties should only occur in those rock volumes accepting the tracer, the method is particularly useful in highlighting permeable fractures (Ramirez et al., 1982). This approach is more time consuming than the usual electromagnetic transmission tomography method because two sets of measurements are needed. It can also be a logistically complex endeavor because it may require the use of pumps and/or packers to force the tracers into the rock.

IV. ELECTRICAL RESISTIVITY METHODS

A. CROSSHOLE SCANNING

Resistivity surveys measure variations in the potential of an electric field set up in a rock mass by an applied current. Properties that affect the resistivity of rock include porosity, fractures, water content, composition (e.g., clay content) and salinity of the pore water. In a repository scenario, the main advantage of resistivity surveys is their sensitivity to porosity and water content of the rock mass. Also, the resistivity method is likely to have longer probing ranges than the other methods discussed in this document.

Resistivity scanning performed within a single borehole is a standard geophysical logging measurement. It has well-known limitations and merits (Telford, 1976). Single-borehole resistivity techniques are well-suited to delineating geologic layers, particularly sedimentary layers and defining porosity changes if the porosity is large. Unfortunately, some geologic formations considered for nuclear waste disposal do not fit these criteria.

Desirable waste disposal sites have low porosity, may not be sedimentary in form (e.g., basalt or granite) and are to be within relatively large homogenous geologic bodies. Conventional single-borehole resistivity scanning typically probes to at most a few meters from the borehole. Thus, it has a well-known limited depth of detection of anomalous conditions remote from the borehole. It should be recognized also that conventional resistivity scanning does not indicate the azimuth (or direction from the borehole) to the anomaly. Resistivity scanning performed between two boreholes is a less standard geophysical logging measurement in the U.S. It has had more application in Soviet technology. Recent theoretical studies have indicated the limitations and merits of this method (Daniels, 1977; Lytle, 1983; Lytle and Hanson, 1983).

B. FACTORS AFFECTING THE ACCURACY OF ELECTRICAL RESISTIVITY METHODS

There is a fundamental limiting factor of all potential field probing methods, including that of electrical resistivity. Potential fields are perturbed by the presence of an anomaly of finite size, but the nominal influence of the perturbation is typically limited to the near vicinity of the anomaly. The perturbation in the resistivity response is typically not observable if the source and receiver electrode locations are more than a few characteristic dimensions removed from the anomaly of finite size.

For surface resistivity measurements, the effect of topography can dominate the results if not properly accounted for. This is particularly true if there is a complex three-dimensional conductivity structure. Measurements performed from within a borehole would be influenced by topography to a lesser extent. Similarly, quantitative resistivity measurements performed near the underground repository (i.e., the shaft and tunnel complex) can be significantly affected by shafts and tunnels.

Prospective geologic repositories are to be chosen with the requirement of low permeability. The porosity of such formations can be low and the resistivity can be high. The net effect is that these physical properties are generally difficult to measure with a high degree of accuracy. Resistivity measurements are more accurate and have been much more extensively used in sedimentary formations where the permeability is high, the porosity is high and the resistivity is low. Tuff is likely to have similar characteristics whereas salt, basalt and granite will not. Hence, calibration of resistivity measurements is needed to attain reliable quantitative results. The calibration should be performed under known controlled conditions. The quantitative interpretation of resistivity results is significantly influenced by drilling fluid invasion, grain density variation, and formation water resistivity.

Recent work has indicated that crosshole resistivity scanning has merit for detecting anomalous features at a greater distance from a set of boreholes than do resistivity measurements performed in either one of the boreholes (Lytle and Hanson, 1983). Crosshole resistivity scanning has the advantage of sensing within a limited sector. Thus, if an anomaly is detected using crosshole resistivity scanning, the direction to the anomaly is relatively well-defined.

Generally, resistivity surveys are used in exploration problems in which a specific kind of geological condition is investigated. Where the range of possibilities has been narrowed down by other geological or geophysical information, resistivity information is useful in defining the types of lithologies and geological structures defined by the survey. Where little complementary information is available, resistivity data is difficult to interpret.

V. UNDERGROUND REFLECTION METHOD

A. REFLECTION TOMOGRAPHY

In certain circumstances, probing between boreholes may not be possible as two boreholes may not be available. When only one borehole exists, only reflection measurements may be possible. Thus, the tomographic concept as adapted to fit the reflection situation has been studied. There have been indications that reflection tomography may have merit (Norton and Linzer, 1979) in medical and nondestructive evaluation probing. An evaluation was performed that focused on the applicability of reflection tomography to geophysical problems pertinent to geologic waste repositories.

The interpretation procedure used with reflection tomography data is analogous to that used for transmission tomography. Details of the procedure and the experimental results have been presented to the NRC in the 1980-1981 Annual Progress Report for this project. Important points relevant to the applicability of the method are discussed here.

This work indicated that if the source and sensor can be rotated 180° around the area to be probed, the reconstructions obtained are very satisfactory. However, a scanning configuration similar to that which would be used in a borehole creates a limited angle of view (likely less than 45°). Reconstructions of experimental reflection tomography data for this situation are much less accurate. There is substantial smearing of the image. It appears that single borehole reflection tomography imaging performed with a severely limited angle of view does not adequately define anomalous features.

Another disadvantage of reflection tomography probing from a single borehole is that reflections return from all directions. Consequently, azimuthal locations of anomalous features are not resolved.

In the case of repository investigations, reflection tomography may be useful in certain situations. The method could be useful to investigate rock pillars that are entirely surrounded by tunnels. In this case, the range of angles of views used would be close to 360°, thus providing the range of views needed for satisfactory resolution. This method is experimental however and will have to be thoroughly tested before it can be used with confidence in a repository environment.

VI. CROSSHOLE TECHNIQUES USED AT THE ORACLE SITE

The hydrological and mechanical behavior of large masses of rock is governed principally by fractures. Thus, fracture characterization is a very important aspect of the site characterization program for high level waste repository sites. The Panel on Rock Mechanics Research Requirements (1981) indicated that the greatest need in fracture characterization work is in developing methods to detect and describe fractures remotely; i.e., in the large volumes of rock beneath outcrops and between boreholes or other underground openings.

Experiments were performed in which various crosshole geophysical techniques were evaluated on their capability to map fractures remotely. Geophysical measurements were made below the water table in a shallow, fractured granitic rock mass near the town of Oracle, Arizona. The geologic setting of the site is described by Hsieh (1983). Because the effectiveness of geophysical methods is generally heavily influenced by site specific factors, the experimental objective was to evaluate the fracture detection capabilities of the various methods in the same geologic environment.

The methods used can be classified as active probing methods because artificial force fields are used. Seismic (P-and S-waves), electromagnetic and electrical fields were applied at various positions throughout the fractured rock. In this section, selected experimental results obtained at the Oracle Site are presented and compared. Other results obtained at the Oracle Site have already been presented in previous chapters. The objective of the experiments was to identify those techniques which can be used successfully to detect fractures and to compare their relative merits.

A. ELECTROMAGNETIC MEASUREMENTS

General considerations pertaining to electromagnetic measurements have been described in Chapter III. This section discusses additional experimental results and their significance for repository investigations. Crosshole electromagnetic measurements of electromagnetic attenuation factor α and relative dielectric constant (ϵ_r) have been performed. Lytle et al. (1976) describes the way in which measurements of α and ϵ_r are made and analyzed. The electromagnetic attenuation factor describes the reduction in signal levels of waves as they travel through rock. The relative dielectric constant is related to the velocity of propagation v of electromagnetic waves; $v = c/\sqrt{\epsilon_r}$ where c is the speed of light in free space. Thus, the relative dielectric constant can be used to describe the velocity of propagation of electromagnetic waves traveling through rock.

Figure 7 shows the locations of boreholes at the Oracle site. Figures 8 and 9 show the results of α and ϵ_r transmission tomography measurements performed between boreholes M-1 and H-2. Darker colors indicate rock regions having high α and ϵ_r. Additional measurements of α, obtained in a previous experiment, have been presented by Ramirez et al. (1982). The α and ϵ_r measurements shown in Figures 8 and 9 were obtained in the same physical region between these boreholes. Geophysical logs of the boreholes used are shown on either side of the image. Deflections shown by the borehole logs are interpreted to be caused by fractured zones intersected by the boreholes.

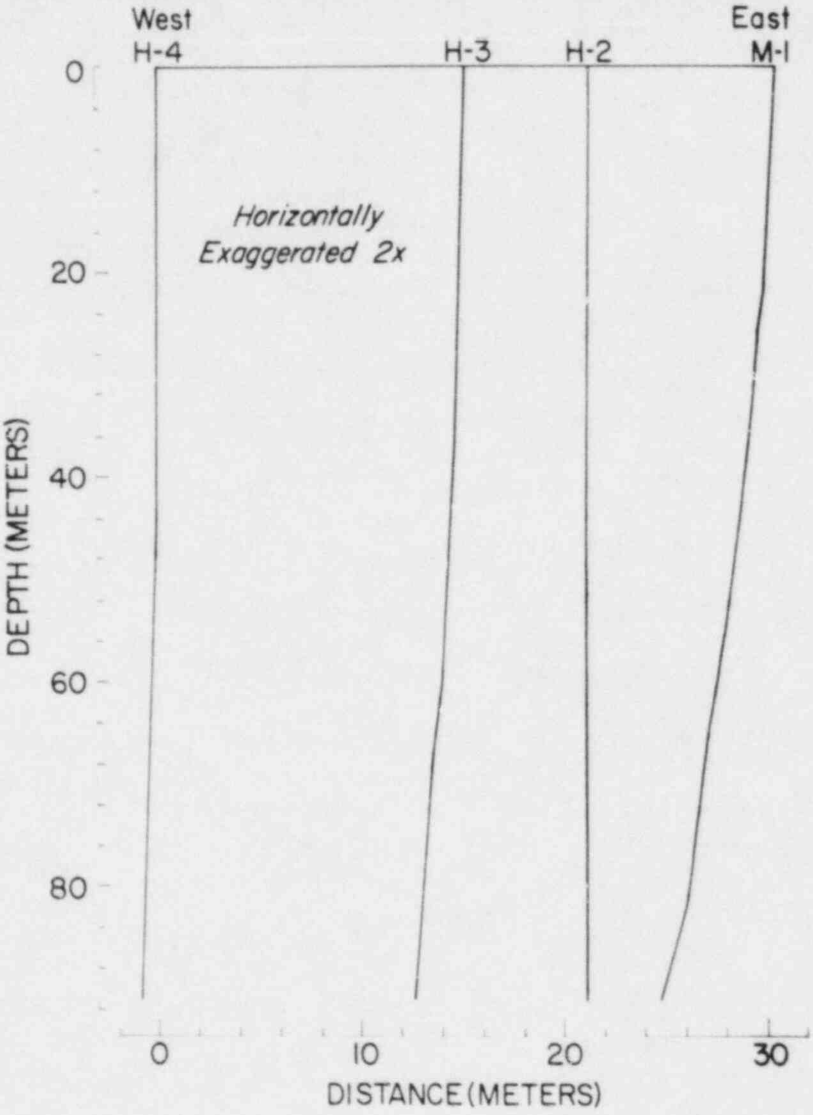

Figure 7

Boreholes available at the Oracle experimental site. The locations of boreholes M-1, H-2, H-3, and H-4 are shown.

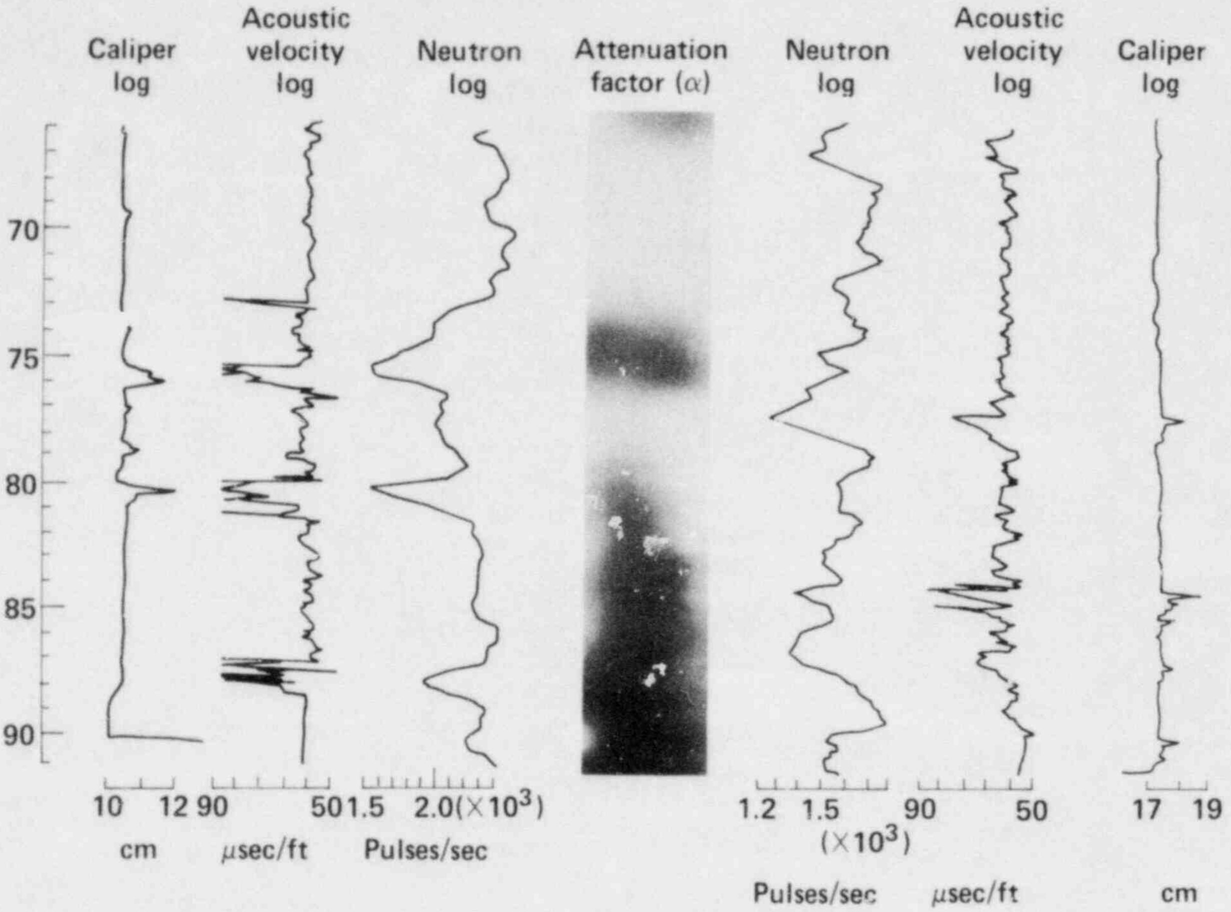

Figure 8

Geophysical tomograph showing variations of electromagnetic attenuation factor throughout a fractured rock mass. Geophysical logs (from Keys, 1981) of the boreholes used for probing are also shown. The excitation frequency is 40 MHz.

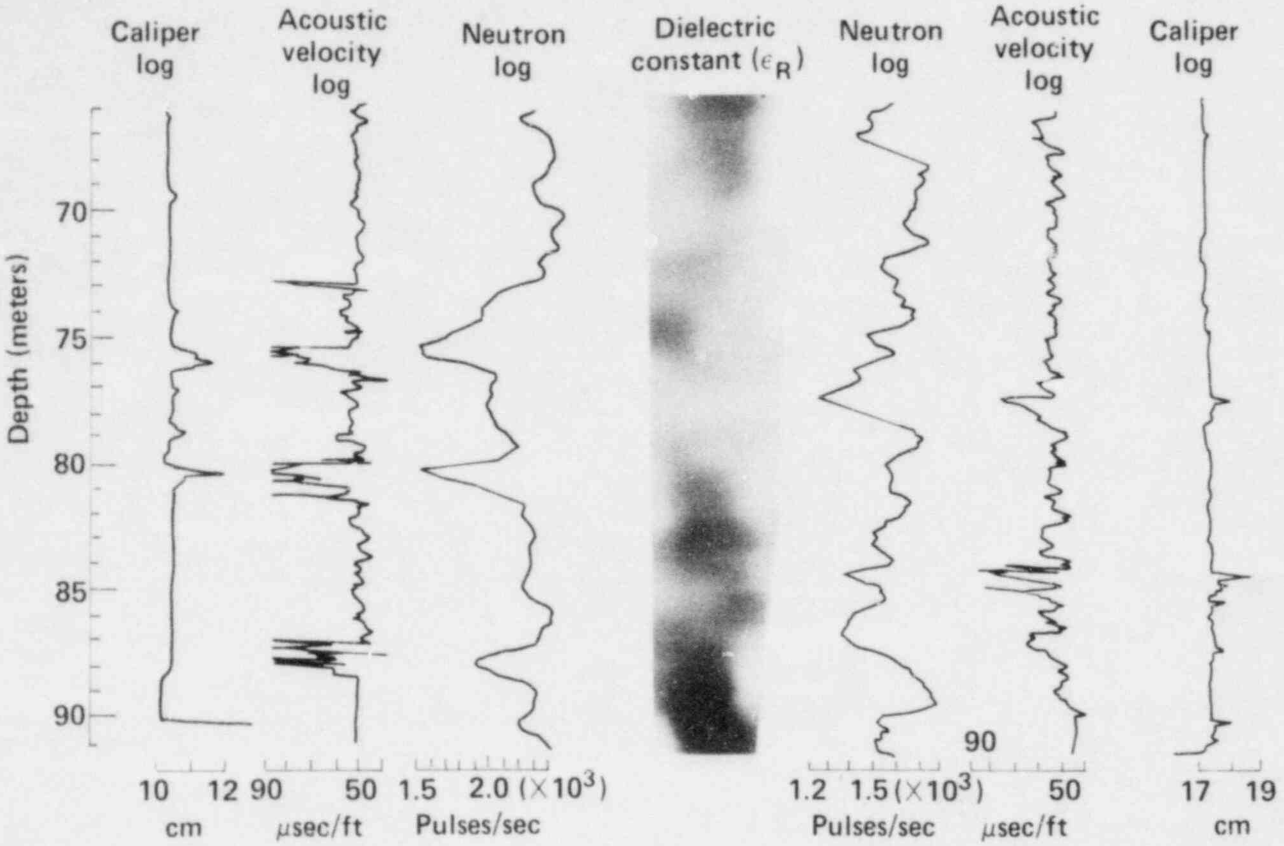

Figure 9

Geophysical tomograph showing variations of dielectric constant throughout a fractured rock mass. Geophysical logs (from Keys, 1981) of the boreholes used for probing are also shown.

Figures 8 and 9 indicate that transmission tomography measurements of α and ϵ_r are indicative of zones of fracturing in the rock. Note that both types of measurements appear to be equally sensitive to fractures.

An additional set of α transmission tomography measurements was obtained between boreholes M-1 and H-4 (refer to Fig. 7 for borehole locations). Figure 10 shows the results of these measurements. Measurements of rock permeability performed by the University of Arizona are also shown. Note that, in a general sense, zones of high electromagnetic attentuation (darker regions in the image) tend to coincide with zones showing the highest permeabilities. The correlation shown in this figure suggests that measurements of α can be used successfully to detect permeable zones of fracturing.

In a repository scenario, part of the rock mass will be dewatered and the contrast between fractured and unfractured rock will be less than if the fractures were completely saturated with water. Thus, α measurements might be better suited to detect fractures under these conditions. However, given that the effectiveness of these methods is controlled by site specific factors, definitive statements cannot be made until these techniques are used under repository-like conditions.

From an operational standpoint, measurements of α offer some advantages over measurements of ϵ_r. Field measurements of ϵ_r are made by sweeping frequency and detecting the changes in phase. Measurements could also have been made of pulse transit time. Measurement of ϵ_r offers one significant advantage: measurements of ϵ_r are independent of the radiation pattern. To measure α, the radiation pattern of the transmitter and receiver antennas must be accurately measured in the field. Measurements

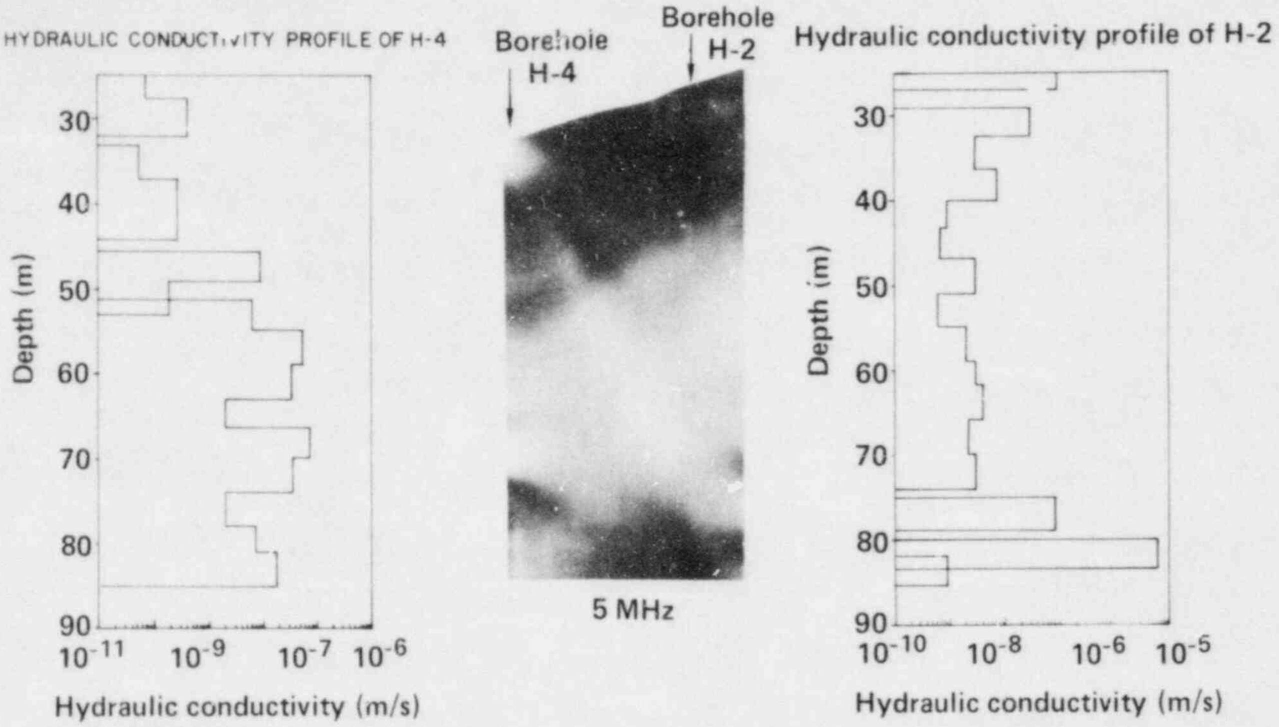

Figure 10

Attenuation tomograph showing variations of electromagnetic attenuation factor throughout a fractured rock mass. Hydraulic conductivity profiles (from Hsieh, 1983) of boreholes H-2 and H-4 are shown for comparison.

of radiation pattern are affected by geological heterogeneities which cause scatter of the data. The measured antenna radiation patterns will be erroneous to some degree. Thus, ϵ_r measurements will generally be more accurate than α measurements.

B. SEISMIC MEASUREMENTS

A general discussion of seismic crosshole measurements and certain crosshole results obtained at Oracle were presented in Chapter II. In this section, we discuss additional experimental results obtained at Oracle and their significance relative to repository investigations. Crosshole compressional (P) and shear (S) wave seismic methods were used to detect fractures in the granitic rock mass. Measurements of the velocity of propagation of P-waves (V_p) and S-waves (V_s) as well as measurements of the attenuation of P-wave amplitude (A_p) were performed.

Two boreholes were used for the measurement of the velocities of propagation. A sparker was used as the source of the P-waves and a borehole shear wave hammer for the source of S-waves. The receivers were placed in a second borehole. Hydrophones were used for the P-wave measurements and geophones clamped against the borehole walls for the S-wave measurements. Low-pass filtering to eliminate the higher frequencies associated with the P-wave train was used to highlight the arrival of the S-wave. Also, S-waves of reverse polarity were generated by using weight drops for one direction and pulling upward on the weight for the reverse direction.

A different measurement procedure involving a three-borehole configuration was used for the wave attentuation measurements. The source was placed in one of the outer boreholes and the receivers in the other two holes. The depths of the source and receivers were adjusted so that their locations defined a straight line. Under these conditions inconsistencies in the amplitude of the wave generated by the source could be eliminated.

Figure 5 shows a geophysical tomography image constructed with V_p data. An image of the same region showing changes in electromagnetic attenuation factor α was shown by Ramirez et al., (1982) and is illustrated in Figure 11. The measurements for these two images were obtained of the same area of rock between boreholes M-1 and H-2 (refer to Fig. 7 for the location of measurement region). Note that, in general, both images show very similar structure. The differences which can be observed may be caused by the fact that the seismic image was constructed with only 40% of the number of data points used for the electromagnetic image. The similarity between images suggests that, given a geologic environment similar to that of the experimental site at Oracle, measurements of α and V_p are equally useful to detect fractured regions.

Figures 12 and 13 show images constructed with V_p and V_s information. The data for these images was collected between boreholes M-1 and H-3. Dark colors indicate rock having low seismic velocities. Note that both V_p and V_s decrease in zones of fracturing. Also note that there are differences as well as similarities between images, the dissimilarities may be caused by various factors. The number of data points used to reconstruct the images is greater for the V_p image. The V_s data set only includes information from ray paths with orientations of less than 45° whereas raypaths with orientations of up to 58° were used for the V_p image.

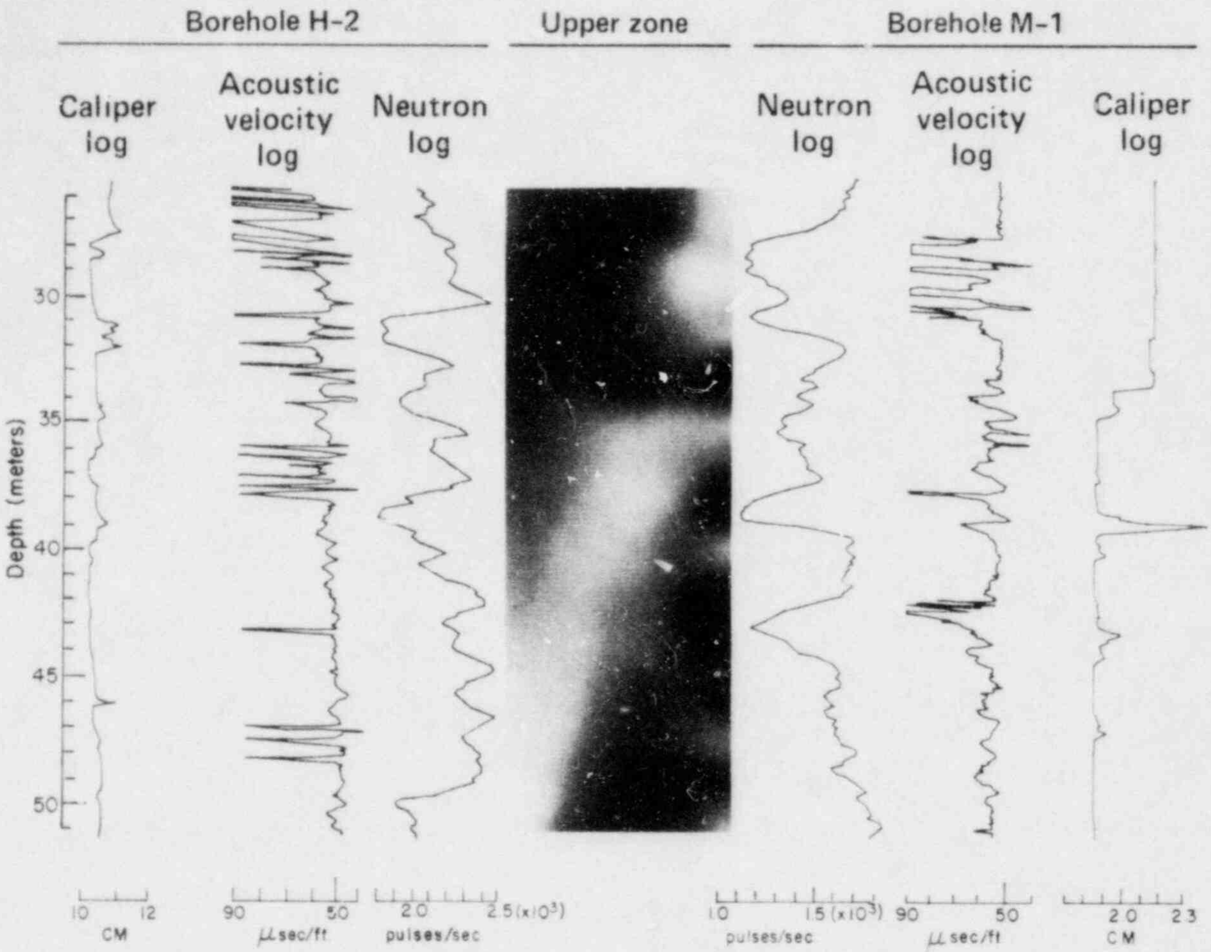

Figure 11

Comparison of the geophysical logs for Boreholes H-2 and M-1 and the difference geotomograph corresponding to the upper measurement zone.

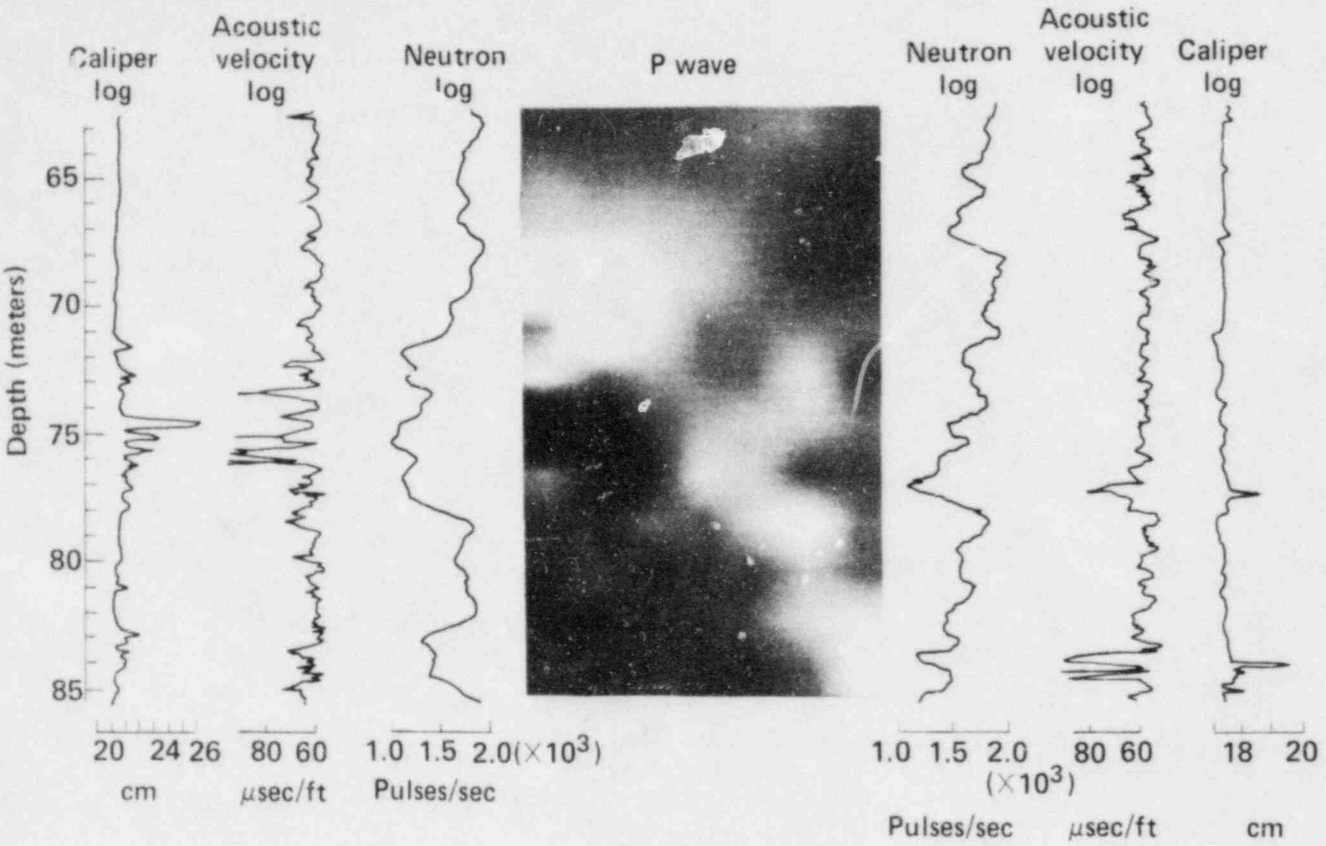

Figure 12

Geophysical tomograph showing variations in P-wave velocity throughout a fractured rock mass. Geophysical logs (from Keys, 1981) of the boreholes used for probing are also shown.

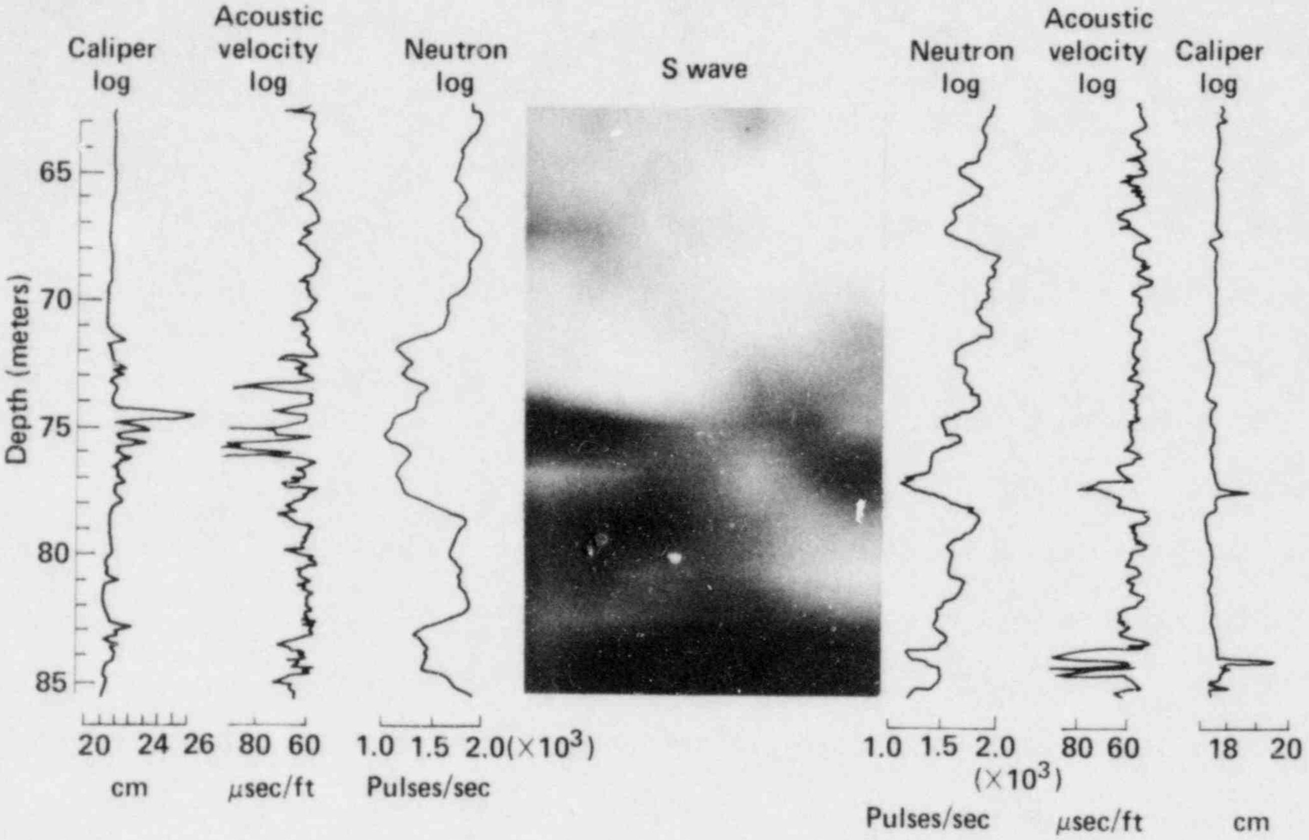

Figure 13

Geophysical tomograph showing variations in S-wave velocity throughout a fractured rock mass.

Shear wave ray paths with orientations greater than 45° were discarded because the arrival of the shear wave was very difficult to recognize in these cases. The shear waves used were polarized parallel to the borehole. For horizontal raypaths a strong S-wave is produced with a small P-wave preceeding it. As the orientation of the ray path changes from horizontal, the amplitude of the P-wave relative to the S-wave becomes larger (refer to Fig. 14). Consequently, the time of arrival of the S-wave becomes more difficult to recognize for the higher angles. The resolution of V_s image is likely to be less because of the fewer data points and the smaller range of ray path angles used.

Even when the orientation effect shown in Fig. 14 is not a problem, precise S-wave arrivals can be difficult to recognize. In our experience, although reversing the shear wave excitation may help differentiate the P-wave train from the S-wave train, even that approach is limited (McLamore et al., 1978). The recognition of S-wave arrivals can involve judgment and errors can occur. In transmission tomography applications, the algorithms selected for image reconstruction should be least susceptible to the "noise" caused by errors in recognizing the S-wave arrival.

Measurements of V_p can be performed very quickly when boreholes are fluid-filled because the fluid serves as an excellent acoustic coupler. The arrival of P-waves can be easily detected and measurements can be made with accuracy. In a repository scenario, however, V_p measurements may be made from dewatered tunnels or boreholes. In such cases, the sources and receivers will have to be physically attached to the borehole wall to achieve acoustic coupling, thereby significantly decreasing the speed with which the survey can be made. This limitation is particularly important when fractures are being mapped because many closely spaced measurements are needed to detect and outline fractured regions.

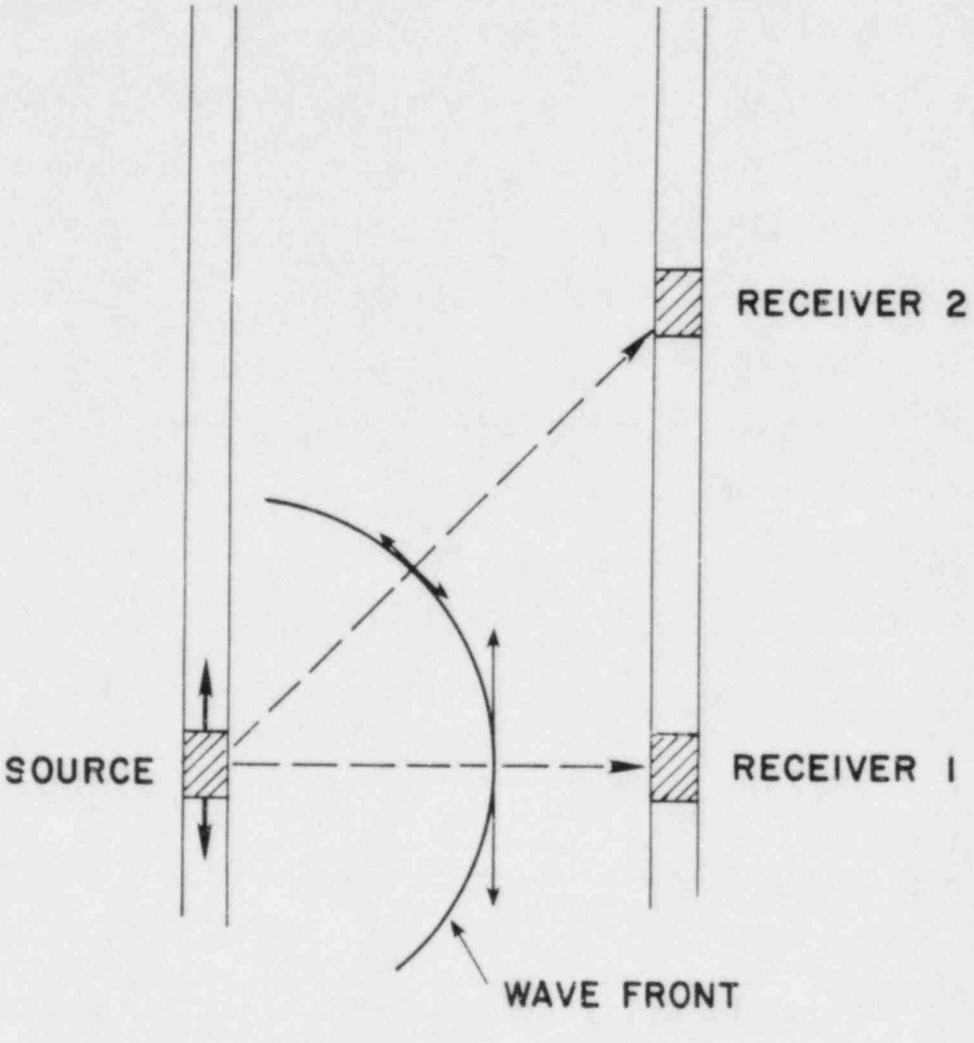

Figure 14

Schematic representation showing the variation in S-wave amplitude for different ray path orientations when the S-wave source is vertically polarized.

Measurements of P-wave attenuation were also made because other investigations had shown that A_p is more sensitive to fractures than V_p (Stacey, 1974). The results of A_p profiling measurements have been shown in Fig. 4. Results shown in Fig. 4 corroborate that A_p is sensitive to fractures in the rock.

A preliminary attempt to reconstruct a transmission tomography image using A_p was unsuccessful. Limited time and resources precluded further work. There is insufficient information to reach definitive conclusions regarding seismic transmission tomography based upon A_p measurements performed at the Oracle site.

The accuracy of measurements of P- or S-wave attenuation is greatly dependent on operational considerations. The radiation pattern of the source, the coupling of the source/receiver with the walls of the excavation and the repeatability of wave amplitudes generated by the source will affect the measured wave attenuation. If a two-borehole measurement is made, the radiation pattern of the seismic source should be measured in-situ because it will be affected by characteristics of the excavation wall and of the rock mass. The radiation pattern measurements should be made in a seismically relatively uniform section of the rock so that refraction and reflection are minimal. This requirement may be difficult to satisfy at sites with abundant fractures or at bedded sites. Modeling calculations by Lee and Balch, 1982 have shown that in the case of shear waves, the radiation pattern will have a complex shape. Complex radiation patterns are likely to be difficult to measure in the field if the rock mass is very inhomogenous.

Coupling of the source and receiver with the wall of excavation can greatly affect measurements of seismic wave amplitude between tunnels. The interaction between seismic waves and tunnels is a complex phenomenon including wave diffraction which will affect the measured wave amplitudes (Lytle and Portnoff, 1984). The details of this interaction need to be adequately understood and taken into account, especially if three tunnels in a line are used to measure wave attenuation.

Consistently good coupling characteristics will be required for accurate amplitude measurements. Inconsistent coupling will cause variations in wave amplitude unrelated to variations in the rock. These inconsistencies can degrade the accuracy of the results.

C. ELECTRICAL RESISTIVITY MEASUREMENTS

General considerations regarding electrical resistivity measurements have been discussed in Chapter IV. This section discusses crosshole resistivity experimental results obtained at Oracle and their signficance for repository investigations.

Crosshole apparent resistivity measurements were conducted between boreholes M-1 and H-2 and between boreholes M-1 and H-4. The measurements were conducted with two source electrodes, separated by 2 meters in one borehole, and two receiver electrodes, separated by 2 meters in the other borehole. Data was collected in the vertical scanning mode; i.e., with source and receiver electrodes lowered in unison and kept at equal depths; and in the skewed scanning mode; i.e. with the source and receiver electrodes lowered in unison and kept at a constant nonzero vertical offset.

Figure 15 shows the vertical scan of "apparent resistivity" between the two sets of boreholes. The "apparent resistivity" is herein defined as the ratio of the measured voltage difference across the receiver electrodes to the drive current in the source electrodes. It is noted that the peaks and troughs of the apparent resistivity variation versus depth generally correlate well between the far-apart boreholes (M-1 and H-4) and the closer boreholes (M-1 and H-2). The "apparent resistivity" results shown are unprocessed data, i.e., no normalization of the data has been interjected to account for the different geometric spacings for the two different probing distances.

Figure 16 shows the "apparent resistivity" variation with depth for three different offsets between source and receiver electrodes. As is normal in most apparent resistivity scans, it is noted that for the skewed cross-borehole profiles, both the qualitative and quantitative variations of apparent resistivity are strongly dependent upon the orientation of the source and receiver electrodes. This is due to the dependence of the apparent resistivity upon the shape and orientation of the anomalous region. The interaction of the probing currents with an anomaly is complicated, thus it is generally difficult to perform an interpretation providing definitive details about the location, size, orientation, and resistivity contrast of the anomaly. Such skewed views, however, do provide qualitative information on these parameters.

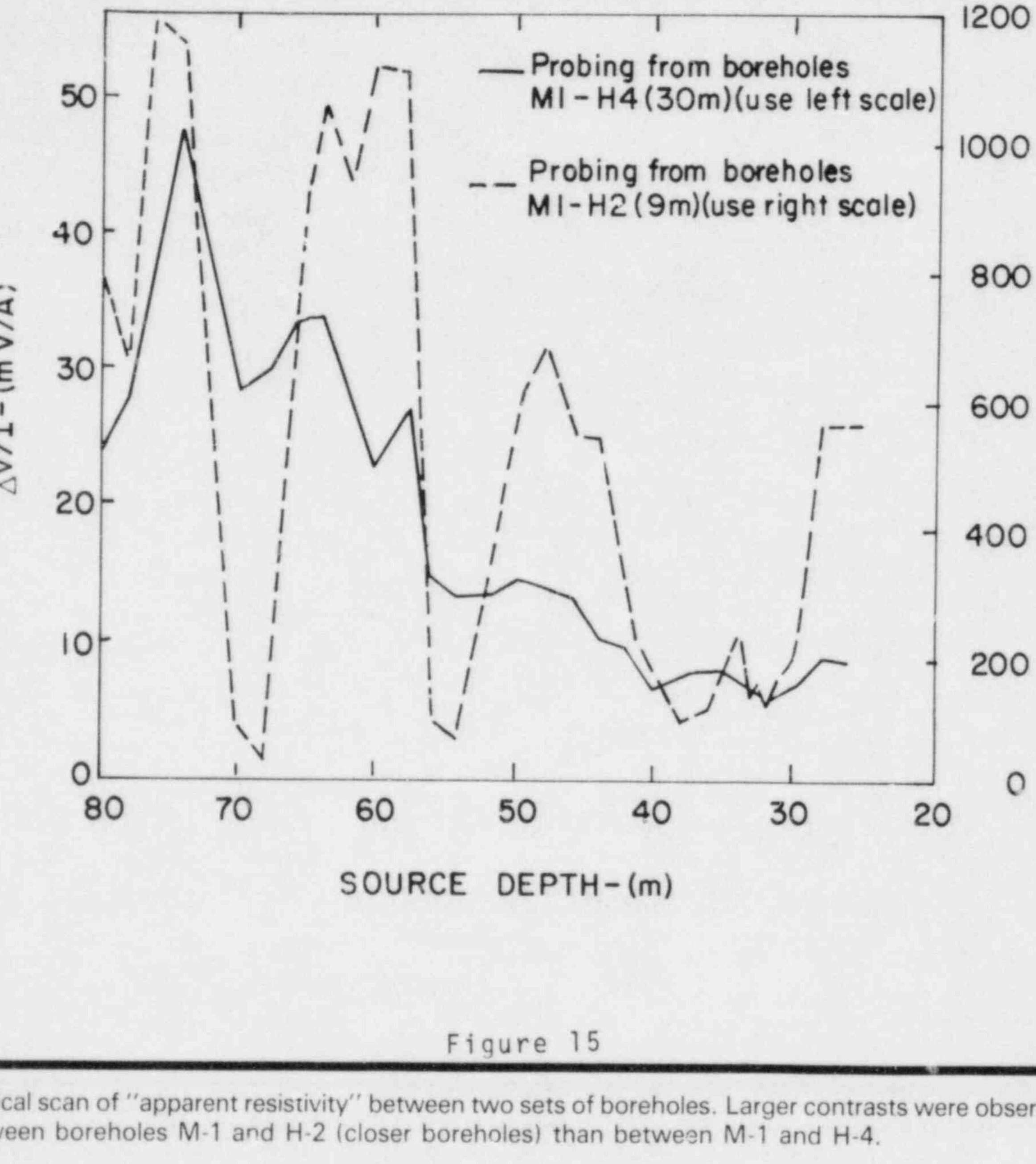

Figure 15

Vertical scan of "apparent resistivity" between two sets of boreholes. Larger contrasts were observed between boreholes M-1 and H-2 (closer boreholes) than between M-1 and H-4.

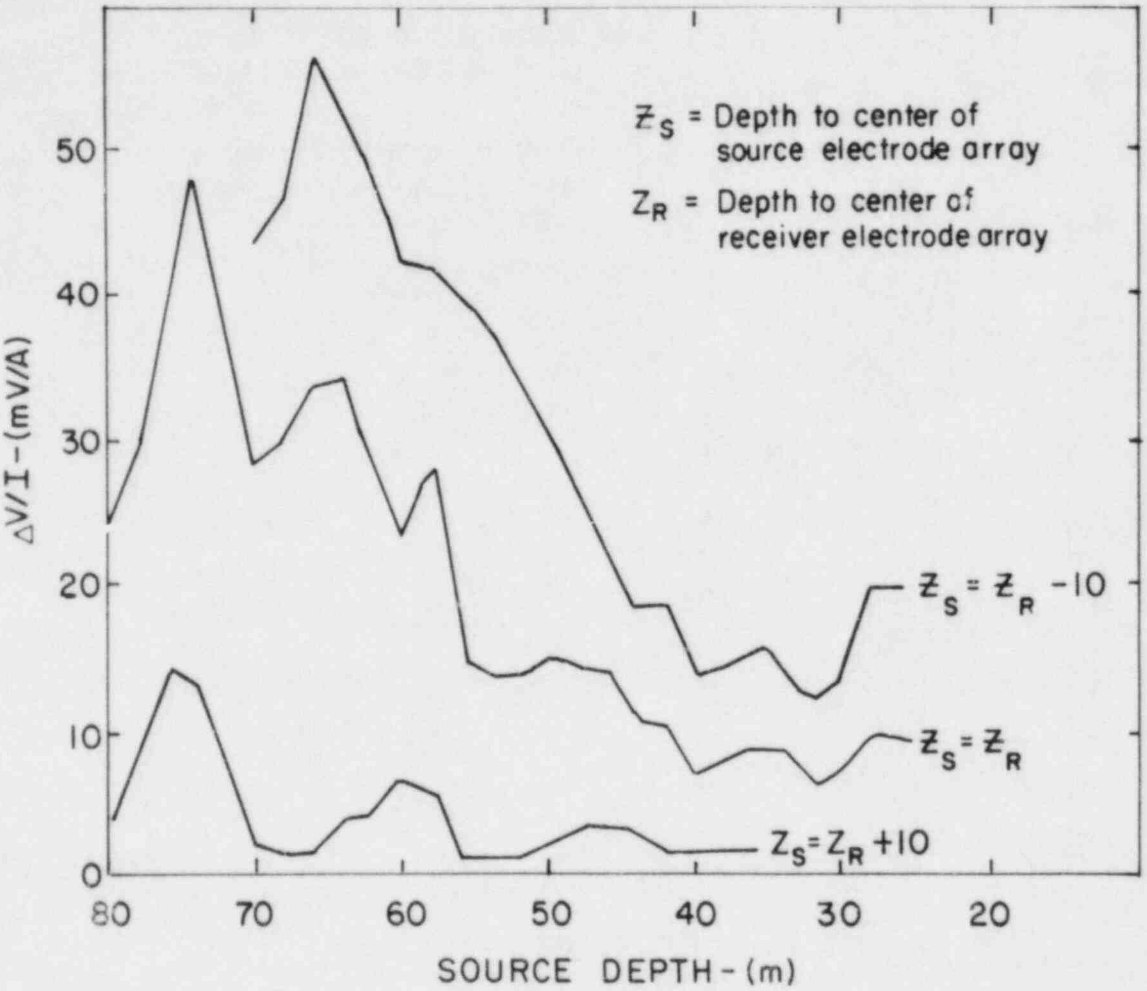

Figure 16

Variation of the "apparent resistivity" with depth for three different offsets between source and receiver electrodes.

VII. GENERAL COMMENTS

The evidence presented in the preceding chapters suggests that crosshole remote probing methods can be used successfuly to detect clusters of fractures in geologic environments similar to the Oracle experimental site. Seismic and electromagnetic transmission tomography methods are best suited to delineate fractured zones, because of their greater resolution. Seismic and electromagnetic scanning techniques are also useful in detecting zones of fracturing. Of the techniques considered, the apparent resistivity scanning technique, while offering the longest probing ranges, offers the poorest resolution and sensitivity to fractured regions.

In the scale of a mined repository, a number of fractured zones may be present. It can be important to detect and delineate the zones with remote probing methods. The remote probing methods discussed in this report have been used successfully to detect zones of fracturing. We stress, however, that no geophysical method available has been proven to be generally effective in remotely delineating single discrete fractures (Panel on Rock Mechanics Research Requirements, 1981).

When field measurements are performed from within tunnels, complex wavefront diffractions induced by the tunnel may affect the signals measured. Reflections from nearby shafts or tunnels may also occur.

Attenuation measurements are generally interpreted by assuming that the algebraic spatial dependence of the field decreases as a function of 1/R, where R is the distance between source and receiver. This assumption is valid only when the receivers are located in the far-field; i.e., when R is much greater than λ, where λ is the wavelength in the medium.

In tomographic images presented here, the number of view angles near the top and bottom of the images is insufficient for good resolution. Near the top and bottom of the image, the probing ray paths are predominantly close to horizontal. Horizontal rays do not provide good resolution laterally because the lateral position of a geologic feature cannot be resolved uniquely. Ray paths which provide good horizontal resolution are those which form acute (steep) angles relative to the borehole axis. When a steeply dipping fracture zone is present near the top and bottom margins, the lateral boundaries of the fracture zone are likely to be poorly resolved because the boundaries of the zone will tend to be smeared in the lateral direction.

VIII. CONCLUSIONS

An assessment of crosshole geophysical probing techniques was performed. The term "crosshole" is used in this report to designate inter-borehole, inter-tunnel and inter-shaft transmission measurements in the near vicinity of the repository. Our evaluation was based on prior theoretical and experimental work and recent experiments performed at the Oracle, Arizona site.

Probing methods considered in detail used active means of seismic, electromagnetic and electrical probing between boreholes. These means of crosshole probing were used to provide scans (one-dimensional representations) and transmission tomographs (two-dimensional representations) of inter-borehole regions at the Oracle site. Experimental results and factors affecting the accuracy of the various methods were illustrated.

Due to their close proximity to the region being probed, crosshole methods can use higher frequencies than more remotely located methods. Crosshole methods are therefore superior in resolution to methods probing from the ground surface.

Experimental results obtained at Oracle indicate that crosshole methods defined the presence of fracture zones. This result was made evident by comparing crosshole scans and tomographs with other data; i.e., single borehole well-logging results and hydraulic conductivity results. Fracture zones were evident in data obtained using electromagnetic wave attenuation, electromagnetic wave velocity, compressional wave velocity, compressional wave attenuation and shear wave velocity. The zones defined were typically resolved to within one meter of their actual location, where known. Due to time limitations, insufficient data were obtained for shear wave attenuation scans and tomographs.

Major factors affecting the uses of the techniques discussed include sensor coupling effects; diffraction and reflection effects of shafts and tunnels; ray bending; source consistency; measurement inaccuracies; closeness of source and receiver in terms of wavelength; the range of view angles and the number of views.

IX. ACKNOWLEDGEMENTS

The authors appreciate the contributions of various individuals and organizations to this study. LLNL colleagues P. Phelps, W. Daily, E. Laine, J. Beatty, and K. Kishiyama helped the authors in designing the experiments and in acquiring the data. Professor E. Simpson of the University of Arizona made the research site available to us. He and his colleagues were congenial hosts. J. Posedly of the University of Arizona and R. Egbert and D. Nuchols of LLNL provided valuable assistance during the field experiments. G. Davis and E. Zurflueh of the Nuclear Regulatory Commission provided helpful comments throughout this research. C. Minichino assisted greatly in editing this document.

X. REFERENCES

Buettner, M. (1984). Final Report on Seismic Detection of High Contrast Anomalies Such as Tunnels and Voids, U.S. Bureau of Mines, to be published.

Daily, W. (1982), "A New Method for Characterization of Borehole Antennas Used in Geophysical Probing", Geophysical Research Letters, Vol. 9, No. 5, pp. 507-509.

Daniels J. J. (1977), "Three-Dimensional Resistivity and Induced Polarization Modeling Using Buried Electrodes", Geophysics, Vol. 42, pp. 1006-1019.

Darracot, B., and C. Orr (1976), "Geophysics and Rock Engineering" Proc. of the Symposium on Exploration for Rock Engineering-Johannesburg, Vol. 1 pp. 147-158, A. A. Balkema, Rotterdam.

Department of the Army (1979), "Geophysical Exploration", Corps of Engineers, Engineer Manual 1110-1-1802.

Dines, K. and J. Lytle (1979), "Computerized Geophysical Tomography", Proceedings of the IEEE, Vol. 67, No. 7, pp. 1065-1073.

Gladwin, M. (1982), "Ultrasonic Stress Monitoring in Underground Mining", Int. J. Rock Mech. Min. Sci., Vol. 10, pp. 221-228.

Glass, C. and D. Higgs (1979), "Indirect Rock Mass Investigations for Optimizing Borehole Drilling Programs", Topical Report Prepared for the U.S. Nuclear Regulatory Commission, University of Arizona, Tucson, Arizona.

Hall, J., J. Christian, E. Kausel and J. Wolfgang (1981), "Instrumentation Corrections to Wave Velocity Data", Journal of the Geotechnical Engineering Division, Am. Soc. Civil Engineerings, Vol. 107, No. GT-10.

Hartenbaum, B. A. and G. Rawson (1980), "Topical Report on Subsurface Fracture Mapping from Geothermal Wellbores", U.S. Dept. of Energy, DOE/ET/27013-T1.

Hsieh, P. (1983), "Theoretical and Field Studies of Fluid Flow in Fractured Rock", Ph. D. Dissertation, Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona.

Keys, W. S. (1981), Technical Memorandum #69. U. S. Geological Survey, Water Resources Division, Denver, Colorado.

Lee, M., and A. Balch (1982), "Theoretical Seismic Wave Radiation from a Fluid-Filled Borehole", Geophysics, Vol. 47, No. 9, pp. 1308-1314.

Lytle, R. J. (1982), "Resistivity and Induced Polarization Probing in the Vicinity of a Spherical Anomaly", IEEE Trans. on Geoscience and Remote Sensing, Vol. GE-20, No. 4, pp. 493-499.

Lytle, R. J., and J. M. Hanson (1983), "Electrode Configuration Influence on Resistivity Probing in the Vicinity of a Spherical Anomaly", Geophysics, Vol. 48, No. 8, pp. 1113-1119.

Lytle, R. J., and M. R. Portnoff (1984), "Detecting High-Contrast Seismic Anomalies Using Cross-Borehole Probing", to be published in the IEEEE Trans. on Geoscience and Remote Sensing, Vol. GE-22, No. 2, pp. 93-98.

Lytle, R. J. (1979), "Cross-Borehole Geophysical Probing for Site Characterization", Proc. of the 1979 Rapid Excavation and Tunneling Conference pp. 87-91, American Institute of Mining Metallurgical and Petroleum Engineers.

Lytle, R. J., D. Lager, E., Laine, J. D. Salisbury, and J. D. Okada (1981), "Fluid Flow Monitoring Usng Electromagnetic Probing", Geophysical Prospecting, Vol. 29, pp. 627-638.

Lytle, R., E. Laine, D. Lager, and J. T. Okada, (1976), "Determination of the In Situ High Frequency Electrical Properties of Permafrost Rock", Radio Science, Vol. 11, No. 4, pp. 285-293.

Lytle, R., and K. Dines (1980), "Iterative Ray Tracing between Boreholes for Underground Image Reconstruction", IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-18, No. 3, pp. 234-240.

Mavko, G. and A. Nur (1979), "Wave Attenuation in Partially Saturated Rods", Geophysics, Vol. 44, No. 2, pp. 161-178.

McKenzie, C., G. Stacey, and M. Gladwin (1982), "Ultrasonic Characteristics of a Rock Mass", Int. J. Rock Mech. and Min. Sciences., Vol. 19, pp. 25-30.

McLamore, V. R., D. G. Anderson, and C. Espana (1978), "Crosshole Testing Using Explosive and Mechanical Energy Sources", Dynamic Geotechnical Testing, ASTM STP 654, American Society for Testing and Materials, pp. 30-55, 1978.

New, B., and G. West (1980), "The Transmission of Compressional Waves in Jointed Rock", Engineering Geology, Vol. 15, pp. 151-161.

Nickel, H., F. Sender, R. Theirback, and H. Weichart (1983), "Exploring the Interior of Salt Domes from Boreholes", Geophysical Prospecting, Vol. 31, pp. 131-148.

Norton, S. J., and M. Linzer (1979), "Ultrasonic Reflectivity Tomography: Reconstruction with Circular Transducer Arrays", Ultrasonic Imaging, Vol. 1, pp. 154-164.

Olhoeft, G. (1974), "Electrical Properties of Rocks", Physics and Chemistry of Rocks, R. Strens (ed.) John Wiley and Sons.

Panel on Rock Mechanics Research Requirements (1981), Rock Mechanics Research Requirements for Resource Recovery, Construction and Earthquake Hazard Reduction, U. S. National Committee on Rock Mechanics, National Research Council, National Academy Press, Washington, D. C.

Paulsson N. and M. King (1980), "Between-Hole Acoustic Surveying and Monitoring of a Granite Rock Mass", Int. J. Rock Mech. Min. Sci., Vol. 17, pp. 371-376.

Ramirez, A. and R. J. Lytle (1983), "Alterant Geophysical Tomography", IEEE Geoscience and Remote Sensing Symposium, San Francisco, California.

Ramirez, A., F. Deadrick and R. Lytle (1982), "Cross-Borehole Fracture Mapping Using Electromagnetic Geotomography", Lawrence Livermore National Laboratory, UCRL-53255.

Sjogren, B., A. Oesthus and J. Sandberg (1979), "Seismic Classification of Rock Masses," Geophysical Prospecting, Vol. 27, pp. 407-442.

Stacey, T. (1974), "Seismic Techniques in the Assessment of Rock Masses", Dissertation, Imperial College of Science and Technology, London.

Stacey, T. (1976), "Seismic Assessment of Rock Masses", Proc. of the Symposium on Exploration for Rock Engineering-Johannesburg, Vol. 2, pp. 113-118, A. A. Balkema, Rotterdam.

Telford, W., L. Geldart, R. Sheriff and D. A. Keys (1976), Applied Geophysics, Cambridge University Press.

NRC FORM 335
(11 81)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-3758
UCID-20060

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
CROSSHOLE GEOPHYSICAL METHODS USED TO INVESTIGATE THE NEAR VICINITY OF HIGH LEVEL WASTE REPOSITORIES

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

7. AUTHOR(S)
A. L. Ramirez, R. J. Lytle, P. Harben

5. DATE REPORT COMPLETED
MONTH March YEAR 1984

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550

DATE REPORT ISSUED
MONTH August YEAR 1984

6. *(Leave blank)*

8. *(Leave blank)*

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Division of Radiation Programs and Earth Sciences
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

10. PROJECT/TASK/WORK UNIT NO.

11. FIN NO.
A0367

13. TYPE OF REPORT
Topical

PERIOD COVERED *(Inclusive dates)*
October 1980 - May 1984

15. SUPPLEMENTARY NOTES

14. *(Leave blank)*

16. ABSTRACT *(200 words or less)*

An evaluation is given of remote-probing geophysical techniques likely to be used to investigate the near vicinity of geologic repositories for nuclear waste. The sensors to be used would be placed inside the boreholes, shafts and tunnels of the repository to provide high resolution information of the rock near the repository. The geophysical methods evaluated are known as active methods because they make use of artificial seismic, electric or electromagnetic fields to probe the rock mass. Techniques involving through transmission measurements are emphasized. These techniques show merit for remote detection of geological heterogeneities such as fracture zones which influence the containment capacity of repository sites. The report discusses the results obtained with exploration methods used at a site near Oracle, Arizona.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

Geotomography
Geophysics
Waste Repositories

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
Unlimited

19. SECURITY CLASS *(This report)*
Unclassified

20. SECURITY CLASS *(This page)*
Unclassified

21. NO. OF PAGES

22. PRICE
$

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

FOURTH CLASS MAIL
POSTAGE & FEES PAID
USNRC
WASH. D. C.
PERMIT No. G 67

NUREG/CR-3758

CROSSHOLE GEOPHYSICAL METHODS USED TO INVESTIGATE THE NEAR VICINITY OF HIGH LEVEL WASTE REPOSITORIES

AUGUST 1984

120555078877 1 1AN1RW1WD
US NRC
ADM-DIV OF TIDC
POLICY & PUB MGT BR-PDR NUREG
W-501
WASHINGTON DC 20555