

GEOPHYSICAL BOREHOLE LOGGING IN THE UNSATURATED ZONE, ^{May 1 1991}
YUCCA MOUNTAIN, NEVADA

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ABSTRACT

Borehole geophysical logging for site characterization in the volcanic rocks at the proposed nuclear waste repository at Yucca Mountain, Nevada, requires data collection under rather unusual conditions. Logging tools must operate in rugose, dry holes above the water table in the unsaturated zone. Not all logging tools will operate in this environment, therefore; careful consideration must be given to selection and calibration.

A sample suite of logs is presented that demonstrates correlation of geological formations from borehole to borehole, the definition of zones of altered mineralogy, and the quantitative estimates of rock properties. We show the results of an exploratory calculation of porosity and water saturation based upon density and epithermal neutron logs. Comparison of the results with a few core samples is encouraging, particularly because the logs can provide continuous data in boreholes where core samples are not available.

INTRODUCTION

The objectives of the logging program at Yucca Mountain are (1) to aid in the definition of the location and character of lithostratigraphic units and contacts between units, and (2) to determine the distribution of rock properties within lithostratigraphic units. Logs can be used to achieve the first objective by showing examples of hole-to-hole correlations among density, resistivity, gamma ray, and magnetic field logs. Density and resistivity logs are particularly diagnostic of changes in porosity and alteration. This paper concentrates on the second objective by illustrating the results of an exploratory calculation of porosity and water saturation in the unsaturated zone. An estimate of mineralogy must be obtained from the logs before the calculation can be carried out.

Geophysical logs are acquired routinely by the petroleum industry to correlate geologic horizons and to estimate the amounts of hydrocarbons present in the pore space of the rock. We are adapting the technology developed by the petroleum industry for logging in sedimentary sequences and applying it to the volcanic rocks at Yucca Mountain. Most of the area of interest at the Yucca Mountain site lies above the static water level, requiring that the logs must be obtained in air-filled boreholes rather than in the mud-filled or water-filled holes usually encountered in petroleum exploration. As a consequence, some logging tools cannot be operated above the water table, and those that can require special calibrations to obtain valid measurements.

Of particular interest in this study are the specific conditions under which the boreholes were drilled. To reduce problems associated with the invasion of drilling fluid into the rock in the unsaturated zone, the boreholes were drilled with air foam. The foam is produced by mixing a detergent with water. Logs obtained from boreholes drilled with air foam may then be thought of as representing the original natural environment to a much closer degree than those drilled with conventional drilling fluids.

The effects upon logs from a borehole that is air-filled and rugose are discussed in greater detail by Nelson et al.². The corrections required to compensate for the borehole environment in air-filled boreholes require a calibration of each tool. Although calibrations are incomplete for all logging tools at this time, enough has been learned that we are able to perform a calculation in order to demonstrate the potential of the logs.

GEOLOGICAL DESCRIPTION

The area of southwestern Nevada encompassing Yucca Mountain has been covered extensively by volcanic tuffs during Tertiary time. Both the stratigraphy and mineralogy of the southwest Nevada volcanic field have been studied extensively³.

The volcanic rocks comprising Yucca Mountain are ash-flow and ash-fall tuffs. Ash-flow tuff is formed when volcanic ash retains sufficient density and viscosity during the course of an eruption such that it flows rapidly from its source and spreads out under the force of gravity, coming ultimately to rest in thick sheets. During the cooling period, welding of the rock mass occurs. Welding can be ranked by the degree of flattening of pumice fragments in the tuff matrix. Porosities in ash-flow tuffs may range from a few percent to greater than 50% in the same flow. Ash-fall tuffs are comprised of ash that has been ejected explosively into the air during an eruption and subsequently settled out as bedded layers.

To illustrate the geological and mineralogical character of the tuffs, data from continuously cored borehole USW GU-3 are shown in figure 1. The left-most track of figure 1 shows the results of an x-ray diffraction analysis. In track 1 the blank area on the left shows the volume percent of feldspar and the blank area on the right shows the calculated porosity. We note the major division between the feldspar and silica, where the silica is comprised of the trimorphous minerals tridymite, cristobalite, and quartz. The minerals tridymite and cristobalite are thought to recrystallize to quartz in the presence of ground water over a prolonged period of time⁴. Glass is a chief constituent of vitrophyre (which is a densely welded tuff), and also of low-density, poorly welded vitric tuff, recognized by its glassy appearance. Zeolites and clays are the products of alteration. Track 2 shows the degree of welding as determined from cores, and also an estimate of lithophysae (or vugs) again estimated from cores. Although degree of welding and lithophysal abundance do not have quantitative scales, the arrows at the top of the track indicate the direction of increase. These lithophysae range from a few millimeters to 5 cm in diameter. The lithophysae are formed during the process of devitrification⁵ and give the rock a decidedly vugular appearance. Also shown are fractures as determined from examination of cores. One should note the extensive amount of fracturing in the welded tuff as opposed to the lack of fracturing in zones where

glass and zeolites occur. The right-hand track shows the grain densities obtained from cores. Note that grain densities are rather uniform within the welded tuff. Grain density values of both the glassy and zeolitic zones are less than those in the welded tuffs.

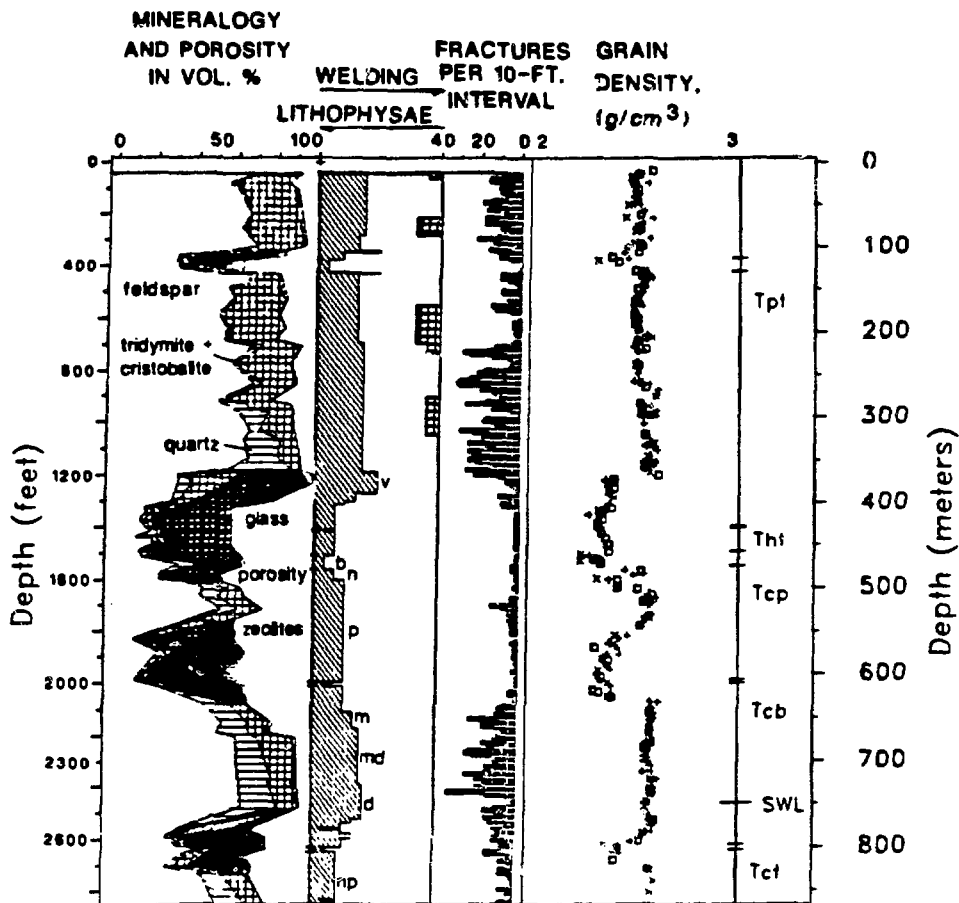
LOGGING TOOLS USED IN THE UNSATURATED ZONE

Logging tools that have been used above the static water level at Yucca Mountain to measure nuclear, electrical, density, and magnetic properties include:

1. Gamma ray, providing a total count rate proportional to the contribution of all naturally occurring radionuclides.
2. Spectral gamma ray, yielding estimates of potassium, uranium, and thorium.
3. Epithermal neutron, measuring the population of epithermal neutrons in the presence of an active neutron source. Responds primarily to the presence of water.
4. Compensated density, measuring the gamma rays scattered by the rock. Responds to electron density which is related to rock density.
5. Induction tools, measuring electrical conductivity.
6. Dielectric tools, measuring dielectric constant.
7. Downhole gravity meter, measuring gravity at discretely spaced intervals.
8. Caliper, measuring borehole diameter.
9. Downhole magnetometer, measuring components of the earth's magnetic field, including perturbations due to remanent magnetization of the rock.

The nuclear tools can be run both in open or cased holes. The gamma-ray logs are useful in determining lithology because of the high potassium content of feldspar. The epithermal neutron tool and the compensated density tool are used to determine the degree of water saturation and porosity in the unsaturated zone.

Electrical parameters such as conductivity and dielectric constant can be obtained in dry boreholes from induction and dielectric logging tools. Rock resistivity measured by the induction tool can be used to compute water saturation in the unsaturated zone. However, in some boreholes where water saturation is low and the rock is unaltered, free of clays or zeolites, the resistivity can be so high that the measurement design limit of the induction tool may be exceeded.



WELDING

- b Bedded
- n Non-welded
- np Non- to partially
- p Partially
- m Moderately
- md Moderately to densely
- d Densely
- v Vitrophyre

STRATIGRAPHIC UNITS

- Tpt Topopah Spring Member of Paintbrush Tuff
- Thl Tuffs and lava of Calico Hills
- Tcp Prow Pass Member of Crater Flat Tuff
- Tcb Bullfrog Member of Crater Flat Tuff
- Tct Tram Member of Crater Flat Tuff

FIG. 1. Lithological and mineralogical description of borehole USW GU-3. Mineralogical data were obtained by x-ray diffraction⁶. Lithologic nomenclature, degree of welding, and lithophysae data are also shown.⁷ Grain density data from Nimick and Schwartz⁸ (+) and Anderson (x), and computed from mineralogy (open square). Unmarked thin units in lithologic column are bedded tuffs. Height of static water level denoted by SWL.

The downhole gravity tool derives densities independently from the density tool, is highly accurate, and is unaffected by borehole rugosity.

RESULTS

Figure 2 shows a suite of logs from borehole USW H-1, entirely above the static water level, with the geologic horizons shown at the right-hand side. The presently proposed repository horizon lies within the Topopah Springs Member of the Paintbrush Tuff, which consists predominantly of moderately to densely welded ash-flow tuffs. At the base of the Topopah Springs Member (Tpt), at a depth of 454 m, the logs show that the physical properties undergo a marked change from the welded and unaltered ash-flow to a nonwelded or poorly welded ash-fall tuff which has been altered to zeolite (Tba and Tht).

In the welded tuff, the hole size as shown in track 1 is not smooth due to collapse of the wall of the borehole, an occurrence which is often associated with the presence of fractures. However, in the altered tuff the hole is relatively smooth and the caliper is about equal to bit size.

At 454 m depth, the bulk density decreases (track 2) from about 2.3 g/cm^3 in the welded tuff to about 1.9 g/cm^3 in the zeolitized tuff. This decrease is caused by higher porosity and lower mineral grain density in the zeolitized tuff.

Both the epithermal neutron count (track 3) and electrical resistivity (track 4) decrease sharply at 454 m. Both logs decrease with increasing water content, and water content increases in the zeolitized tuff because both porosity and water saturation are greater.

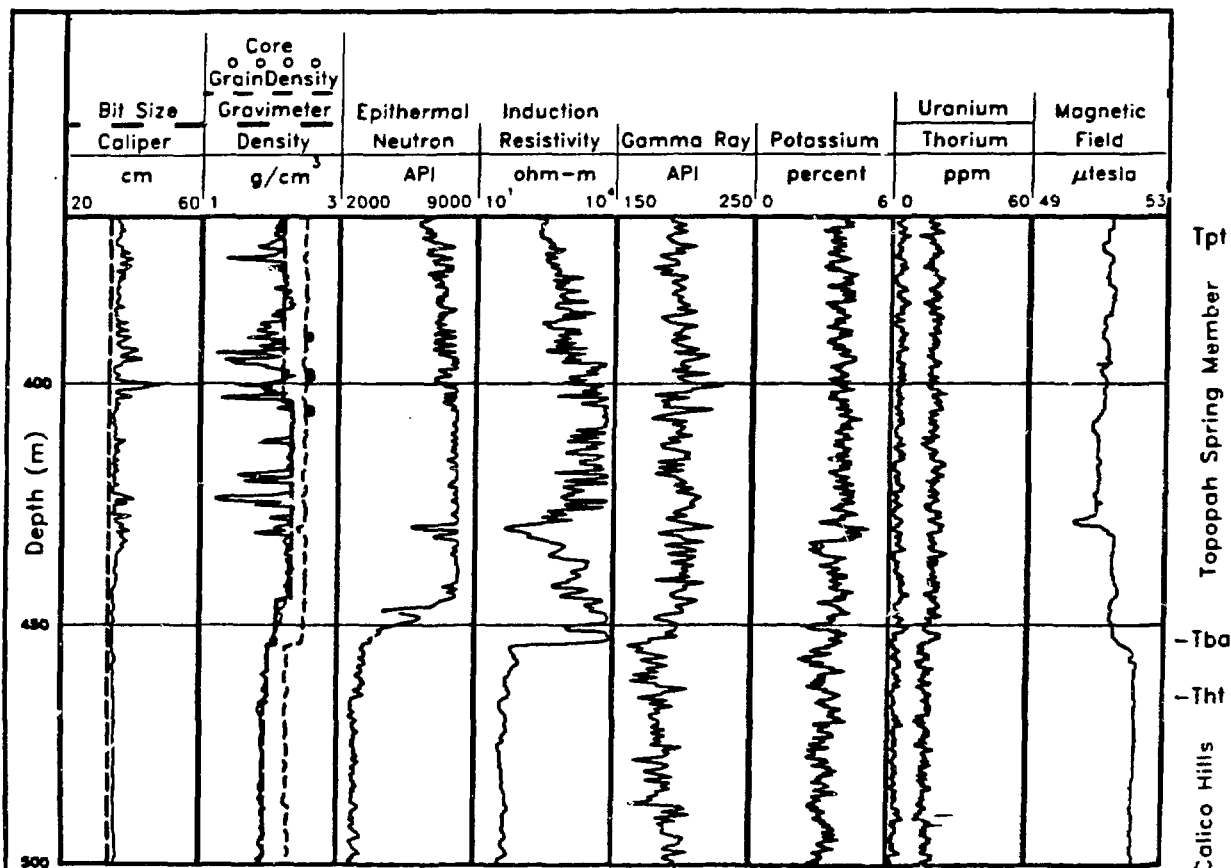


FIG. 2. Logs from borehole USW H-1. Grain densities determined from core samples are shown as open circles in Track 2. Bedded tuff unit designated as Tba.

The gamma-ray response (track 5) is reduced in the zeolitized tuff as compared with the welded tuff. Even better as a lithologic indicator is the total magnetic field (track 8) which shows an unperturbed value of the earth's field within the zeolitized sequence. However, in the Tpt, the field is reduced and varying due to remanent magnetization. The magnetic signature can be used to correlate lithology between wells.

Figure 3 shows rock property values computed from the logs of figure 2. Porosity and water saturation were computed from the density and epithermal neutron logs using calculated grain density values (track 2 of fig. 2).

The value of grain (matrix) density, zoned by depth, must be determined before porosity can be computed from the density log. Determination of grain density requires

an estimate of the type and amount of minerals present. In the absence of continuous core, a technique for "rock typing" must be developed which provides a zonation of the rock sequence by its major mineral constituents. Histograms of density and resistivity are shown in figure 4. Note that the zeolites are distinguishable from the tuffs on both the density log and the resistivity logs. The resistivity log shows a third peak associated with low-porosity segments within the welded tuff. The logs allow us to separate unaltered tuffs from zeolitic tuffs. Having obtained an estimate on volume percent of feldspar and silica as shown in figure 3, we can now estimate the matrix density. The result of this calculation is shown in figure 2 (track 2). It compares favorably to the few core samples taken in this borehole.

Total water content is taken directly from the epithermal neutron tool. Porosity

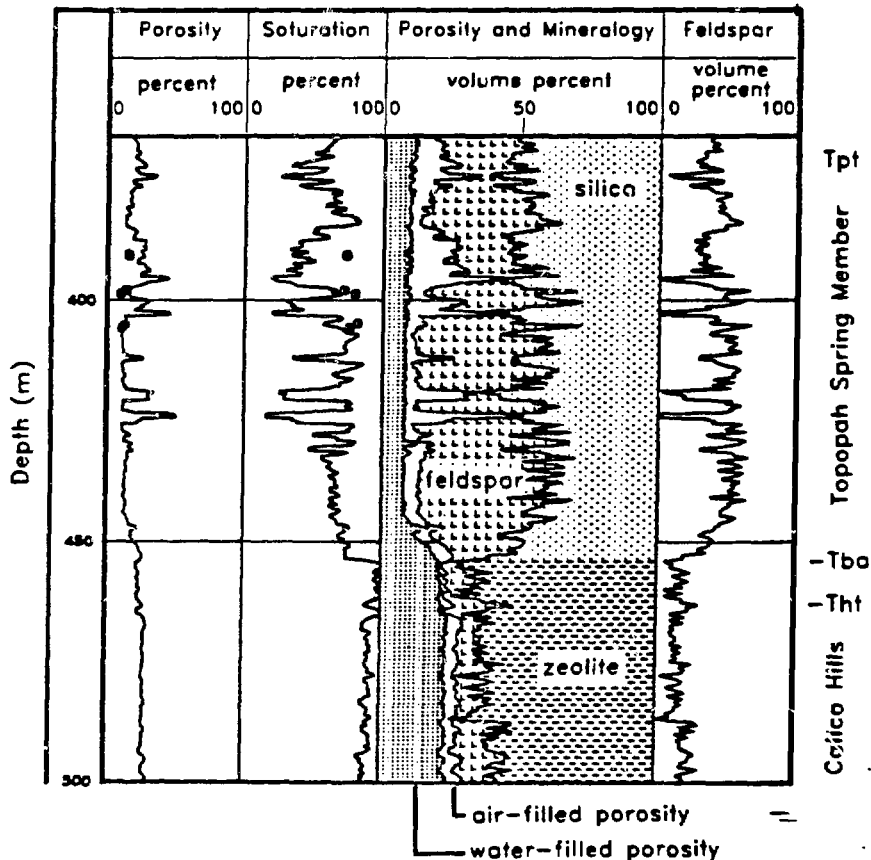


FIG. 3. Logs from borehole USW H-1; also shown are measurements from cores (Track 2 and 3).

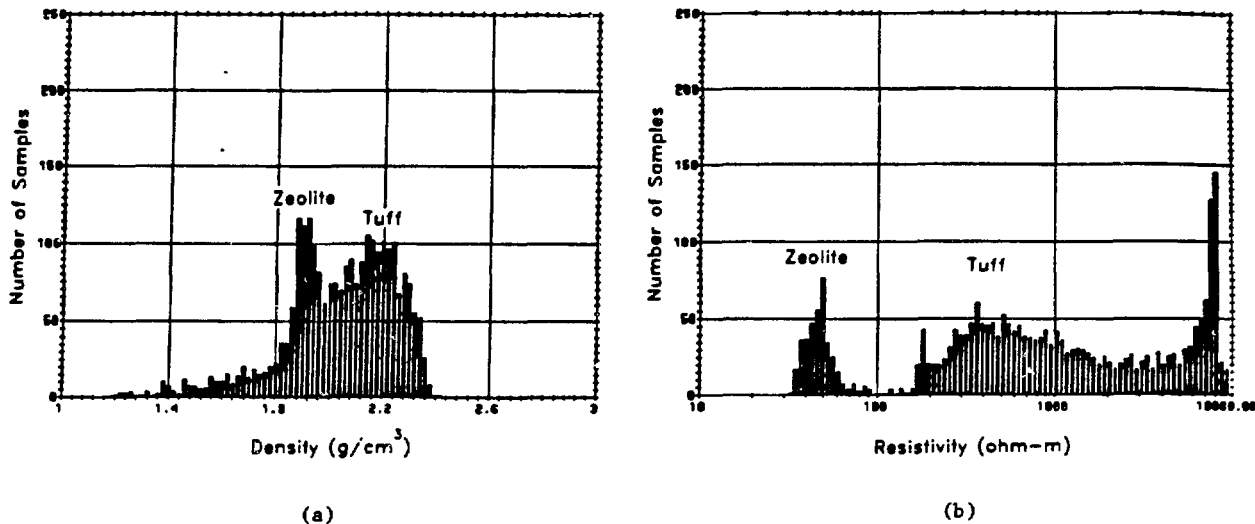


FIG. 4. Histograms of (a) density log and (b) resistivity log above the static water level. The logs were digitized at half-foot spacing to produce the samples.

is computed from the density log, making use of the estimates of grain density and water content. Then the water saturation, or fraction of pore space occupied by water, is computed as the ratio of water content to pore space. Again, note that both porosity and water saturation are highest in the zeolitized tuffs. Note the good agreement between the porosity values from core and the computed porosity (track 1 of figure 3) and the fair agreement between the saturation from core and the computed saturation (track 2).

A lithologic indicator, designated "Feldspar" in track 4, was computed from the normalized product of the density and gamma-ray logs. This indicator reflects the volume fraction of dense, naturally radioactive rock, predominantly feldspar. In the zeolitized section this indicator drops to about 10% of rock, in the welded ash-flow it is 50% or greater. This indicator is repeated again in track 3, where it is combined with the computed porosity and saturation to indicate the total composition of the rock. In this presentation, from left to right are shown the saturated pore space (stipple), the air-filled pore space (open area), the feldspar indicator (L-symbol), and undifferentiated rock matrix. Above 454 m, the undifferentiated matrix is predominantly silica (tridymite, cristobalite, and quartz),

while below 454 m it is predominantly zeolites. This simple indicator provides an initial rock typing that can be refined by incorporating additional logs and by utilizing statistical techniques.

CONCLUSIONS

Logs can be successfully obtained at Yucca Mountain, although air-filled and rugose boreholes complicate the acquisition of good data and reduce the types of logs that can be run. In the unsaturated zone, porosity and water saturation are best determined by simultaneous solution of measurements from two logs. Here we have illustrated the results obtained using the density and neutron logs. Because grain density changes substantially between altered and unaltered zones, the state of alteration is first determined using a log-based "lithology indicator". Knowing the state of alteration, grain density can then be estimated.

Past experience has shown that improvement in log acquisition, log calibration, and documentation of rock properties is highly desirable. This preliminary investigation demonstrates that the effort will produce continuous, quantified estimates of physical properties in the tuffs at Yucca Mountain.

ACKNOWLEDGEMENT

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