UCRL--53462

TI84 010635

Basalt Nuclear-Waste Repository Remote Sensing Using Electromagnetic Techniques

W. D. Daily

H. M. Buettner

Manuscript date: January 1984

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

LAWRENCE LIVERMORE NATIONAL LABORATORY
University of California • Livermore, California • 94550

Available from: National Technical Information Service • U.S. Department of Commerce
5285 Port Royal Road • Springfield, VA 22161 • \$7.00 per copy • (Microfiche \$4.50)

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Contents

List of Figures	iv
Abstract	1
Introduction	1
Experimental Procedure	2
Experimental Results	2
Discussion and Summary	2
Acknowledgments	6
References	6

List of Figures

1. The electromagnetic permittivity, $\epsilon = (\epsilon' - j\epsilon'')\epsilon_0$, of basalt as a function of frequency for various volume fractions of water content 3
2. The real part of relative permittivity for basalt as a function of volume fraction water content for various frequencies 4
3. Attenuation rate (inverse skin depth) for basalt as a function of volume fraction water content for various frequencies 5

Basalt Nuclear-Waste Repository Remote Sensing Using Electromagnetic Techniques

Abstract

The electromagnetic permittivity and attenuation rate of basalt, from the Near Surface Test Facility of the Basalt Waste Isolation Project at Hanford, Washington, have been measured in the laboratory as a function of water content at frequencies from 25 MHz to 1000 MHz. Both the permittivity and the attenuation rate are strongly related to water content of basalt in this frequency range. Completely dehydrated, the rock has a frequency-independent relative permittivity of about 8 and attenuation rates (inverse skin depths) of 0.04 m^{-1} and 3.2 m^{-1} at 25 MHz and 1000 MHz, respectively. When completely saturated by tap water to 6% by volume, the relative permittivity ranges from 16.5 to 10.0 and the attenuation ranges from 0.3 m^{-1} to 5.5 m^{-1} between 25 MHz and 1000 MHz. The data indicate that high-frequency electromagnetic remote sensing techniques, such as those used in radar, cross-borehole tomography, and borehole logging, may be useful in characterizing proposed basalt repositories and monitoring established waste repositories. Electromagnetic methods are particularly suited to delineating water content of the rock and, when completely saturated, crack and pore porosity of the rock mass within a repository.

Introduction

Several techniques have been developed recently for geophysical remote sensing using high-frequency electromagnetic waves. Surface and borehole radar systems have been used to locate anomalies (e.g., Suhler *et al.*, 1970); cross-borehole radio-frequency tomography has been used for high-resolution mapping between pairs of boreholes (e.g., Dines and Lytle, 1979). Interest in dielectric well logging for oilfield characterization has increased with the successful development of high-frequency well logging tools (Calvert, 1974; Rau, 1976). All of these techniques rely on propagation of relatively high-frequency (above a few megahertz) electromagnetic waves through the ground—a process only partially understood at present. As a result, interpretation of data from these techniques is usually qualitative. The exception is electromagnetic well logging, which now allows quantitative evaluation of oilfield formation parameters (Poley *et al.*, 1978).

Water is the principal constituent controlling the electromagnetic characteristics of most geologic formations. Therefore, the objective of our

laboratory experiments was to determine the quantitative relation between measurable high-frequency electromagnetic parameters and the water content of basalt. From these data, we evaluated the value of geotomography and other electromagnetic techniques to quantitative characterization of the hydrology of a nuclear-waste repository in basalt.

The sample used in our study is from the Near Surface Test Facility of the Basalt Waste Isolation Project at Hanford, Washington. Although the data presented in this paper are for this specific basalt, they are useful for interpretation of data for different basalt types from a variety of geologic settings. These implications are discussed later.

The Experimental Procedure section describes the procedure used to prepare the rock samples and measure their high-frequency properties. The results of these experiments are presented under Experimental Results and evaluated in the Discussion and Summary.

Experimental Procedure

The basalt core was provided by Rockwell International from the Near Surface Test Facility, Hole 5501-5504, at a depth of 3.29 inches from the rock face. From this core, a cylinder was machined 5.025 cm long by 1.430 cm in diameter, with a hole 0.620 cm in diameter along the cylinder axis. The cylinder axis was oriented horizontally in the formation so the electric field was radial to it. No cracks were visible in the machined sample.

The sample was dehydrated in a vacuum at 90°C for 144 hours, during which its weight reached a minimum, indicating the loss of all moisture. The sample was then electromagnetically characterized to obtain its properties when completely dehydrated.

To achieve saturation, the sample was placed in tap water under 100 psi for 12 days, until its

weight reached a maximum. The sample was again electromagnetically characterized; its porosity was calculated from the dry and saturated weights to be 5.95% of the total volume. After being air-dried for a short time, the sample was placed in a hermetically sealed container for 7 days to allow it to equilibrate with humidity in the container and produce homogeneity of the sample moisture content. Air-drying and equilibrating were repeated several times at different water contents to ensure a homogeneous water distribution in the sample before each measurement sequence. The sample was also characterized when saturated with a saturated solution of potassium chloride.

Experimental Results

The basalt sample was electromagnetically characterized between 25 MHz and 1013 MHz at 52-MHz intervals. The complex magnetic permeability, $\mu = (\mu' - j\mu'')\mu_0$, and the electrical permittivity, $\epsilon = (\epsilon' - j\epsilon'')\epsilon_0$, were calculated from the measured scattering parameters of the sample. The permeability and permittivity of free space are μ_0 and ϵ_0 , respectively; $j = \sqrt{-1}$.

When $\mu = (1.0 - 0.0j)$, the parameters more easily determined from field-measured quantities are propagation velocity, which is approximately $c/\sqrt{\epsilon'}$, and attenuation rate (inverse skin depth), which is

$$\frac{2\pi}{\lambda_n} \left[\frac{\epsilon'}{1 + \tan^2 \delta} - 1 \right]^{1/2}$$

where,

$$\begin{aligned} c &= \text{speed of light in vacuum} \\ \lambda_0 &= \text{free space wavelength} \\ \tan \delta &= \epsilon''/\epsilon' \end{aligned}$$

Figure 1 shows the relative permittivity spectra of the basalt. For all measurements, the magnetic permeability of basalt, within measurement accuracy, was that of a nonpermeable material: $\mu' = 1$, $\mu'' = 0$.

To emphasize the relationships between the electromagnetic properties of basalt and its water content, Figs. 2 and 3 show the real relative permittivity and attenuation factor as functions of volume water content.

Discussion and Summary

The most obvious and expected conclusion from the results shown in Figs. 1-3 is that both permittivity and attenuation rate are strongly and systematically related to the water content of basalt. The data indicate a monotonic increase in permittivity and an approximately linear increase in attenuation rate with water content at all measured frequencies. Measurements of both propagation velocity and signal amplitude in basalt should be sensitive to the moisture content of the rock mass. Therefore, below the water table,

where the rock is completely saturated, measurement of signal amplitude and velocity would be a direct indication of porosity in the rock.

Because of this, data from cross-borehole tomography could be particularly useful since the measured distribution of electromagnetic attenuation between two boreholes could be interpreted as spatial variations in rock porosity. For example, at 25 MHz the measured attenuation rate would be $\sim 0.1 \text{ m}^{-1}$ for a saturated region with porosity of 2-1/2%; it would be $\sim 0.3 \text{ m}^{-1}$ for a saturated

Figure 1. The electromagnetic permittivity, $\epsilon = (\epsilon' - j\epsilon'')\epsilon_0$, of basalt as a function of frequency for various volume fractions of water content.

Figure 2. The real part of relative permittivity for basalt as a function of volume fraction water content for various frequencies.

region of 6% porosity, as might be expected in rock fractured by the large thermal load near a high-temperature-waste canister.

Such attenuation contrasts are not difficult to resolve using geotomography (Okada *et al.*, 1980). The data also show that, at frequencies typical of cross borehole tomography (between 25 MHz and 100 MHz), dry basalt has exceptionally small attenuation rates (0.04 m^{-1} , or 25-m skin depth, at 25 MHz), which permit long transmission paths and large borehole separations.

The dispersive character of basalt is strongly dependent on its water content. Figure 1 shows that, with no moisture, basalt is approximately nondispersive over a wide frequency range. Both permittivity and attenuation are independent of frequency, making it an attractive medium for probing by radar. The presence of moisture makes the basalt dispersive, dispersion being proportional to moisture content. This fact could be useful in differentiating between inhomogeneities in a basalt mass caused by pore or crack water and those caused by another factor, such as variation in mineral composition.

Electromagnetic probing relying on measurement of signal velocity is used for both cross-borehole imaging and radar. Propagation velocity is approximately proportional to $(\epsilon')^{-1/2}$, and accurate timing requires fast rise-time, high frequency-

sensitive to variations in moisture content (Fig. 2). It appears, therefore, that these time-of-flight techniques will be relatively insensitive to moisture content variations in a basalt rock mass. This will be advantageous for radar and cross-borehole applications used to locate or map anomalies not related to moisture variations. However, for applications to monitor changes in or map spatial variations of water content, time-of-flight techniques will be relatively ineffective. This conclusion would probably also include mapping of fractured zones where the principal interaction mechanism results from enhanced water content in the fractured rock.

By contrast, attenuation rate is more sensitive to moisture changes, especially at the higher frequencies (Fig. 3). Received signal strength is proportional to $e^{-2\alpha r}$, which means that measured amplitude is a strong function of attenuation rate. Because α is more sensitive at higher frequencies to variations in moisture, any electromagnetic attenuation measurements of moisture content should use the highest practicable frequency.

The sometimes irregular spectra of Fig. 1 above 800 MHz are artifacts of data reduction. This noise is present because, at approximately 900 MHz, the length of the saturated sample is one-half wavelength; in this spectral region, the algorithm used to convert the measured scattering

Figure 3. Attenuation rate (inverse skin depth) for basalt as a function of volume fraction water content for various frequencies.

content pulses. At higher frequencies, ϵ' is less susceptible to experimental errors. The other prominent spectral feature seen in Fig. 1, at about 450 MHz, is also caused by data error resulting from inexact calibration standards.

The data presented here quantitatively relate water content of basalt to measurable electromagnetic parameters. Undoubtedly the details of the relationship, will vary, even for different rocks of the same type but with different histories. When the relation is quantified for a given rock mass, however, high-frequency electromagnetic probing may be a useful tool in remotely characterizing the rock.

Especially below the water table where the rock is saturated, electromagnetic tomography and borehole logging could be used to map porosity distribution. Both spatial and temporal measurements of porosity in a rock mass could be useful. For example, stress can result in opening or closing of microcracks or pores; delineating these high-stress regions may help identify potential repository containment-failure modes.

In addition, long term monitoring of stress changes during part of a repository lifetime could be accomplished using high frequency electromagnetic techniques. Especially where porosity is dominantly from fractures and joints, electromagnetic techniques could provide a high-resolution

map of these zones of high permeability. In fact, Ramirez *et al.* (1982) have already demonstrated that fracture zones in granite can be mapped with high resolution using geotomography. Certainly,

it is also simple to map fractured regions in basalt; using the laboratory data in this paper, it may be practical to make quantitative measurements of water content in the rock mass.

Acknowledgments

The authors would like to thank Dr. K. Thirumalai for making available a basalt core sample from the Near Surface Test Facility at the Rockwell-Hanford Operations, as well as K. Kishiyawa and J. Beatty for computer programming assistance. This work was funded by Rockwell International, Hanford Operations, and by the U.S. Department of Energy, Office of Basic Energy Science, G. Kolstad, Monitor.

References

- Calvert, T. J. (1974), *Microwave Logging Apparatus Having Dual Processing Channels*, U.S. Patent 3,849,721.
- Dines, K. A. and R. J. Lytle (1979), "Computerized Geophysical Tomography," *Proc. IEEE* **67**, 1065-1073.
- Okada, I. T., E. F. Laine, R. J. Lytle, and W. D. Daily (1980), *Geotomography Applied at the Stripa Mine in Sweden*, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-52961.
- Poley, J. Ph., I. I. Nootboom, and P. J. de Wall (1978), "Use of VHF Dielectric Logging Measurements for Borehole Formation Analysis," *Log Analyst* **19**(3), 8-30.
- Ramirez, A. L., F. J. Deadrick, and R. J. Lytle (1982), *Cross-Borehole Fracture Mapping Using Electromagnetic Geotomography*, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-87536.
- Rau, R. N. (1976), *Method and Apparatus Utilizing Microwave Electromagnetic Energy for Investigating Earth Formations*, U.S. Patent 3,944,910.
- Suhler, S. A., T. E. Owen, and J. P. Cloassen (1970), *Development of an Advanced Prototype VHF Tunnel Detector*, USAMRDC, Ft. Belvoir, Va., Final Technical Report, Contract No. DAAK02-70-C-0101 (title U report C).