BOREHOLE TO BOREHOLE GEOPHYSICAL METHODS APPLIED TO INVESTIGATIONS OF HIGH LEVEL WASTE REPOSITORY SITES[a]

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ABSTRACT

This discussion focuses on the use of borehole to borehole geophysical measurements to detect geological discontinuities in High Level Waste (HLW) repository sites. The need for these techniques arises from: a) the requirement that a HLW repository's characteristics and projected performance be known with a high degree of confidence, and, b) the inadequacy of other geophysical methods in mapping fractures. Probing configurations which can be used to characterize HLW sites are described. Results from experiments in which these techniques were applied to problems similar to those expected at repository sites are briefly discussed. The use of a procedure designed to reduce uncertainty associated with all geophysical exploration techniques is proposed; key components of the procedure are defined.

INTRODUCTION

The characteristics and performance of a repository system must be known with a high degree of confidence to provide reasonable assurance that the waste will be adequately isolated for thousands of years. Geophysical techniques available to investigate the characterization of a repository site have limitations (such as insufficient resolution to detect fractures, or insufficient range of probing) which reduce our ability to adequately investigate rock masses. Fortunately, each geophysical method has a different set of limitations. Geophysical surveys can be planned such that each method selected provides complementary information. In this manner, information gaps caused by the limitations of some techniques are resolved or minimized with data derived from other geophysical methods.

On the scale of a mined repository, no rock mass is completely homogeneous. The physical properties of the rock mass are strongly dependent upon discontinuities within the rock. Experts agree that during the site characterization investigations rock discontinuities, such as fractures, must be mapped in detail so that their impact on rock mass behavior can be correctly assessed. The hydrological, mechanical and thermal properties which must be known to predict behavior of a respository all depend strongly on the composition and structure of a rock mass. For example, averaged values of some rock mass parameters cannot be used in models since overall rock mass behavior, such as stability and failure, may be strongly dependent upon the discontinuities.[1]

This article will briefly discuss the following; A) The limitations of conventional geophysical techniques (i.e. those routinely used by the geophysical exploration companies) relative to the detection of discontinuities of rock masses, B) The use of borehole to borehole geophysical techniques which, by virtue of getting closer to discontinuities, can fill information gaps created by the limitations of conventional techniques, and C) The need for a procedure designed to reduce data-interpretation uncertainty associated with all geophysical techniques, including borehole to borehole techniques.

SURFACE-BASED TECHNIQUES

Most surface geophysical techniques (i.e. those where the probing sensors are placed at the ground surface) are well suited for reconnaissance exploration. In this type of exploration, large areas are explored and the targets of interest are major geologic features such as faults, deformed strata, breccia pipes and changes in rock type. Surface techniques which can be used to explore candidate repository sites include gravity, magnetic, electrical resistivity and, seismic refraction and reflection methods. Experts agree that the seismic reflection method is the most useful because it provides accurate information about subsurface stratigraphy; the method can be used to locate faults, and to map the attitude and continuity of rock strata.

Surface-based techniques are limited in their usefulness because the distance between the areas of interest and the groundsurface is very large (the depth of a repository horizon is expected to be on the order of 1 km). As a result, these techniques lack resolution to detect geological heterogeneities such as fracture zones, brine pockets and small scale faults that will affect a repository's performance.

The data provided by surface-based techniques is useful but insufficient to provide a high level of confidence in the projected performance of a site.

UNDERGROUND TECHNIQUES

Underground geophysical techniques (those where the probing sensors are placed inside

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boreholes, shafts or tunnels) complement the information obtained from the surface. Geophysical logs of boreholes (i.e., well logs) provide a continuous vertical record of certain physical properties of subsurface rocks and their fluid content. These are particularly useful in establishing correlations between beds.

Well logging techniques provide only localized information of the subsurface; i.e., most variations in rock properties which exist more than a very few feet from the borehole log are not detected in the well logs. As a first approximation, the fracture intercepts at the borehole can be extrapolated into the far-field. However, extrapolations from borehole logs laterally for more than a few meters are impossible.[1] Consequently, conventional logs are not adequate to map the lateral extent of fracturing.[2] Very few boreholes will be drilled at a repository site and the characteristics of large volumes of rock will not be known adequately if only well logging techniques were used.

The preceeding paragraphs suggest that conventional geophysical methods provide useful information on the overall characteristics of a HLW repository site. However, these techniques will do an inadequate job of mapping discontinuities in the rock. Additional information will be needed to assess the influence of discontinuities on the characteristics and performance of a repository system.

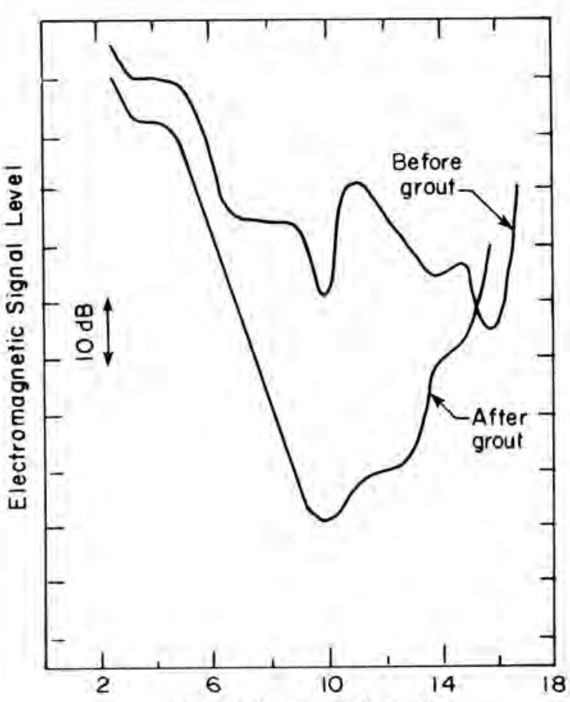

Fig. 1. Borehole to borehole measurements can be used to detect the extent of grout invasion into a rock mass (after Laine et al, 1979).

BOREHOLE TO BOREHOLE TECHNIQUES

Other underground geophysical techniques are available to detect geological discontinuites in the rock mass. These techniques, known as borehole to borehole techniques, involve the use of various energy fields such as seismic, electrical and electromagnetic fields which are transmitted thru rock. These fields are used to probe the rock mass between a source and receiver in separate boreholes, shafts, and tunnels. For example, the borehole to borehole seismic method has traditionally been used to measure in-situ the elastic properties of rocks.

These techniques can improve the level of confidence in the sites' characteristics and projected performance by: a) corraborating information obtained from rock cores, well logs and surface geophysical measurements, and b) probing the rock mass for undetected geological heterogeneities such as fractured zones, surrounding the repository system.

Recent Experimental Results

The effectiveness of repository sealing measures involving grout injection could be investigated with measurements between boreholes. Experiments have shown that if the region in question is probed before and after the grout is injected the extent of the grout front can be mapped.[3] Figure 1 shows an example of the results of this experiment. In this case, the increased attenuation of high frequency electromagnetic waves was used as the diagnostic response to detect the region of grout penetration.

Recent experiments performed at Stripa suggest that the borehole to borehole seismic method may be useful in monitoring stress changes in the rock.[4] In this experiment, high frequency waves probed a rock mass during a heater experiment. The authors have tentatively concluded that changes in

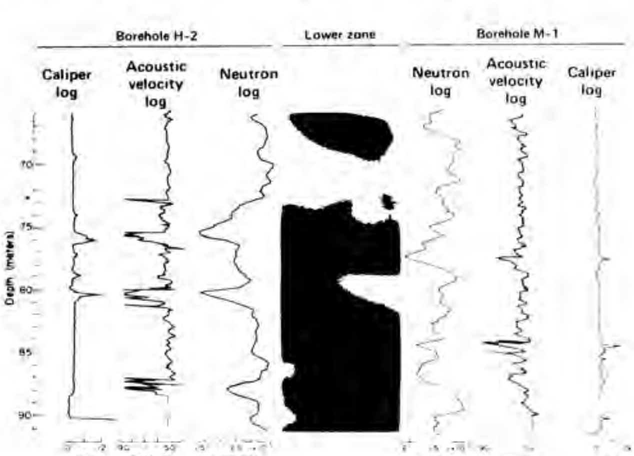

Fig. 2. Results from a recent experiment in which borehole to borehole methods were used successfully to map fractures in granite. Deflections of the borehole logs correlate with attenuating regions (dark zones) in the central image.

stress caused open fractures to close as the rock was heated. These changes in fracture aperture where in turn detected by the seismic waves propagated thru this region.

Figure 2 shows the results of a recent experiment in which electromagnetic waves were used successfully to map fractured regions within a granitic rock mass. In this case, the data was collected and analyzed following the geotomography method (described later). Regions shown in dark colors represent zones within the rock which caused the largest attenuation of the signal; hence, fractured zones should correlate with darker colored regions.

Geophysical logs of the boreholes used to perform the electromagnetic measurements are also shown.[b] Note that deflection in the borehole logs (which correlate with fractured zones) generally coincide with darker zones in the figure. Fractured regions suggested by the image can also be observed in the logs.[5]

These results suggest that this method may be useful in detecting important fracture characteristics such as hydraulic links between fractures, fracture extent and perhaps, movement of tracers through the rock.

Limitations and Suggested Remedies

Borehole to borehole measurements suffer from many of the same limitations associated with other geophysical techniques. One major problem with all techniques is that the interpretation of geophysical data is inherently ambiguous because more than one geologic model can be found which will fit the data given the same set of measurements. This introduces a degree of uncertainty in the final interpretations which degrades the level of confidence on a HLW site's characteristic and performance projections.

The degree of uncertainty with interpretations can be reduced in several ways. The use of different geophysical techniques to probe the rock will usually provide complementary data sets which will reduce the uncertainty associated with the final interpretation. Computer simulations are also helpful in predicting the geophysical signature of an anomaly of interest for a given geologic setting; the predicted response can then be compared to the field measurements and informed judgements can be made regarding the anomaly detected.

One's confidence in the interpretation of geophysical data can also be improved by conducting experiments in which the interpretation of geophysical data is verified by excavation and drilling. These experiments would be much more useful if performed at the repository site because the effectiveness of geophysical techniques will be controlled by the site-specific geologic environment.

Conventional borehole to borehole methods can be used to detect anomalies in the vicinity of a proposed repository, but are inadequate in defining their location or shape. These methods utilize a data collection scheme with which one can only position an anomaly in one dimension. For example, in the conventional seismic cross-borehole method the source and geophones are moved such that their locations define lines (i.e., ray paths) which have similar orientations; consequently, if an anomaly is intersected by any given ray path, we can only say that the anomaly is located somewhere along the line. An example of results from a conventional borehole to borehole survey is shown in Fig. 1. In a repository scenario, where the boreholes will be separated by distances of several tens to a few thousands of feet, the uncertainty associated with the locations of any anomalies detected will be very large.

Borehole to borehole measurements can also be performed using geotomographic techniques such that accurate positioning and shape of detected anomalies can be accomplished in two dimensions. In this method, ray-paths having multiple orientations are propagated through the rock mass. The major difference between geotomography and conventional cross-borehole methods is that the ray paths used to probe the rock mass have many different orientations and that the information obtained is mathematically analyzed to produce a cross-sectional picture of the rock. Many different perspectives of an anomaly are used to substantially improve the resolution of the anomaly. The information derived is analyzed mathematically to accurately locate the anomaly and define its shape.[5,6]

Geophysical exploration is used not only to detect geological features but also to obtain quantitative information on various rock parameters. The ability to quantitatively correlate geophysical data with geotechnical parameters of interest (such as fracture density, porosity, elastic constants) also needs to be improved.[7,8] Fundamental research concerning the correlation of geophysical signals with critical geotechnical parameters can be conducted by means of computer simulation. The results of these simulations could be complemented by empirical correlations based on data obtained by excavation.

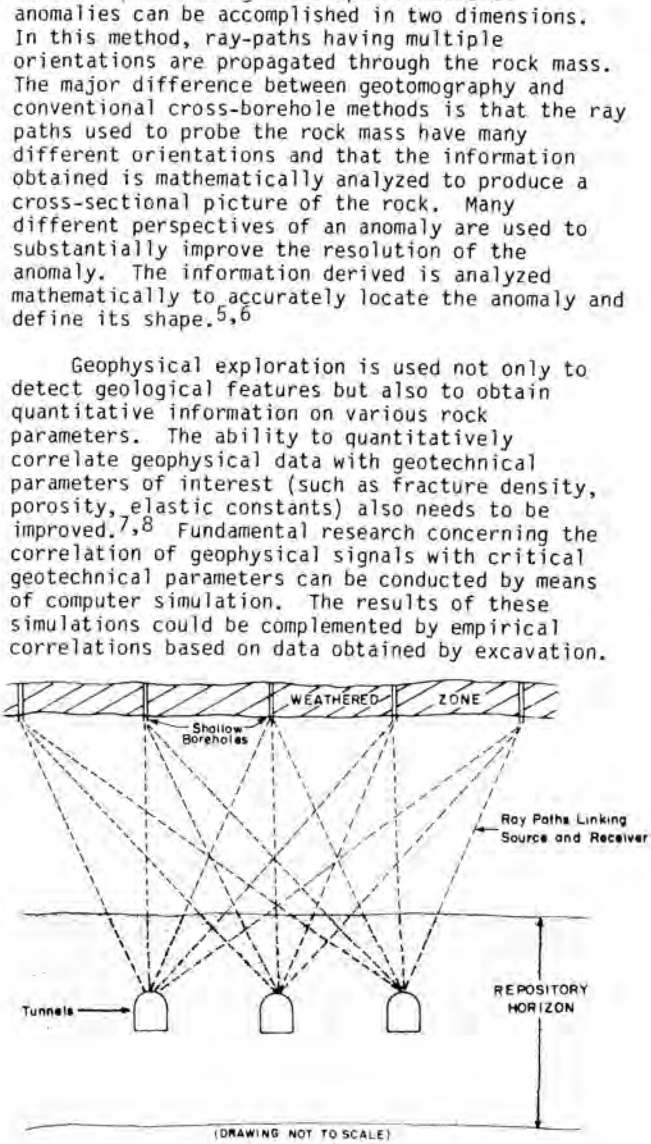

Fig. 3. Energy fields propagating between the ground surface and the emplacement tunnels may be useful in detecting geological defects above the tunnels.

b) The geophysical borehole logs were recorded by W. Scott Keys of the U.S. Geological Survey.

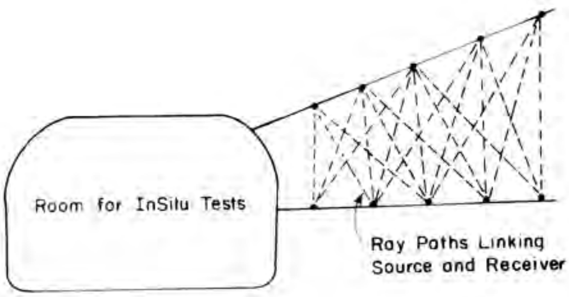

Fig. 4. Rock discontinuities affecting the results of in-situ tests can be investigated with borehole to borehole methods.

Examples of Applications

Figure 3 illustrates a probing configuration which can be used to probe the rock mass above the emplacement tunnels holding the HLW waste. Note that boreholes which penetrate the containment horizon are not needed to probe this region. In this case, shallow boreholes would be used to place sources (or receivers) below the highly attenuating weathered zone and improve the signal level of the received waves.

Rock mechanics and geohydrology in situ tests used to investigate rock mass characteristics will be strongly affected by the presence of fractures. Around the in-situ test openings, fracture characteristics need to be known in detail. For example, accurate model validations using in situ tests information can only be performed if the detailed characteristics of fractures present are known. Also in situ tests results can be misleading if adequate fracture data is unavailable. Borehole to borehole probing can be used to map the fracture network present.

Figure 4 illustrates how the rock around the chamber where in-situ tests will be performed can be investigated. One of the most useful applications of borehole to borehole measurements

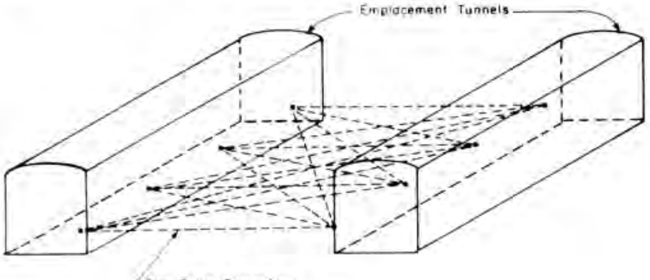

Fig. 5. The emplacement tunnels can be used as "boreholes" to characterize the pillars of the repository.

will be to map discontinuities affecting the results of in-situ tests. Seismic techniques, for example, can be used to establish the degree of velocity anisotropy within the rock mass. This anisotropy is partly dependent on the aperture, orientation and contact area of fractures. Thus, velocity anisotropy can be used to estimate the orientation of the principal axes of permeability; this information will be very valuable when planning and interpreting hydrologic experiments.

Borehole to borehole techniques can also be used to map discontinuities within the pillars (rock between tunnels). Pillars support the load of the rock above the repository. Pillars may also serve as emplacement structures if the horizontal emplacement holes are used as proposed. It is clear that pillars will be a critical part of the repository system and should receive particular attention.

Pillar stability and deformation are strongly influenced by fractures. Figure 5 shows how the tunnels can be used as large boreholes to probe the pillars using "borehole to borehole" measurements. These measurements will serve to detect or map the fractures between tunnels. In addition, seismic measurements thru the pillars' may be used to estimate the pillars deformation behavior using the petite sismique concept.[9,10]

REDUCTION OF UNCERTAINTY

Confidence in the "final" interpretation of geophysical data is of particular importance in repository investigations because the characteristics of a site must be known with a high degree of confidence. It is clear that a rigorous procedure designed to keep the uncertainties associated with geophysical data-interpretation to a minimum needs to be developed. The design of this procedure will have to take into account the geologic enviroment at each site and, therefore, will be site-specific. However, key components of such a procedure can be identified:

1. The geophysical survey should be designed to accommodate site-specific conditions such as size and configuration of targets of interest, as well as unimportant geologic features which may create noisy data.

2. A detailed model of the expected geologic enviroment at the site should be defined. Modelling calculations can then be used to predict the effectiveness of the geophysical techniques to be used.[11] These results are then used to plan the geophysical investigations.

3. Given that the interpretation of geophysical data is generally non-unique, a procedure should be defined to discriminate among the possible data interpretation alternatives. a) This procedure should incorporate results from field experiments in which geophysical interpretations have been verified by excavation or drilling. It should also incorporate results from modelling studies which calculate synthetic geophysical signatures for a given anomaly. The combined theoretical-field results provide a data base which should be very useful for data analysis and interpretation of subsequent geophysical surveys. b) Complementary

data sets such as those produced by well logging and borehole to borehole techniques should be used to help fill information gaps created by the limitations of the various techniques. c) Inversion of the exploration data should be an iterative process.[11] Initial geologic and geophysical data can be translated into geologic models and their mathematical representations. These models are then used to plan and to improve the interpretation of future geophysical surveys. As additional geophysical data is obtained and analyzed, the geologic models are updated and used to refine the interpretations of available geophysical results. In this manner, cross-checks are performed between different sources of data. Furthermore, any information gaps are minimized by combining information from complementary sources.

SUMMARY

This discussion has focused on the application of borehole to borehole geophysical measurements to complement information derived from other exploration techniques. Borehole to borehole measurements are needed because other geophysical techniques lack sufficient resolution or probing range to map discontinuities around the repository. Examples of probing configuration which involve the use of exploratory boreholes, tunnels, or shafts to perform "borehole to borehole" investigations are briefly described. Examples of recent experiments in which these techniques have been used to investigate conditions similar to those a high level waste repository have also been presented. A procedure designed to reduce the uncertainty associated with geophysical exploration is proposed.

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