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A BRIEF OVERVIEW OF GEOPHYSICAL
PROBING TECHNOLOGY ✓

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ABSTRACT

An evaluation of high-resolution geophysical techniques which can be used to characterize a nuclear waste disposal site is being conducted by the Lawrence Livermore National Laboratory (LLNL) at the request of the U.S. Nuclear Regulatory Commission (NRC). LLNL is involved in research work aimed at evaluating the current capabilities and limitations of geophysical methods used for site evaluation. This report provides a brief overview of the capabilities and limitations associated with this technology and explains how our work addresses some of the present limitations. We are examining both seismic and electromagnetic techniques to obtain high-resolution information. We are also assessing the usefulness of geotomography in mapping fracture zones remotely. Finally, we are collecting core samples from a site in an effort to assess the capability of correlating such geophysical data with parameters of interest such as fracture continuity, orientation, and fracture density.

EXECUTIVE SUMMARY

Safe long-term disposal of radioactive waste must be assured through effective functioning of the NRC regulatory process. To achieve this goal the NRC has to be aware of the limitations and capabilities of existing geophysical probing technology. Thus, NRC has requested that LLNL evaluate high-resolution geophysical techniques which can be used to characterize a nuclear waste disposal site. This document provides an overview of information that will help the reader to: a) recognize capabilities and limitations associated with existing geophysical probing technology; and b) understand how the work being performed by LLNL in this area addresses some of these problems. A brief overview of the realm of geophysical site characterization techniques is given. The emphasis here is on those techniques that offer high-resolution information.

There are numerous geophysical techniques available to assess repository sites. In general terms, current geophysical techniques can be used effectively to establish the spatial variation of the large-scale average properties of a site. However, geological heterogeneities can create variations from the large-scale average properties. Such localized heterogeneities are more difficult to detect and recognize. This is an important limitation because small-scale geological heterogeneities such as fractures can have a significant impact on the containment properties of a repository site. The current state of the art is not adequately advanced in terms of characterizing and detecting fractures not intersected by a free surface. Most techniques that offer sufficient resolution to detect fractures at depth lack penetration into the rock mass and vice versa. Other promising techniques need evaluation for their applicability to these particular problems. As the detection and characterization of fractures is of significant interest to NRC, we have concentrated our attention here upon those geophysical techniques suitable for remote fracture mapping.

The effectiveness of geophysical techniques is difficult to quantify because of the wide variety of effects that site-specific conditions have on the techniques' performance. Technique characteristics which have to be assessed are: 1) resolution (the ability to separate two features which are very close together); 2) sensitivity (minimum change in a parameter which can be detected); and 3) size of the target which can be detected relative to the horizontal and vertical spacing between sources and receivers. These characteristics are affected by the local geology/geophysical conditions. For example, the confidence with which geophysical data can be quantitatively correlated with parameters of interest (such as fracture density) is poorly developed for most rock types. This problem is particularly severe for the case of igneous and metamorphic rocks, because many of the geophysical methods available to obtain quantitative correlations were developed for petroleum exploration in sedimentary rock. Thus, there is a limited body of confirmed experimental data for igneous and metamorphic rocks which are of interest to NRC. Hence, evaluations of techniques have to concentrate on experiences gathered in these media of interest to NRC.

To address such needs, the Lawrence Livermore National Laboratory is currently involved in research work aimed at evaluating the current capabilities and limitations of remote probing geophysical methods used for site evaluation. LLNL is assessing both theoretically and experimentally high resolution, remote probing geophysical techniques which can be used to assure that site characterization is effectively performed. Particular emphasis is being given to active probing wave methods (i.e., seismic and electromagnetic) that have been successfully used to detect anomalous features in detail. A

key part of our evaluation is the comparison of results using a variety of methods with direct geologic information obtained from geologic cores. An example of such an effort is a recent collaborative experiment (with University of Arizona and U.S. Geological Survey personnel) concerning fracture mapping which was performed near Oracle, Arizona in a granitic rock mass.

I. INTRODUCTION

One solution to the problem of nuclear waste disposal consists of disposing the waste in subsurface rock formations which will effectively isolate the waste for long time periods. For this to be feasible, a very thorough site characterization program will be needed to insure that an adequate site has been selected. The Nuclear Regulatory Commission is chartered to protect the public health and safety through regulatory means. Safe long-term disposal of radioactive waste must be assured through effective functioning of the NRC regulatory process. To achieve these goals, the NRC needs to recognize the current deficiencies and capabilities associated with the use of geophysical techniques for site characterization purposes.

The Department of Energy states that the site characterization program will have two objectives: a) to describe the average properties of a site; and b) to characterize those geological heterogeneities that might override the average properties (Ref. 1). Numerous technical factors will be considered during the site characterization stage of the repository development process. Many of these factors will be studied using geophysical measurement techniques. The purpose of this document is to provide background information that will help the reader: a) understand problems associated with existing geophysical technology; and b) understand how the work being performed by LLNL under NRC's Geophysical, Environmental, and Radiological Field Measurements Systems Evaluation project addresses some of these problems. The authors have relied heavily on various published evaluations of the current state of the art relative to geophysical site characterization. This report provides a brief overview of capabilities and limitations associated with available geophysical techniques, in particular those that may be useful when mapping local geological heterogeneities. Particular emphasis is given to those techniques providing high-resolution capabilities. The report does not address specific capabilities or limitations of individual techniques. Such assessments are to be provided in future reports.

II. BRIEF OVERVIEW OF CURRENT CAPABILITIES

The measurements needed to characterize a site will be made from the ground surface, from boreholes, and from exploratory shafts and tunnels. There are numerous geophysical techniques available to make these measurements. A comprehensive summary of available geophysical techniques has been presented by the International Engineering Company (Ref. 2).

It is difficult to develop general guidelines concerning the capabilities and limitations of various geophysical techniques because the effectiveness of each technique is strongly controlled by site-specific factors (Refs. 3-4). Even sites which have the same rock types may have significant differences which could render all generalizations invalid. Thus, selection and application of appropriate techniques depend on the geological setting and the particular question being studied (Ref. 1). On the other hand, if geophysical techniques are considered as a group, several generalizations can be made concerning their capabilities and limitations.

Geophysical techniques can be divided into those that measure natural fields (e.g., gravity, magnetic, telluric currents) and those that measure man-induced signals (e.g., seismic reflection, gamma density, electromagnetic wave methods). The former are referred to as passive techniques, and the latter are known as active techniques.

Passive methods are typically used to measure some of the gross (large scale) properties of a region (Ref. 3). Typically these techniques offer low resolution but are useful for reconnaissance exploration. As with the active techniques discussed below, these techniques yield information which may allow nonunique interpretations. Thus, such techniques are typically used in combination with other exploration techniques. When corroborating data is available, these surveys can provide valuable information about regional and local subsurface geology.

Active techniques, i.e., techniques which involve the use of man-induced energy to probe the rock, typically offer better resolution than passive techniques and thus are used in surveys which seek more detailed information. These techniques are useful not only to measure gross or average properties but also to detect localized geological heterogeneities which might be of some contrast to the average properties. For example, various electrical

resistivity probing methods are used for exploration and depend upon detecting variations in the electrical resistivity of the rock through which the induced electric current flows. Electrical resistivity is strongly influenced by the amount and nature of fluids in the rock; consequently, hydrologic features such as groundwater tables and variations in porosity are particularly amenable to electrical methods. Another example of active techniques are the seismic exploration methods, which are among the most useful geophysical tools for obtaining accurate information about subsurface stratigraphy and structure (Ref. 1). They rely on the changes in acoustic impedances which are typically caused by changes in lithology and/or subsurface structure. These techniques are useful when mapping the attitude and degree of continuity of subsurface strata. The seismic reflection technique, for example, has been developed to the point where high-resolution information of the subsurface geophysical environment may be obtained even in relatively complex geologic environments. It should be kept in mind that there is a wide variance in resolution attainable using the active probing techniques as is evidenced by the differences obtainable from resistivity (relatively low resolution) and seismic exploration methods (relatively high resolution).

As noted above, there are very important differences in the degree of resolution which various passive and active geophysical techniques can offer. Table 1, which is adapted from a U.S. National Research Council report, graphically illustrates the relative degrees of resolution which common exploration techniques can offer when used to map fractures. Techniques which utilize sensors closer to the features of interest in the subsurface generally offer a higher degree of resolution as indicated at the top of the table.

The techniques which offer the greatest resolution (e.g., surface geologic mapping, borehole televiewer, impression packers) suffer from a very limited probing range. Very accurate knowledge is obtained of the immediate surface or within several millimeters of the free surface (i.e., tunnel/borehole wall, ground surface), but little is accurately known about the conditions at distances of several tens of meters from the surface. The electromagnetic and seismic methods offer promise for providing a suitable trade-off in terms of

Table 1. Range (penetration) - resolution (ability to separate closely spaced features) continuum offered by current geophysical techniques.*

High ←———— Scale of Resolution —————→ Low
 Small ←———— Distance between Source and Receiver and Fracture —————→ Large

Surface geologic mapping

Borehole acoustic televiewer
 Borehole photography
 Impression packer
 Core analysis

EM and acoustic reflection and through transmission
 Acoustic full-wave-form log

Photogeology
 High-resolution seismic reflection
 Side-scan sonar and radar
 Borehole electrical resistivity
 Density log
 Vertical seismic profiling

Seismic reflection and refraction
 Satellite imagery
 Borehole gravimetry

Gravity
 Magnetic
 Electrical resistivity

Electrical surface potential
 Passive microseismic and acoustic emission
 Tilt measurement

Airborne magnetic
 Airborne low-frequency electromagnetic

*Figure excerpted and modified from Panel on Rock Mechanics Research Requirements (Ref. 4). The report was prepared by the U.S. National Research Council.

adequate resolution and adequate penetration range. Such methods need to be evaluated for their use in fracture mapping and in site characterization in general. We are thus concentrating on the active probing techniques that offer the promise for achieving such suitable trade-offs. We first, nowever, briefly review a broader class of geophysical techniques.

There are a number of useful geophysical instruments which are used in boreholes. These instruments are typically used to obtain information on subsurface rocks and fluids. Borehole instruments can be used in one borehole (i.e., single-borehole techniques) or may require that the signal source and sensors be located in different boreholes (cross-borehole techniques). Borehole techniques typically provide higher resolution than equivalent techniques used at the ground surface because the sources and receivers are closer to the features of interest and, as a result, are more sensitive to them (for example, see Cristaglio and Worthington (Ref. 5). These instruments commonly provide higher resolution than surveys conducted from the ground surface.

Single-borehole techniques may offer high-resolution information of the rock and fluid located very near the borehole walls. Many of these techniques generally penetrate less than 1-2 feet into the rock mass. There are, however, notable exceptions to this generalization, such as single-borehole resistivity and induction methods, borehole gravimetry, and, in some types of geologic environment, radar techniques. Note that these techniques (i.e., resistivity, induction, and gravimetry) also offer lower resolution but increased penetration over such techniques as acoustic televiewer and photography. Many types of borehole techniques are available. These include resistivity techniques which provide a reliable measure of in situ rock and fluid characteristics; microresistivity techniques which measure the properties of small volumes of rock just behind the borehole wall and thus permit the boundaries of permeable and/or electrically resistive formations to be sharply defined; gamma ray techniques which indicate the clay content of various formations and are valuable in interpreting sedimentary rock sequences; radioactive techniques which aid in identifying water content and density of rock strata; and acoustic techniques which help determine the porosity and fracture characteristics of a formation.

Cross-borehole techniques can be used to penetrate into the rock mass a few tens to over a few hundreds of meters. Dependent upon the particular technique used, the trade-offs attainable in resolution/penetration which can be obtained with cross-borehole techniques can be less than or greater than what can be obtained with the single-borehole techniques. Typically, however, the cross-borehole techniques offer significantly greater resolution than is attainable with surface-based techniques. Cross-borehole techniques have the advantage that they can be used to map subsurface regions which need not be intersected by exploratory boreholes, i.e., regions which exist between two or more boreholes. Cross-borehole methods have recently been improved so that electrical, ultrasonic, and electromagnetic wave signals are being used to probe into the rock mass between two boreholes to provide high-resolution images of the subsurface. Better resolution is being obtained as evidenced by recent field investigations and improvements in equipment and data reduction algorithms (see Lytle, et al. (Ref. 6); Panel on Rock Mechanics Research Requirements (Ref. 4)).

The area of geophysical modeling has been actively developed in the last decade, and significant progress has been made. Romig and Applegate (Ref. 3) suggest that it is possible to predict geophysical capabilities with reasonable accuracy using existing models if a detailed site model is described. Thus, once a proposed site has been described, it is possible to predict the results of the application of various geophysical techniques by generating synthetic data. However, it is evident that the usefulness of this approach is limited by the fact that many geophysical techniques will have to be used at a time when enough data might not be available to produce a detailed site model; consequently, it will be difficult to predict the capabilities of the techniques to be used at a given site.

III. BRIEF OVERVIEW OF CURRENT DEFICIENCIES

Geophysical probing combines the science of measuring physical phenomena with the art of interpreting those measurements in terms of inferred geologic and engineering parameters at depth (Ref. 3). Typically the ability to develop the hardware needed for geophysical investigation far surpasses the ability to utilize and interpret the information collected. Major advances in

hardware development have occurred as a result of the need for better equipment in the mining and oil industries and as a result of the development of digital recording and microprocessor technology.

Perhaps the main limitation of geophysical probing is that interpretation of the data is inherently inferential. Consequently, some corroborative and/or confirmatory information is in all cases desirable and in many cases essential. In the case of underground repositories, it may not always be possible to confirm an interpretation of geophysical data because this may require drilling or excavation which may compromise the isolating capabilities of a given site. One's confidence in a particular site will thus be enhanced by geophysical probing, but knowledge of the site properties will still not be totally definitive.

The ability to interpret the data is limited by the degree to which theoretical models describe the real subsurface conditions. Current theoretical models typically lead us to make assumptions (homogeneity, isotropy, elasticity) that are not always valid (Ref. 3). In fact, geological features such as fractures and faults which commonly are the targets of geophysical surveys, are major causes of inhomogeneity, anisotropy, and inelasticity. Obviously, these assumptions can create problems because they may diminish one's ability to accurately interpret the data. Regardless of these limitations, site parameters obtained through geophysical probing will be much more reliable than any estimate or extrapolation of the parameters made in the absence of geophysical data.

Modeling techniques can be used with reasonable success to improve the interpretation of field data. This method generally involves an iterative approach whereby the model results are compared with field data, and then the model is adjusted to reduce the differences. In most cases, however, more than one geologic model may fit the data and uncertainties may exist with the interpretation. The degree of uncertainty about the site character is usually significantly decreased by the use of geophysical probing because the number of geologic models that can be used to represent a site is reduced to a minimum thereby increasing the degree of confidence in the remaining models.

Various investigators have recognized that the ability to quantitatively correlate geophysical data with some parameters of interest (such as elastic

constants, fracture density, porosity) is poorly developed for most rock types (Refs. 3, 7-8). This problem is particularly acute for the case of igneous rocks because many of the data interpretation techniques available to obtain quantitative correlations were developed for petroleum exploration in sedimentary rocks (Ref. 7). Igneous and metamorphic rocks typically present different petrophysical properties from those of sedimentary rocks; consequently, the interpretation of geophysical logs in igneous and metamorphic terrain is different.

The active probing wave methods have been used successfully to detect various geologic features. However, these methods have been much more useful in locating anomalous regions than they have been in identifying the types of geologic features that produce the anomalies or reflections. In other words, the present capability to answer the "where" part of the question, is much better developed than the ability to answer the "what" part of the question (Refs. 4 and 9). This is true for both electromagnetic wave and seismic methods, although it is also a problem with other geophysical techniques. One factor contributing to this situation has been described in the preceeding paragraph. Furthermore, the interpretation of this type of survey is largely dependent on the quantity of corroborating information as well as on the interpreter's experience. There is abundant experience with seismic probing. There have been only a few instances in which electromagnetic wave data obtained in the field have been analyzed and compared with abundant corroborating information obtained using other geophysical or geological techniques. As a result, our ability to interpret electromagnetic wave data even in rather simple geologic environments is not well assessed.

In the last decade, electromagnetic wave methods have been used with increasing frequency to characterize subsurface conditions, and significant progress has been reported (Refs. 6, 10-11). These methods have been proven particularly useful in rock salt media because of the long ranges of penetration and increased resolution which can be obtained. In other rock types, the range of penetration is diminished due to the increased conductivity of these rock masses. Nevertheless, electromagnetic wave methods have the potential to provide high-resolution information of geological features which are removed from repository openings. These methods are

consequently receiving increasing attention from researchers.

Much work remains to be done in the area of electromagnetic wave methods. Keller (Ref. 10) suggests that further information is necessary to understand the capabilities and limitations of electromagnetic transmission methods. He suggests that the behavior of the electrical properties of rocks over the frequency range from 1 MHz to 1 GHz should be studied. The level of understanding of the role that electrical conductivity and the dielectric constant play in the transmission properties of electromagnetic waves propagating through various rock masses is presently deficient.

Deficiencies associated with current borehole antennas are also limiting the usefulness of some electromagnetic wave methods. Present antennas are omnidirectional and, consequently, cannot provide the azimuthal resolution needed to locate various geologic features (Ref. 12). This deficiency is particularly troublesome when backscatter radar is used from a single-borehole to map various features of interest such as margins of salt domes, bedding planes, and fractures.

IV. CURRENT FRACTURE CHARACTERIZATION CAPABILITIES

Fractures are of particular importance to the underground nuclear waste disposal problem; these deserve special attention. Fractures will limit the hydrologic isolation or containment capabilities of the rock mass in which nuclear waste has been permanently emplaced. Furthermore, fractures will affect the mechanical stability of the rock mass. The Department of Energy has recognized the importance of fractures and their impact on nuclear waste disposal and has recognized existing deficiencies in our ability to map fractures (Ref. 1).

Other organizations and researchers have also concluded that current capabilities available for characterizing fractures are not sufficiently developed for repository applications (Refs. 4, 13-14). Fractures can be mapped and characterized when they intercept a borehole wall or other free surfaces. At present, however, there is a large contrast in the detail which can be obtained when fractures are mapped along a free surface and when mapped remotely. It is very difficult to map and characterize fractures which do not intersect free surfaces. Presently, fractures are extrapolated between

boreholes by comparing the logging responses of various geophysical tools. Significant uncertainties are inherent in the process of fracture extrapolation between boreholes on the basis of geophysical and/or geologic data. The continuity of fractures is difficult to determine. Other fracture characteristics which are also very difficult to investigate include connectivity between fractures, and fracture density and aperture within the rock mass. All these fracture properties have direct bearing on the geohydraulic and isolation properties of any given site.

A larger fracture density usually improves the chance of geophysical detection when using both single- or cross-borehole geophysical techniques. However, one of the major problems is that, in most cases, fracturing does not increase the total porosity of the rock drastically (Ref. 15). Heflin also points out that no single-well logging method will always be successful in detecting fractures. Different well logging methods can be successful depending upon the rock characteristics and borehole conditions. Well logging methods typically used to detect fractures are not useful to remotely delineate the presence or the characteristics of fractures which exist more than a few feet away from the borehole wall. Present geophysical methods are generally incapable of remotely delineating single, discrete fractures. However, current technology is capable of remotely detecting anomalies associated with the aggregate effects of a zone of fractures (Ref. 4).

V. RESEARCH RECOMMENDATIONS

Several organizations and researchers have recently evaluated the state of the art in geophysical exploration (examples given below). As a result of these evaluations various suggestions have been formulated. A listing which summarizes some of these recommendations is presented here. These suggestions are not listed necessarily in order of priority.

1. There is a need for major improvements in methods used for mapping fractures and for extrapolating surface or borehole fracture data into the rock mass interior (Refs. 4, 9, 13-14). The Panel on Rock Mechanics Research Requirements (Ref. 4) suggests the following:

- a) High-frequency electromagnetic, acoustic, and seismic imaging techniques (including borehole radar, sonar, and geotomography) should be assessed for their use in detection and description of single fractures.
 - b) Calibration test sites should be identified where one can conduct experiments in a variety of geologic provinces.
 - c) Research should be performed which addresses the correlation of geophysical signal responses with parameters of interest such as fracture density, orientation, and size.
2. Romig and Applegate (Ref. 3) have suggested that long-range research programs should concentrate on data processing and interpretation with emphasis on the development of theoretical models that more accurately describe subsurface conditions and application of statistical techniques to improve signal-to-noise ratio. Short-term research programs, on the other hand, should concentrate on using existing models to design optimum survey techniques for specific sites and to predict the results expected from those surveys.
3. Romig and Applegate (Ref. 3), Keys (Ref. 8), and the Panel on Rock Mechanics Research Requirements (Ref. 4) agree that the ability to correlate geophysical data with various parameters of interest (such as elastic coefficients, porosity, fracture characteristics) should be improved. Much additional laboratory work and basic research are needed in this area. This problem is particularly acute for the case of borehole geophysical exploration in igneous rocks. Keys (Ref. 8) suggests that significant improvement in the state of the art can be achieved if theoretical petrophysical models are developed for the response of various logging tools in igneous rocks. He also suggests that the modification or redesign of various logging tools for igneous rock exploration would improve the state of the art.
4. The key to understanding the capabilities and limitations of radar and electromagnetic transmission methods (see Keller, Ref. 10) lies

in further research in these areas. An important aspect of the development of improved ground probing radar methods is an understanding of the role played by the physical properties, namely the electrical resistivity and dielectric constant. The electrical resistivity and dielectric constant of the rocks depend upon the lithology, the water content, and the frequency. Water content is one of the most important parameters in determining both the magnitude and the frequency dependence of the electrical properties of the rock masses.

It has also been suggested that our ability to interpret data from wave methods can be improved if field experiments are performed in which abundant corroborating data from other exploration techniques can be correlated with the electromagnetic wave data (Ref. 9). This is of particular importance in the case of electromagnetic wave methods which have not been used often enough to identify the types of geologic features which are detected.

Hartenbaum and Rawson (Ref. 12) suggest that some hardware development is needed to make electromagnetic wave methods useful for fracture mapping purposes. They suggest that the development of a directional borehole antenna for frequencies less than 300 MHz is required to be able to map fractures in situ.

VI. SCOPE OF LLNL RESEARCH ACTIVITIES RELATIVE TO CURRENT RESEARCH NEEDS IN GEOPHYSICAL EXPLORATION

LLNL is currently performing research for the Nuclear Regulatory Commission which addresses some of these research needs. The emphasis in our research is to assess both theoretically and experimentally those high-resolution geophysical techniques which promise to be useful for mapping fractures. We are assessing the cross-borehole geophysical methods which have the potential to offer significantly improved resolution over conventional techniques. As interrogating signals, we have experimentally used high-frequency electromagnetic waves and will use seismic waves in the future.

Our first fracture mapping experiment has been performed at a site where

several other exploration techniques have been or will be used. Thus, we hope to obtain sufficient corroborating information to analyze our results. This data has been supplied by W. Scott Keys of the U.S. Geological Survey and will be supplied by Professor Eugene Simpson of the University of Arizona, Department of Hydrology. This experiment has been performed on a site which is underlain by a fractured granitic rock mass near the town of Oracle, Arizona. At this site, the primary targets of our surveys have been the fractures in the granite. Our hope was to obtain detailed information on the continuity and connectivity of these zones. The initial results of our experiment appear encouraging and will be presented in an upcoming report. We plan to return to the Oracle site to perform exploratory coring of the region along which the measurements were made and to make additional measurements. The data obtained from the coring activities will serve to assess our results as well as to establish whether the techniques can provide quantitative information on fracture density.

This following brief description of the scope of our work should allow the reader to recognize the various areas of overlap between our current research interests and various research recommendations summarized in the previous section. In summary:

- a) We are examining seismic and electromagnetic techniques which may offer high-resolution information and, if successful, should allow us to map fracture zones remotely.
- b) We are utilizing geotomography, a technique that has been proposed by the Panel on Rock Mechanics Research Requirements (Ref. 4) as one that should be assessed for its use in mapping fracture zones remotely.
- c) We are conducting experiments at a site where direct geologic information (core samples) has been or will be collected. This type of information will allow us to assess the capability to correlate such geophysical data with parameters of interest such as fracture continuity, fracture orientation, and fracture density.

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