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ABSTRACT

Alterant tomography has been evaluated for its ability to delineate *in-situ* water flow paths in a fractured welded-tuff rock mass. The evaluation involved a field experiment in which tomographs of electromagnetic attenuation factor (or attenuation rate) at 300 MHz were made before, during, and after the introduction to the rock of two different water-based tracers: a plain water and dye solution, and salt water and dye. Alterant tomographs were constructed by subtracting, cell by cell, the attenuation factors derived from measurements before each tracer was added to the rock mass from the attenuation factors derived after each tracer was added.

The alterant tomographs were compared with other evidence of water movement in the rock: borescope logs of fractures, and postexperiment cores used to locate the dye tracer on the fractured surfaces. These comparisons indicate that alterant tomography is suitable for mapping water flow through fractures and that it may be useful in inferring which of the fractures are hydrologically connected in the image plane. The technique appears to be sensitive enough to delineate flow through a single fracture and to define fractures with a spatial resolution of about 10 cm on an imaging scale of a few meters.

INTRODUCTION

The Nevada Nuclear Waste Storage Investigations (NNWSI) Project is studying the suitability of the tuffaceous rocks at Yucca Mountain, Nevada Test Site, for the construction of a high-level nuclear waste repository. Lawrence Livermore National Laboratory (LLNL), Livermore, California, has been given the task of designing and verifying the performance of waste packages for the NNWSI Project. In order to reliably predict the performance of a waste-package design, the properties of the geologic environment around the package must be well characterized.

In this paper, we discuss an experiment performed to evaluate the applicability of alterant geophysical tomography to delineate water flow paths in fractured welded-tuff rock mass. *In-situ* measurements of electromagnetic (EM) attenuation factor (or attenuation rate) at 300 MHz were made before, during, and after water-based tracers were introduced to the rock. The data were used to construct alterant tomographs from which water flow paths are postulated. The alterant tomographs are compared with other geophysical evidence related to water movement in the rock: borescope logs and postexperiment cores to locate fractured surfaces.

EXPERIMENTAL CONCEPT: ALTERANT
GEOPHYSICAL TOMOGRAPHY

Geophysical tomography is conceptually similar to the medical tomography that inspired it. (1,2) An underground region is examined by transmitting energy (e.g., EM energy) through it from many points and detecting the altered signal along pathways hav-

ing many orientations. The transmitted signal must be chosen for its ability to be influenced (e.g., attenuated) by the property of interest (e.g., water) in the region.

Instrument access to the region was achieved by drilling parallel boreholes. A space—the region of interest—between the boreholes was plotted into a regular grid system, with each enclosed area (a square) defining a “cell.” The multiple, overlapping signal pathways were planned such that a computer code by an iterative matrix inversion process could estimate the signal parameter of interest (attenuation factor) for each cell and thereby yield a cell-by-cell map of that parameter. Finally, the property of interest was inferred from this map based on a conceptual model that relates the measured parameter and the property.

For this study, measurements of very high frequency (VHF) EM energy were used, because rock-mass EM attenuation is a sensitive function of (among other things) water content of the rock. (3,4) Typically, the larger the water content, the larger the attenuation factor. We used a technique known as alterant geophysical tomography where measurements are made before and after a tracer (water) of contrasting electrical properties (attenuation factor) is introduced to the rock. (5) The image formed by subtracting values of corresponding cells of the “before” and “after” tomographs is the alterant tomograph; the degree of rock penetration by the water is represented in the alterant image by the changes in attenuation factor between the before and after conditions. Conceptually, alterant tomography would define flow paths by distinguishing between: (1) moisture content changes along fractures or through the rock matrix, and (2) static anomalies, such as those caused by water trapped in the matrix.

FIELD EXPERIMENT

Geologic Setting

The experiment was conducted in an ash flow tuff formation of the Grouse Canyon member of the Belted Range tuff, in the rib of the extensometer drift in the G-tunnel complex at the Nevada Test Site. This formation is readily accessible and is lithologically similar to that of the proposed repository horizon, the Topopah Spring tuff at Yucca Mountain. The Grouse Canyon tuff exposed in G-tunnel is a partially welded to densely welded tuff striking N 55-deg E and dipping 9-deg W. (6) This formation is in the unsaturated zone but has a degree of saturation greater than 85%. Porosity ranges from 13 to 25%. (7)

The measurements of EM attenuation factor were made between three horizontal, parallel, coplanar boreholes drilled 90 cm apart. Figure 1 shows the borehole layout relative to the drift. Boreholes 2, 3, and 4 served as measurement holes. Borehole 1 was drilled 2 deg below the horizontal to provide a reservoir from which water could infiltrate the rock mass. All boreholes are 6 m long.

The top of a rubble zone is located about 30 cm below the collar of borehole 4. This contact marks the transition between a welded-tuff zone, above, and nonwelded tuff, below. Previous fracture mapping near this region of G-tunnel indicates that most fractures are nearly vertical, with two predominant sets striking

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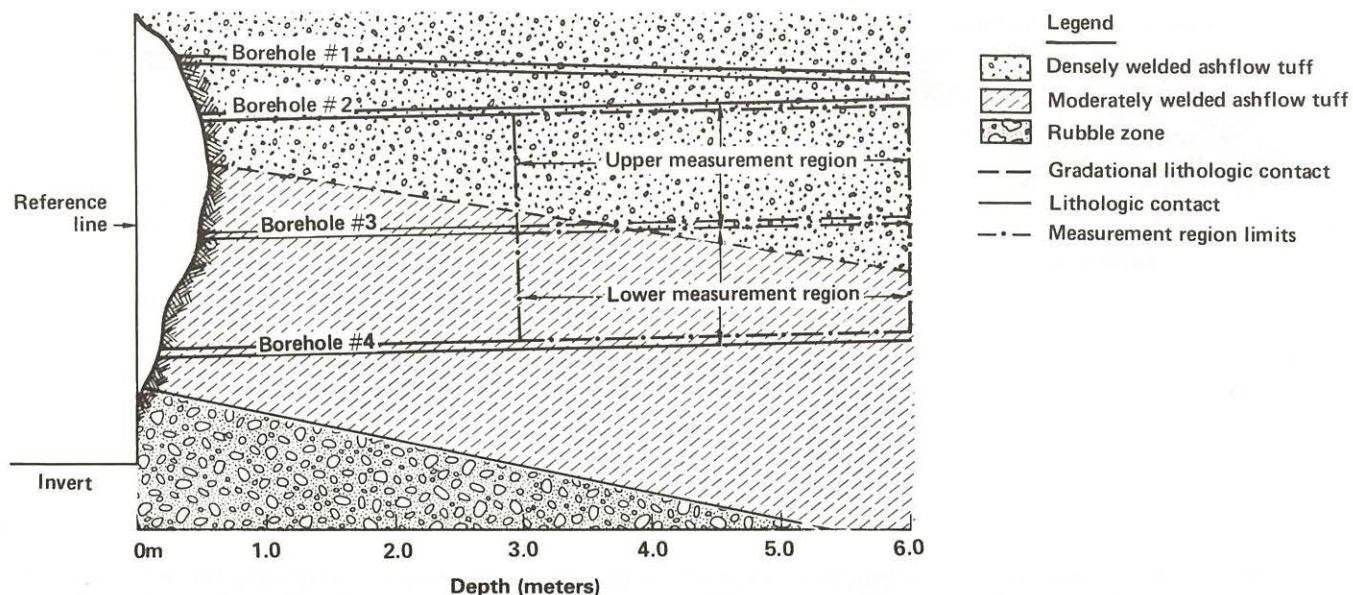


FIGURE 1: BOREHOLE LAYOUT AND TOMOGRAPHIC PLANE RELATIVE TO LOCAL GEOLOGY, WHICH WAS EXTRAPOLATED FROM MAP BY B. S. LANGKOPF AND E. ESHOM. (6)

approximately N 40- to 60-deg W and N 20- to 40-deg E. (6) The azimuth of the measurement boreholes is N 15-deg W.

Experimental Procedure

Prior to the start of tracer flow, initial measurements were made between boreholes 2 and 3 (upper measurement region) and between boreholes 3 and 4 (lower measurement region) (see Fig. 1). These measurements provide the baseline data of EM attenuation factor of the rock and are designated as "before" measurements. Then borehole 1 was filled with a solution of water and methylene chloride dye, which stains the rock dark blue on contact. Subsequently, measurements were taken for a tomograph nearly every weekday for the next 2 weeks, alternating each day between the upper and lower regions. These sets of measurements are designated as the "after" measurements. Finally, a salt water and dye solution (dc electrical conductivity of 2.1×10^{-1} S/m) was added to borehole 1 and allowed to infiltrate the formation for 3 days. Three tomographic data sets were then collected from the upper and lower regions.

Additional information on the rock mass was collected in an effort to corroborate our inferences from the tomographic data. Borehole cores were obtained from the rock represented by the tomographs to locate fractures stained by the blue dye and identify the location of those fractures that conducted water. Also, a bore-scope was used to log fractures in boreholes 2, 3, and 4.

RESULTS AND DISCUSSION

Alterant Geophysical Tomographs

Each of the images shown in Figs. 2 and 3 consists of an array of 7.5-cm-square cells in rows 40 cells long and in columns 12 cells high. The gray scale represents the values of the change in EM attenuation factor, with the darker tones corresponding to larger changes. Thus, regions of the rock mass serving as flow paths would be represented by dark gray, or black.

Figure 2 shows two alterant tomographs of the upper measurement region, which compare the changes in EM attenuation factors caused by the plain-water and salt-water tracers. The left image shows water-content changes in the rock mass 15 days after the plain-water tracer was introduced. The right image shows changes caused by the salt-water tracer approximately 2 days after it was introduced. The general shape and location of anomalies are similar in the two images.

As expected, the changes in the EM attenuation factor of the anomalies are larger with the higher conductivity salt-water tracer in the formation than with the plain-water tracer. However, both tracers caused changes in EM attenuation that are small compared to the bulk attenuation of the rock mass. The average EM attenuation factor through the rock before the tracer was added was 1.43 m^{-1} . The water tracers caused changes on the order of 0.1 m^{-1} , whereas the salt-water tracer caused changes averaging 0.15 m^{-1} . These relatively small changes in EM attenuation are indicative of the fact that rock-mass fracture porosity is relatively small compared to the matrix porosity.

Computer simulation tomographs, made with and without measurement system noise, were used to determine the influence of measurement imprecision on the images, since the induced changes in attenuation were on the order of 10% of background, or baseline, attenuation. Figure 3 is an alterant tomograph in which the anomalies shown are at least two standard deviations larger than the image anomalies expected to be introduced by measurement errors. The results show that the major image anomalies are not likely to be caused by random measurement errors.

Comparison with Other Data

For both the upper and lower measurement regions, the fracture location and orientation data (obtained from bore-scope logs) has been combined with the tomographic data in Fig. 3. Note that the trends defined by the larger anomalies in Fig. 3 approximately match the orientation of mapped fractures.

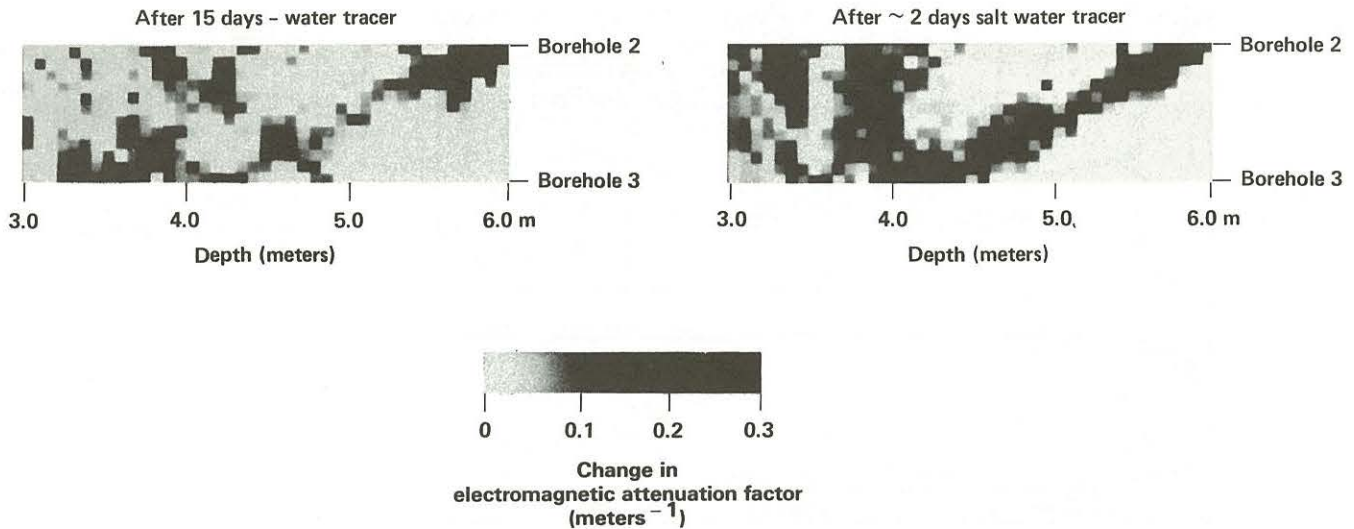


FIGURE 2: ALTERANT TOMOGRAPHS OF UPPER MEASUREMENT REGION. LEFT IMAGE SHOWS CHANGES CAUSED BY 15-DAYS INFILTRATION OF PLAIN WATER INTO ROCK MASS. RIGHT IMAGE SHOWS CHANGES CAUSED BY APPROXIMATELY 2-DAYS INFILTRATION OF SALT WATER.

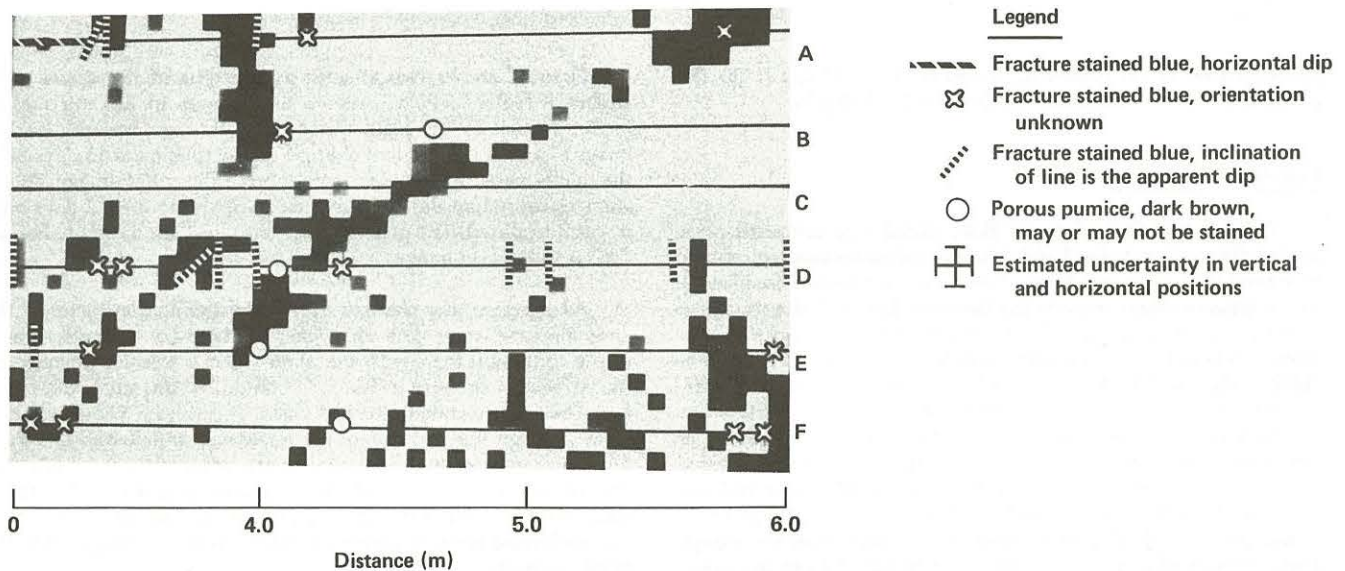


FIGURE 3: ALTERANT TOMOGRAPHS OF UPPER AND LOWER MEASUREMENT REGIONS SUPERIMPOSED ON TRACER-STAINED FRACTURES LOCATED BY POSTEXPERIMENT CORING ALONG SIX BOREHOLES (LABELED A THROUGH F). (CELL GRAY SCALE IS DEFINED IN FIG. 2.) ANY CELL WITH A VALUE THAT COULD HAVE BEEN CAUSED BY MEASUREMENT ERROR WAS SET TO ZERO (WHITE). ESTIMATED UNCERTAINTY IN FRACTURE POSITIONS ALONG THE CORED BOREHOLES IS SHOWN IN LEGEND.

The two vertical anomalies between boreholes 2 and 3, centered at depths of 3.4 m and 3.9 m, may be water-filled fractures. This interpretation is consistent with geologic data (6,8), indicating that most of the fractures in this unit are vertical. A diagonal anomaly, beginning at a depth of 4.0 m, in borehole 3 is present for both plain- and salt-water tracers. This anomaly suggests flow paths other than vertical in the rock mass.

Figure 3 also shows that some anomalies occur where no dyed fractures were recovered. Several hypotheses have been considered that could explain this:

(1) Other studies have shown that the tomographic process can exaggerate the extent of anomalies of interest. (9) Thus, the

anomalies in the alterant tomographs may be of greater extent than the actual flow paths. This would make some of the inferred flow paths incorrectly appear to be intersected by postexperiment coreholes.

(2) The dye failed to visibly stain the flow paths. This hypothesis is applicable to those locations where highly porous pumice was found to occur. Dye tests indicate that the dark blue stains on this dark brown rock are not visible.

(3) Sources of water other than from the reservoir borehole containing the dye solution may have caused image anomalies. Other activities that injected water into the neighboring rock were inadvertently occurring within the tunnel at the same time as our

experiment. These activities occurred at higher elevations and were within a 15-m radius of the tomographic plane. Grout injected at one location traveled a distance of approximately 10 m and was intercepted by the postexperiment coreholes. The extent of grout penetration shows that the water flow paths could have been continuous over distances of at least 10 m.

(4) The drilling process destroyed some of the stained core. Fractures are the weakest elements in a rock mass and, thus, are the most likely to be damaged by the drilling process. At several locations, the recovered core had disintegrated, and small sections were missing, especially those along the lower part of the lower region near borehole 4.

However, despite these problems, the comparison of alterant tomographs with other data has provided positive evidence concerning the applicability of alterant geophysical tomography for studying flow paths in welded tuff. Indications of the technique's effectiveness are: (1) the correlation between most image anomalies and dyed fracture flow paths, and (2) the general agreement between the larger image anomalies in Fig. 3 and the orientation of fractures mapped by the borescope surveys.

CONCLUSIONS

Our work has shown the applicability of alterant geophysical tomography to delineate water flow paths in fractured welded-tuff rock mass. A comparison of the image anomalies with the recovered rock core indicates that all of the stained fracture planes have corresponding image anomalies. The cores show that several of the image anomalies represent flow paths along single fractures. The image anomalies also coincide in location and orientation with fractures mapped by borescope surveys. Therefore, corroborating evidence shows that fracture flow was imaged by the alterant geophysical tomography method. The technique appears to be sensitive enough to delineate flow through a single fracture and to define fractures with a spatial resolution of about 10 cm on an imaging scale of a few meters.

There are some image anomalies for which no stained fractures were recovered. However, most of these anomalies coincide in location and orientation with fractures mapped by the borescope logs. It seems unlikely that such a correlation would be caused by coincidence. Measurement error analysis suggests that those anomalies for which dyed rock was not recovered probably represent actual flow paths.

The work to date has involved the delineation of flow paths in a thermally undisturbed, welded-tuff rock mass. Experiments are now being conducted to evaluate the applicability of the method in a thermally disturbed environment similar to the environment to be created by the Waste Package Environment Tests in Yucca Mountain.

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