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ELECTROMAGNETIC EXPERIMENT TO MAP IN SITU WATER IN HEATED WELDED TUFF: PRELIMINARY RESULTS

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Electromagnetic experiment to map in situ water in Heated Welded Tuff: Preliminary Results*

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ABSTRACT: An experiment was conducted in Tunnel Complex G at the Nevada Test Site to evaluate geotomography as a possible candidate for in situ monitoring of hydrology in the near field of a heater placed in densely welded tuff. Alterant tomographs of 200 MHz electromagnetic permittivity were made for a vertical and a horizontal plane. After the 1 kilowatt heater was turned on the tomographs indicated a rapid and strong drying adjacent to the heater. Moisture loss was not symmetric about the heater but seemed to be strongly influenced by heterogeneity in the rock mass. The linear character of many tomographic features and their spatial correlation with fractures mapped in boreholes are evidence that drying was most rapid along some fractures. When the heater was turned off an increase in moisture content occurred around the heater and along the dry fractures. However, this process is much slower and the magnitude of the moisture increase much smaller than the changes observed during heating of the rock. The interpretation of the tomographs is preliminary until they can be processed without the restrictive assumption of straight ray paths for the signals through the highly heterogeneous rock mass.

1. 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 assessing the performance of waste packages for the NNWSI Project.

One of the key issues regarding waste package performance is the hydrologic behaviour of the rock mass under the environmental conditions that will be perturbed by the waste package. Recently developed measurement techniques are being used to monitor the hydrologic behaviour of in situ welded tuff under thermal loading.

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This report discusses the results of an experiment in which one of the candidate measurement techniques, alterant geophysical tomography, (Ramirez and Lytle, 1986; Ramirez and Daily, 1986) was used to infer changes in moisture content created by a heater in welded tuff. The objective of the experiment was to evaluate the capability of alterant geophysical tomography to map the changes in moisture content occurring within a few meters of the heater location. Other heater experiments conducted at G-Tunnel are described by Zimmerman and Blanford (1986), and Zimmerman, et al. (1984).

2. EXPERIMENT DESCRIPTION

Measurements of very high frequency electromagnetic energy (185-215 MHz) were used because rock mass electromagnetic properties depend strongly on (among other things) water content of the rock (Poley, et al., 1978; Daily and Ramirez, 1984; Hearst and Nelson, 1985). The complex permittivity of the rock depends on the permittivities of its two basic constituents: silicate matrix and water. For the rock matrix, at the frequency of interest, the real part of the complex permittivity ϵ_r is approximately 2-4 but for water ϵ_r is approximately 80 (Von Hipple, 1954). It is this large contrast that makes the real part of the permittivity for rock a valuable diagnostic of its water content. Small changes in water content can result in measurable changes in ϵ for the rock mass.

The tomographic reconstruction algorithm used for this study was based on the common simplifying assumption of geometrical optics -- diffraction or refraction effects resulting from inhomogeneities in the medium are ignored and the energy propagating between antennas follows straight ray paths. An effort is underway to account for these phenomena by relaxing the constraint of straight ray paths in the tomographic inversion algorithm. We consider the tomographs and their interpretations discussed in the following sections preliminary until this effort is completed.

All of the images reported herein are alterant tomographs (Ramirez and Lytle, 1986). They are generated by subtracting values of pixels in one tomograph from values of corresponding pixels in another tomograph. In this way a differential or alterant tomograph is formed which shows only features which change between the time the two data sets were taken. For the purpose of the experiment, this technique allows imaging of water content changes in fractures and rock matrix without the confusion of static background features such as lithology or unchanging pore water. Tomographs taken during the heating phase were subtracted from the corresponding tomographs taken just before the heater was turned on. Ideally, these alterant tomographs should delineate water content changes as the thermal field expands from the heater. Tomographs taken during cooling are subtracted from the corresponding tomograph taken just before the heater was turned off. These alterant tomographs should delineate water content changes, relative to the driest state in the rock mass, as the thermal field collapses and water is moved by capillarity and gravity back into the tomographic plane.

2.1 GEOLOGIC SETTING

The experiment was conducted in G-Tunnel at the Department of Energy's Nevada Test Site, Nye County, Nevada. This tunnel provides access to an ash flow tuff formation of the Grouse Canyon member of the Belted Range Tuff. This formation was of interest because it has similar properties to the proposed repository horizon, the Topopah Spring tuff, at Yucca Mountain. The Grouse Canyon member is in the unsaturated zone but has a degree of saturation greater than 60% and a porosity ranging from 15 to 46% reported by Zimmerman and Blanford (1986). For the same formation Johnstone and Wolfsberg (1980) report a porosity ranging from 13 to 25 percent and a saturation greater than 85%.

2.2 BOREHOLE CONFIGURATION

Measurements were made between a series of horizontal boreholes drilled into the rib of the small diameter heater alcove in the tunnel (Figure 1). Three of the boreholes define two planes in the rock mass which were sampled for tomographic reconstruction; each plane was two meters long and one meter wide. Both measurement planes were at least 3.4 meters from a tunnel rib. One measurement plane was vertical (plane A-B between boreholes B and A) with the heater borehole intersecting it nearly perpendicular. The other tomographic plane was nearly parallel to, and about 1/2 meter below the heater axis.

2.3 DATA COLLECTION

The experiment was more than three months in duration. Initially, tomographs were made of measurement planes A-B (vertical) and B-D (horizontal). The heater was turned on and heater power was adjusted to one kilowatt electrical. During the 34 days of heating, E.M. data and neutron logs were taken periodically . After sufficient cooling, the boreholes were logged with a borescope to locate fractures and map their orientation. Core from these holes was also examined to locate fractures and other structures which may have played a role in local hydrology during the test.

3. RESULTS AND DISCUSSION

3.1 ROCK MASS HEATING

Figure 2 shows an alterant tomograph, which presents all of the permittivity changes detected during the entire heating phase of the experiment. These data show an overall decrease of permittivity in both planes during heating. This is reasonable since we might expect a general dehydration throughout the region as the thermal field expands. In fact this permittivity decrease is monotonic during heating throughout the A-B image plane. The dehydration appeared to be less intense in plane B-D than plane A-B and this is reasonable since the former was further removed from the heater. Early tomographs (not

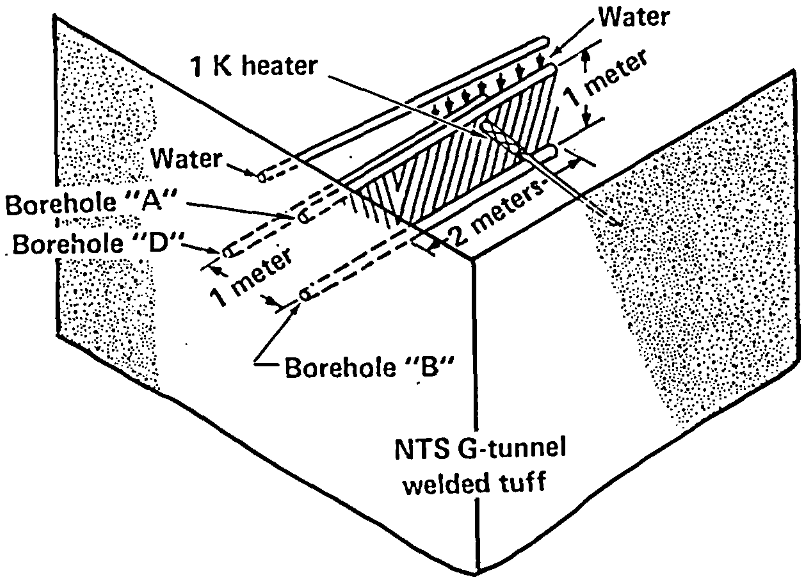

Figure 1. Borehole layout and measurement planes relative to the location of the heater borehole. Vertical (A-B) and (B-D) horizontal measurement planes were sampled.

shown due to space limitations) show that after only two days of heating a definite pattern of decreased permittivity (drying) appears in the A-B image. This pattern persists, largely with the same shape and location throughout the 34 day heating period. The last tomograph obtained during the heating phase (shown in Figure 2) differs from the early tomograph only in the magnitude of the anomalies, while the pattern of the anomaly remains constant. After only two days, changes in permittivity are measured as far as 0.8 m from the heater. Two processes may contribute to this early decrease--higher pore water temperature and drying (especially along fracture surfaces). Of course, both processes require heating the rock mass. At this distance from the heater, thermal conduction could contribute to about 10°C temperature increase. The heat transfer rate may be enhanced, however, by steam from near the heater moving outward along fractures.

Larger decreases in permittivity are observed as time progresses. The greatest drying occurs nearest the heater location in plane A-B. This region is undoubtedly the hottest in the rock mass. Drying is not restricted to the immediate vicinity of the heater -- it is also not radially symmetric about the heater. Some pixels on the image plane 1/2 meter from the heater show little or no change in permittivity. Other pixels at the same distance show relative permittivity change of 1.0. The distribution of drier rock is apparently controlled by strong heterogeneity in the rock mass. Dominant is a drying zone, roughly vertical, about 1/2 meter wide and centered on the heater. The vertical extent of this anomaly may be somewhat exaggerated or distorted because of contrast in permittivity between dry rock near the heater and the wetter rock around it. This is evident since the anomaly extends to the tomograph edges in plane A-B but does not appear as a prominent anomaly in plane B-D. Another source of non-uniqueness

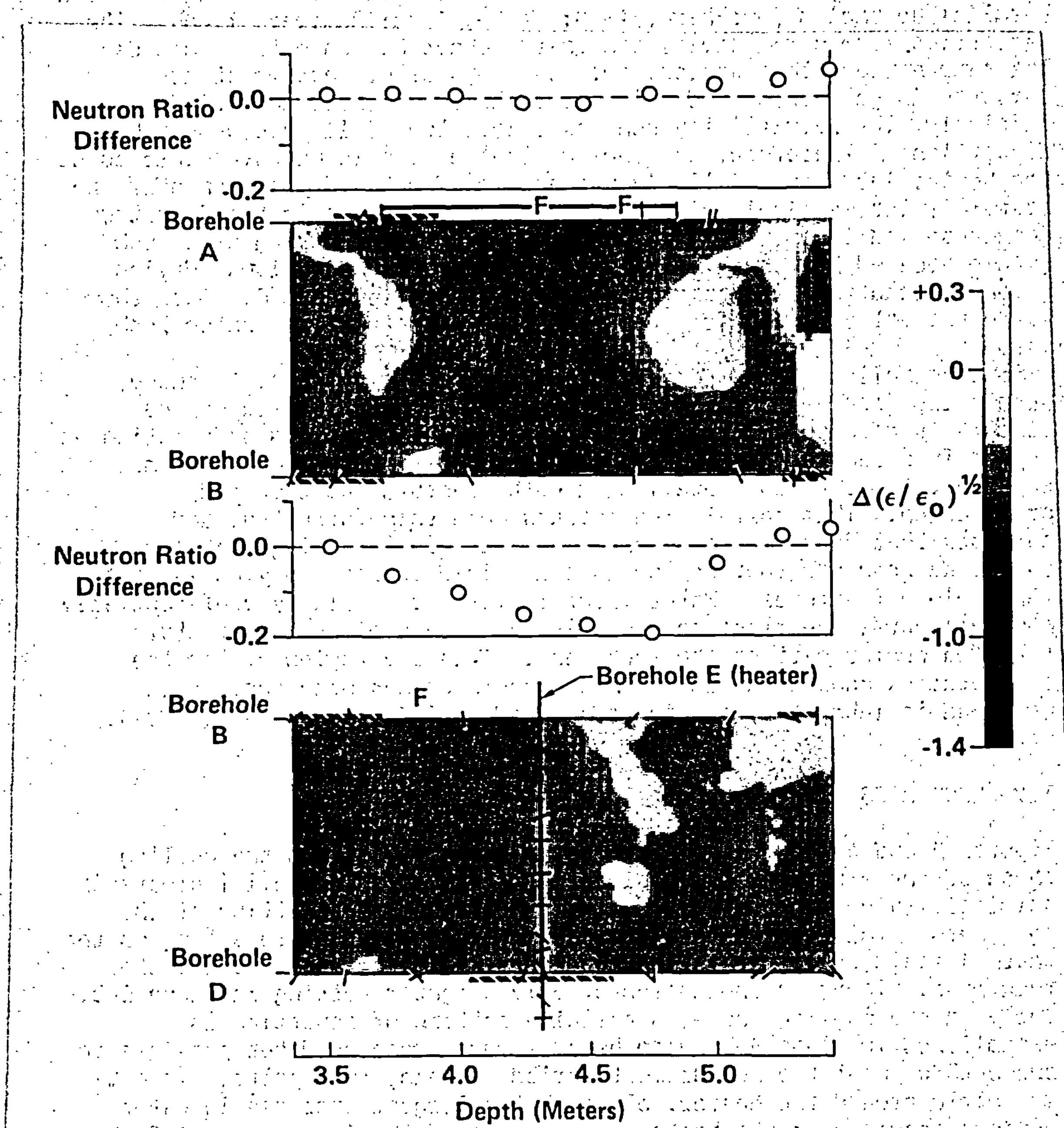

Figure 2. Alterant tomograph showing the changes in the square root of the relative permittivity $\Delta\ (\varepsilon_r/\varepsilon_0)^{1/2}$ after 34 days of heating. Negative values are interpreted as decreases in water content. The top and bottom images represent the vertical and horizontal measurement planes, respectively. The location and approximate orientation of fractures is indicated by the short lines or by the letter (F) where orientation could not be determined. The black lines with white stripes indicate highly fractured regions along the borehole.

is caused by the limited angles of view available for sampling from two parallel boreholes (Burkhard, 1980; Menke, 1984; Ramirez, 1986). The distortion from permittivity contrasts cannot be too extreme because the same pattern that appears only two days after heating starts persists largely unchanged throughout the 34 day heating period. Initially, the permittivity contrasts were too small to cause such distortions. Therefore, we conclude that drying is not symmetric about the heater location. A likely explanation for the dry region near the heater is the vertical orientation of most fractures in the formation (Langkopf and Eshom, 1982). The image may reflect drying of a rock volume bounded by nearly vertical fracture sets. Additional drying probably occurred along the boreholes, especially A and B, since they are excellent conduits for steam escaping away from the heated rock mass.

Some anomalies in the tomographs of Figure 2 are linear in shape, suggesting fracture influence during drying. Superimposed on the tomographs of Figure 3 are actual fracture locations and orientation as mapped in boreholes A, B and D. Several anomalies at the A-B tomograph edge correspond approximately with both fracture location and orientation. This correlation appears more than fortuitous and suggests that fractures play an important role in drying the rock mass. We conclude that as the thermal field expands, drying is most rapid along fractures. Water vapor leaves the matrix by preferentially moving towards the fracture where it then moves along the fracture toward a cooler part of the rock mass. This dry region around the fractures expands with time. This phenomenon has previously been observed in laboratory studies of welded tuff (Daily, et al., 1987).

3.2 ROCK MASS COOLING

Figures 3 and 4 show alterant tomographs chosen to span the cooling phase of the experiment. In plane A-B there is an overall increase in permittivity during the period, implying a general rewetting of the rock mass. This is reasonable since we expect gradual rewetting as the thermal field collapses, steam condenses and water can re-enter the rock mass. There is indication of only slight rewetting in plane B-D. Early in the cooling phase, a definite pattern of rewetting is established in plane A-B which becomes more pronounced but persists in shape throughout the measurement period. Again, this pattern is not symmetric around the heater, although the largest increase in water content occurs near the heater. Over most of the image plane A-B the moisture increase is apparently controlled by heterogeneity of the rock mass. The nearly vertical zone, so prominent in the heating phase, rewets quite slowly. The structures showing rewetting in Figure 4 are even more linear in nature than those which dry during heating. Again, the images are suggestive of fractures dominating the hydrology. In fact, there is a good enough correlation between the heating and cooling tomographs to argue that the same fractures may be participating in both drying and rewetting of the rock mass (compare Figures 2 and 4).

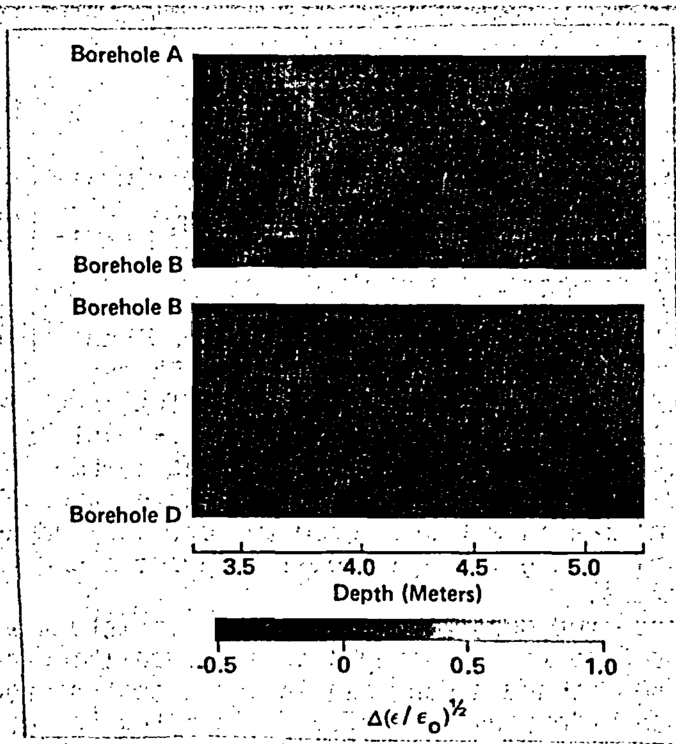

Figure 3. Alterant tomographs of changes in the square root of the relative permittivity $\Delta\,(\epsilon_r/\epsilon_0)^{1/2}$ in both vertical and horizontal measurement planes 4 days after the heater was turned off. Positive values are interpreted as increases in water content.

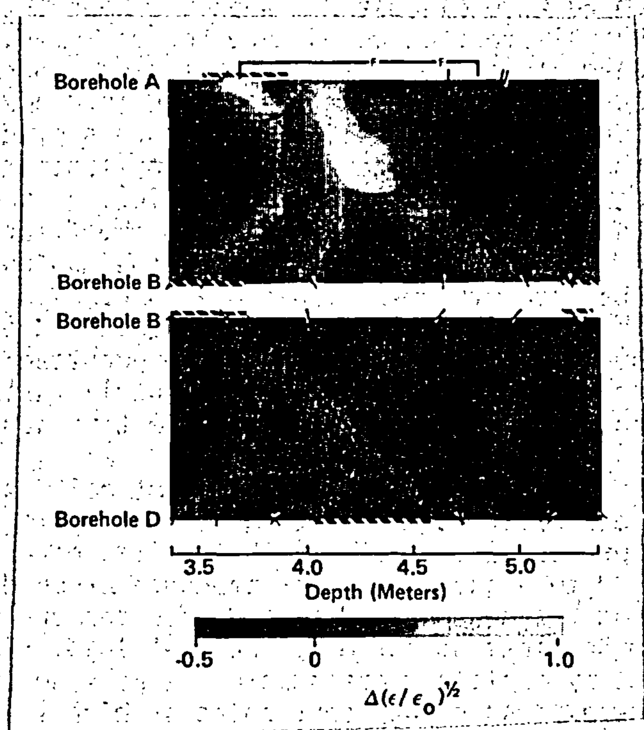

Figure 4. Alterant tomographs of changes in the square root of the permittivity $\Delta\,(\epsilon_r/\epsilon_0)^{1/2}$ in the vertical and horizontal measurement planes 56 days after the heater was turned off. Positive values are interpreted as increases in water content.

We suggest that as the thermal field collapses, rewetting is most rapid in the matrix along those fractures which were the driest during the heating. The gradient in the moisture content would be largest along these fractures. There are two possible sources of water for this process; that which was driven as vapor out of the matrix, through the fractures and deposited in the cooler rock mass, and that which remained in the matrix away from the hottest region. There is evidence in Figure 4 that this latter source may provide water for rewetting along the lineaments during cool down. This evidence is manifested as a slight permittivity decrease in some regions adjacent to the rehydration features and is most evident in the cool down tomograph of Figure 4. If the residual matrix water entered the dry rock adjacent to fractures, it did so by moving through capillary paths along the gradient in matrix potential.

The neutron log data acquired during cool down are consistent with the interpretation of the tomographs. They show an overall increase in water content below the heater and a decrease in water content above the heater. However, saturation levels (inferred from the tomographs) did not return to the pre-experiment, background levels during the two month cool down period.

3.3 POSSIBLE INTERPRETATION OF DATA

A possible hydrologic scenario can be postulated based on the experiment results which we have discussed. When the heater in the rock was turned on a thermal front expanded into the rock mass. As the pore temperature increased, the vapor pressure increased and the thermal gradient imposed by the heater was translated into a vapor pressure gradient. Water vapor moved as a result of this gradient through the matrix to the nearest pressure sink -- any fracture hydrologically connected to the large pressure reservoir of the rock mass environment. The steam migrated upward through the fracture network until it reached rock which cooled it below the dew point. There it condensed on the fracture wall. This drying process occurred initially adjacent to the heater. This is also the location of largest water content loss. The next most pronounced drying occurred farther from the heater along fractures. In general, rock matrix furthest from fracture surfaces did not loose much water within the time scale of our experiment.

When the heater was turned off and the thermal front collapsed, some of the rock mass that lost water during heating began to gain water. However, the rewetting process is not simply the reverse of drying. As the temperature decreased in a pore the vapor pressure dropped. A capillary gradient formed between pores depleted of water and pores further from the heater and less affected by the heat load. This gradient tended to rewet by capillary pressure pores previously depleted of water at the expense of adjacent pores at higher water content. This rewetting was most pronounced where drying was most severe and the moisture gradients highest -- adjacent to the heater. This volume achieved the largest increase in water content. Further from the heater, where drying was predominately along fractures, the same phenomenon occurred. The driest regions adjacent to the fracture gained water at the expense of wetter rock further into the matrix.

4. SUMMARY AND CONCLUSIONS

The effectiveness of electromagnetic geophysical tomography to detect cross-hole changes in moisture content in a thermally disturbed welded tuff rock mass is evaluated by comparing the tomographs with other geological and geophysical data. Based on these comparisons, inferences were made on how moisture moved. If these inferences are sensible and consistent with other data and a priori expectations of rock behaviour, one can suggest that electromagnetic geophysical tomography may provide a viable way of monitoring in situ moisture content changes. This evaluation approach is, by necessity, indirect because we know of no other proven techniques which could be directly compared to the electromagnetic tomographs.

Tomographs of electromagnetic permittivity at 200 MHz represented two planes in the rock, each one meter by two meters. Measurements were made over a three month period as the rock was heated by a 1 kilowatt heater and as the rock cooled. A total of 44,982 electromagnetic measurements were made and used to reconstruct 51 tomographs, six of which are presented above.

The electromagnetic tomographs, the neutron logs and the fracture maps were used to infer water flow paths. Conclusions based on analysis of these data are as follows:

1. The changes in moisture content inferred from the tomographs generally agree with prior expectations of the hydrologic response. As the rock temperatures increased the tomographs show that rock in the immediate vicinity of the heater loses moisture and that this drying region grows larger with time. The greatest decrease in moisture content was observed around the heater.

2. Anomalies indicative of drying approximately coincided in location and orientation with fractures mapped along the borehole walls. This inferred preferential drying along fractures has been independently observed during laboratory experiments (Daily, et al., 1987).

3. After the heater was turned off and the rock cooled, the largest increases in moisture content occur in the immediate vicinity of the heater. Also, anomalies indicative of rewetting coincide with several fractures mapped in the boreholes. The tomographs suggest that fractures play an important role in how the rock dries and rewets.

4. The changes in $(\epsilon_T/\epsilon_0)^{1/2}$ measured were typically much larger than the variation which would be introduced by imprecision ($\pm$0.04) associated with the measurement noise.

From the results of this experiment we conclude that geophysical tomography can provide useful information on the hydrology in the near field of a heater in densely welded tuff. This conclusion is based on the fact that the experimental results were self consistent and in good agreement with a priori knowledge. We consider this conclusion preliminary, however, until the tomographic data can be analyzed using an inversion algorithm consistent with the large contrasts in measured signal velocity. This analysis is presently underway.

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