The influence of topography, stratigraphy, and barometric venting on the hydrology of unsaturated Bandelier Tuff

Donald A. Neeper and Gilkeson, Robert, H.

1996, pp. 427-432. https://doi.org/10.56577/FFC-47.427

in:

Jemez Mountains Region, Goff, F.; Kues, B. S.; Rogers, M. A.; McFadden, L. S.; Gardner, J. N.; [eds.], New Mexico Geological Society 47th Annual Fall Field Conference Guidebook, 484 p. https://doi.org/10.56577/FFC-47

This page is intentionally left blank to maintain order of facing pages.

THE INFLUENCE OF TOPOGRAPHY, STRATIGRAPHY, AND BAROMETRIC VENTING ON THE HYDROLOGY OF UNSATURATED BANDELIER TUFF

DONALD A. NEEPER and ROBERT H. GILKESON
ERM-Golder Los Alamos Project Team, 2237 Trinity Dr., Bldg. 2, Los Alamos, NM 87544

Abstract—This paper presents a preliminary analysis of observations of vadose zone hydrology below two mesas of the Pajarito Plateau near Los Alamos, New Mexico. Abnormal quantities of moisture extend to depths as large as 90 ft beneath asphalt-covered areas on the mesas. Comparison with moisture profiles beneath unpaved ground with and without vegetation indicates that atmospheric venting removes moisture from the deep subsurface. At several locations, the profiles of hydraulic head as a function of depth also suggest that the atmosphere may be removing moisture. The profiles reveal intervals where the gradient is such that moisture would flow upward (reversed gradient). A reversed gradient could be generated if moisture were removed from a particular horizon faster than it arrived by conduction and/or vapor diffusion. The vertical intervals with reversed gradient present barriers to downward aqueous transport of contaminants. At some locations, the barriers may be associated with atmospheric venting through nearby excavated disposal pits or open disposal shafts. However, the barriers also occur in stratigraphic horizons that are exposed to the atmosphere at the canyon walls, suggesting that venting may occur at the sides of the mesas. Although continuing investigations of subsurface air flow and rock properties have not yet revealed a model for natural venting that could remove the moisture far from ground surface or a canyon wall, a barrier might be maintained by barometric pumping via fractures or high-permeability layers.

INTRODUCTION

This paper reports a preliminary analysis of data obtained during an ongoing RCRA Facility Investigation at the Los Alamos National Laboratory (LANL). To detect migration of contaminants, the investigation includes sampling of rock core and soil gas from boreholes near and beneath pits and shafts in which wastes were buried. For comparison, some boreholes were placed in natural settings away from the disposal pits and shafts. In selected borehole sampling activities, the investigations include measurements of moisture, geohydrologic properties of the matrix, and subsurface air flow as driven either by natural barometric variation or forced vapor extraction. The vertical profiles of moisture appear to be influenced by topography, stratigraphy, atmospheric venting, and human intrusion, although it is sometimes difficult to separate effects of multiple causes. One objective of these studies is to develop knowledge that applies across the entire Pajarito Plateau, and which may be useful in the design of new landfills or in the remediation of other waste disposal units.

TOPOGRAPHY AND STRATIGRAPHY OF THE STUDY SITES

Los Alamos National Laboratory and the communities of Los Alamos and White Rock are located in northern New Mexico on the Pajarito Plateau, which extends eastward from the Jemez Mountains. The plateau is 10 to 15 mi wide and 25 to 30 mi long, and slopes from an altitude of about 7800 ft along its western margin to about 6200 ft. Erosion has cut the surface of the plateau into numerous finger-shaped mesas separated by deep canyons that contain intermittent streams. The plateau is semi-arid; annual precipitation varies from 13 in. in the east to 18 in. in the west. The stratigraphic sections within the two mesas discussed here are volcanic rocks of the Bandelier Tuff, an ignimbrite erupted from the Jemez volcanic center (Griggs, 1964).

The physical properties of the Bandelier Tuff (Fig. 1) vary both vertically and laterally. The Tshirege Member is underlain by the Otowi Member, a massive pumiceous ash-flow tuff, and the Guaje Pumice Bed, a bedded pumice-fall deposit. The Cerro Toledo interval, which lies between the Tshirege and Otowi Members, is not considered part of the Bandelier Tuff because of its unique properties and different source. The Tshirege Member is a compound cooling unit divided into the basal Tsankawi Pumice Bed and four ash-flow tuff cooling units. The cooling units represent episodes of ash-flow deposition separated by partial cooling breaks. Zones of distinct lithologic or hydrologic properties occur within the cooling units; these zones are specified as subunits. The Colonnade subunit is so named because it appears in canyon walls as a more indurated, cliff-forming outcrop with vertical joints.

Most units of the Tshirege Member commonly contain nearly vertical joints formed during the cooling process. The presence and properties of these joints, studied by Purtymun and Kennedy (1971) and Reneau and Vaniman (LANL internal report, 1994), vary among the different cooling units. The average joint spacing varies from 3.2 to 4.2 ft. The maximum joint openings are 2 in., but most are less than 0.25 in. Clay fillings are generally present to a depth of 10 ft, but are rarely present more than 20 ft below ground surface. Powdered tuff occurs in many joints and may be present at all depths. Air permeabilities measured in the laboratory and in situ ranged from 0.35 to 170 darcies. The largest values are from straddle packer measurements across jointed intervals in open boreholes.

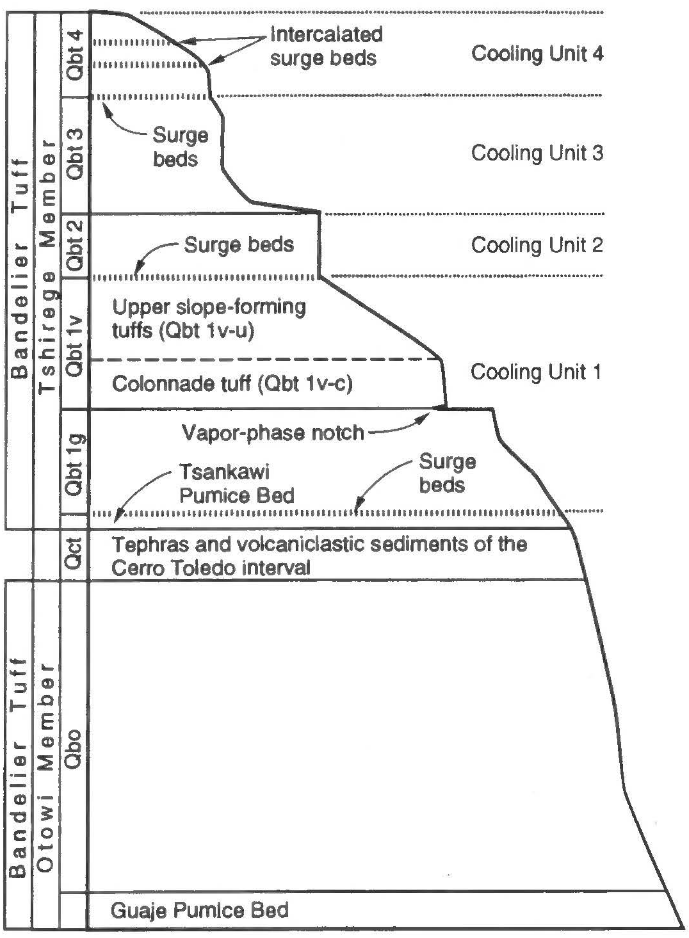

FIGURE 1. Nomenclature of the Bandelier Tuff (Broxton and Reneau, 1995).

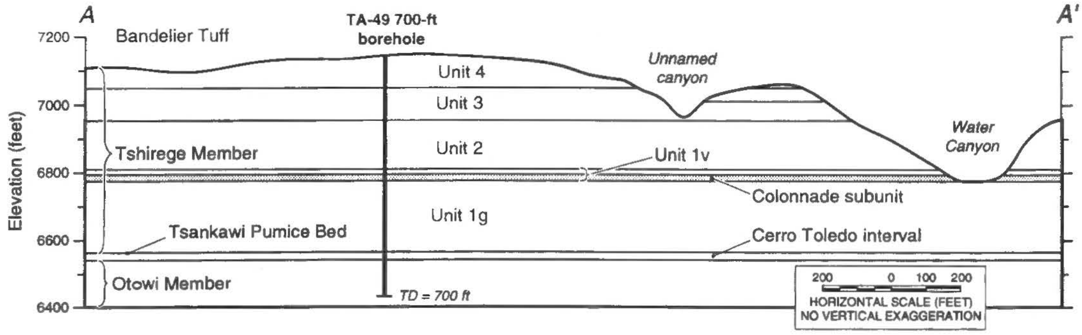

FIGURE 2. Approximately north-south cross-section, showing topographic setting in the vicinity of the 700-ft deep borehole at TA-49.

Our study concerns the vadose zone hydrology within cooling units of the Tshirege Member at three LANL sites located on two mesas where wastes were buried in pits and shafts. The three sites are known as TA-49 MDA AB, TA-54 MDA L, and TA-54 MDA G, and are referred to here as TA-49, MDA L, and MDA G, respectively.

TA-49 (Fig. 2) is located in the western half of the plateau, closest of the three sites to the volcanic source. The mesas are wider and both the ash deposits and the canyons are deeper than at the eastern region of the plateau, where MDA L and MDA G are located on Mesita del Buey. Underground explosive tests were conducted in shafts at TA-49 (RFI work plan for Operable Unit 1144, Los Alamos National Laboratory document LA-UR-92-900, 1992). The tests were conducted in six shaft fields, each with an area of approximately 10,000 ft^2. The experimental shafts were typically 6 ft in diameter and varied from 31 to 142 ft in depth.

MDA G and MDA L (Fig. 3) are located about 0.5 mi apart on Mesita del Buey, a narrow mesa farther from the volcanic source. Cooling unit 2 is the uppermost unit at MDA G and MDA L. MDA L is a 2.6 acre site that was used for disposal of hazardous chemicals from the late 1950s until 1986. Aqueous and other chemical wastes were deposited in open, unlined evaporation pits that ranged from 10 to 12 ft in depth, and in unlined shafts that ranged from 60 to 65 ft in depth. Disposal of solid low-level radioactive wastes began at MDA G in 1957, and continues to the present. Wastes are buried in unlined pits excavated to depths ranging from 25 to 60 ft. Pit dimensions are commonly 50 to 100 ft wide by 300 to 600 ft in length. Wastes are also buried in disposal shafts that are either unlined or lined, with dimensions commonly 3 to 6 ft in diameter and depths of 50 to 60 ft.

MOISTURE ASSOCIATED WITH ASPHALT PAVEMENT

TA-49

An asphalt pad was installed over one shaft field at TA-49 in 1961. The paved area, approximately 100 by 100 ft, was intended to seal fill material covering slightly contaminated ground. The asphalt pad has a history of developing long cracks that extended over much of the paved surface. A subsidence hole, approximately 20 ft^2 in area, developed in the pad during the autumn of 1974. In autumn 1976, the void was filled and the entire pad was again paved with asphalt (Purtymun and Ahlquist, 1986, LANL internal memorandum HSE-8-86-1183.) The asphalt pad continued to develop cracks, which have been sealed when discovered.

Two boreholes, each 150 ft deep, were drilled vertically through the asphalt. One borehole, 700 ft deep, was drilled in undisturbed ground approximately 150 ft from the pad (Fig. 2). Moisture profile data (Fig. 4) suggest that the asphalt pad may be responsible for the accumulation of moisture in the 75 ft interval below ground level. The moisture beneath the pad may be the result of infiltration through breaks in the asphalt, because the volume of moisture is equivalent to only a small fraction of the precipitation incident since the pad was installed. The asphalt evidently inhibited normal evaporation and vegetative transpiration process, with the result that the moisture accumulated rather than being returned to the atmosphere. The corresponding evidence at MDA L indicates that evaporation is an important process.

MDA L

MDA L has approximately two acres covered by well-maintained asphalt. Figure 5 displays the gravimetric moisture at two boreholes, both in the undisturbed piñon-juniper forest approximately 150 ft from the nearest corner of the MDA L asphalt. Regions with less than 1% gravimetric moisture are not unusual at depths between 20 and 100 ft beneath an undisturbed surface. For comparison, Figure 6 presents gravimetric moisture at borehole 1008 (in bare, denuded ground within MDA L) and at borehole 1009 (near the middle of the MDA L paved area).

Removal of vegetation from sites in arid climates can result in accumulation of subsurface moisture (Gee, 1994). Seasonal effects or the absence of vegetation in the vicinity of borehole 1008 may have contributed to the accumulation of excess moisture to a depth of about 30 ft. Below this depth the moisture profile is similar to the profiles of nearby boreholes located in natural terrain settings (Fig. 5). In contrast, borehole 1009 clearly indicates excess moisture beneath the asphalt to a depth of 90 ft. Elimination of vegetation alone does not account for all of the excess moisture in borehole 1009. Borehole 1009 is located adjacent to a former unlined evaporation pit that was once used for disposal of liquid waste. It is possible that infiltration during active disposal in the pit is responsible for the excess moisture at borehole 1009. However, comparison of two sites at MDA G leads us to suggest that asphalt inhibits moisture removal that would normally occur due to atmospheric venting.

MDA G

Borehole 1102 (Fig. 7) is slanted at an angle of 58° from the vertical to penetrate beneath a closed disposal pit in MDA G (suction data is discussed below). Borehole 1102 begins in bare ground but precedes beneath a 1/2-acre asphalt pad that covers the pit. Moisture increases to a depth of 40 ft (Fig. 7) when compared with the moisture profile of bore-

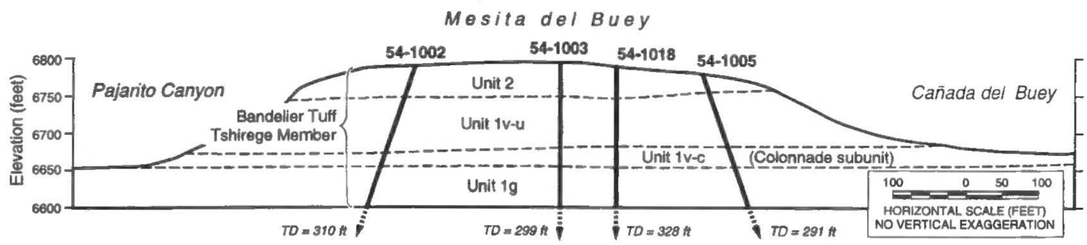

FIGURE 3. North-south cross-section of Mesita del Buey near MDA L, TA-54.

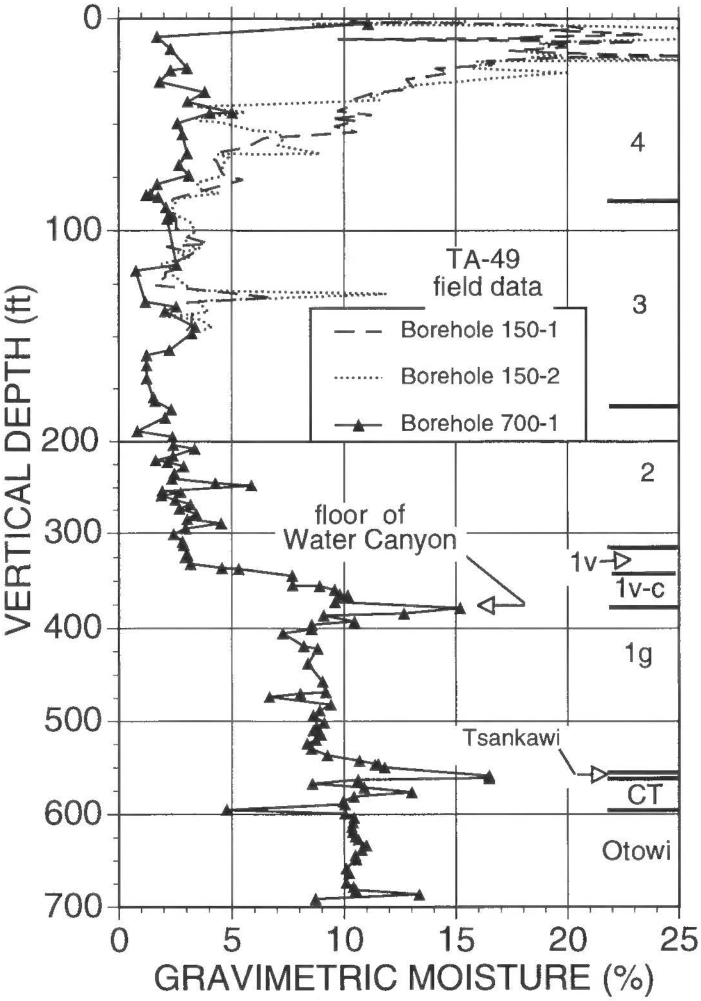

FIGURE 4. Profile of moisture in three boreholes at TA-49. The vertical scale of the upper 200 ft is expanded. Stratigraphic units are indicated at right margin.

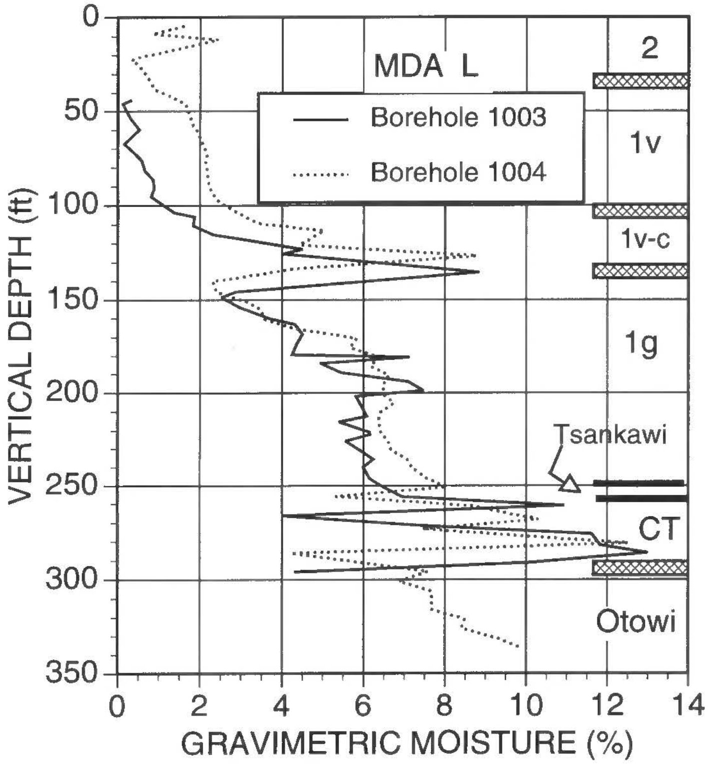

FIGURE 5. Profile of gravimetric moisture in two boreholes in undisturbed ground. Wide markers at right margin indicate range of hydrologic unit contacts among the boreholes.

hole 1106 (Fig. 8). Borehole 1106 was drilled at the same angle as borehole 1102, but extends beneath a closed pit with a cover of sparse grass. The major difference between these two sites is that one is very lightly vegetated while the other is largely covered by asphalt. This strongly suggests that the asphalt has inhibited some moisture removal mechanism other than vegetative transpiration. It was recognized long ago that barometric and wind pressure fluctuations remove moisture from the uppermost foot of ground (Scotter and Raats, 1968). The repeated association of moisture with asphalt (Figs. 4, 6, 7), leads to the hypothesis that atmospheric ventilation may remove moisture from much greater depths in Bandelier Tuff. This suggests that waste disposal units, or any other subsurface regions where moisture is unwanted, should not be covered with airtight caps.

MOISTURE ASSOCIATED WITH TOPOGRAPHY AND STRATIGRAPHY

The moisture profiles in boreholes drilled into mesas exhibit relationships to both topography and stratigraphy, displayed in the moisture profile of the 700-foot borehole at TA-49 (Fig. 4). Gravimetric moisture increases from approximately 3% at depths above 340 ft to approximately 9% at depths below 360 ft. This interval where the moisture within the mesa increases occurs at the same elevation as the floor of Water Canyon (Fig. 2). Although the canyon wall is 1400-1600 ft laterally from the 700-ft borehole, the relatively low moisture content in the mesa above the canyon floor raises a possibility that atmospheric venting into and out of the mesa over long periods might be responsible for removal of moisture. Investigations of moisture removal at TA-49 are continuing.

A pronounced moisture peak occurs near the bottom of the Colonnade subunit in boreholes at widely separated sites (Figs. 4, 5, 6). At these borehole locations, the Colonnade subunit is located near the floor of the adjacent canyons (Figs. 2, 3), and the moisture peak that occurs in the lower part of the Colonnade subunit is superimposed on the moisture increase that occurs below canyon floors (Fig. 4). The moisture peak within the Colonnade subunit also occurs in boreholes where that subunit is located above the elevation of the adjacent canyon floor (Fig. 9). The Colonnade moisture peak probably reflects a change in rock matrix properties through this subunit, and may be due to intense vapor phase alteration and its effects on rock properties, in which the maximum alteration occurs at the base of the subunit. This interval corresponds to the vapor phase notch at the base of Unit 1v (Fig. 1). The pronounced moisture peak at 561 ft and the moisture minimum at 595 ft (Fig. 4) occur at or near other stratigraphic contacts. Like the moisture peak near the base

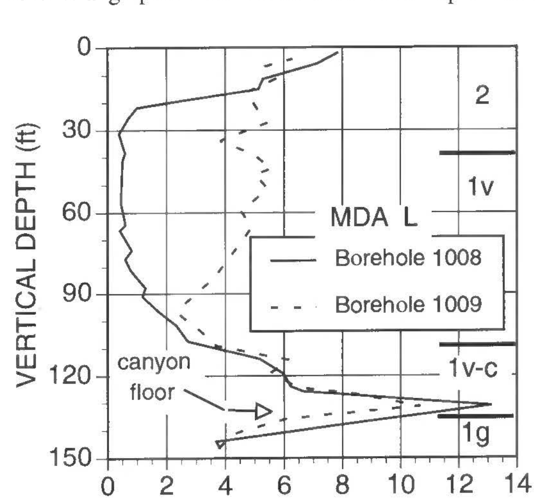

FIGURE 6. Profile of gravimetric moisture at borehole 1008, in bare ground; and at borehole 1009, beneath asphalt.

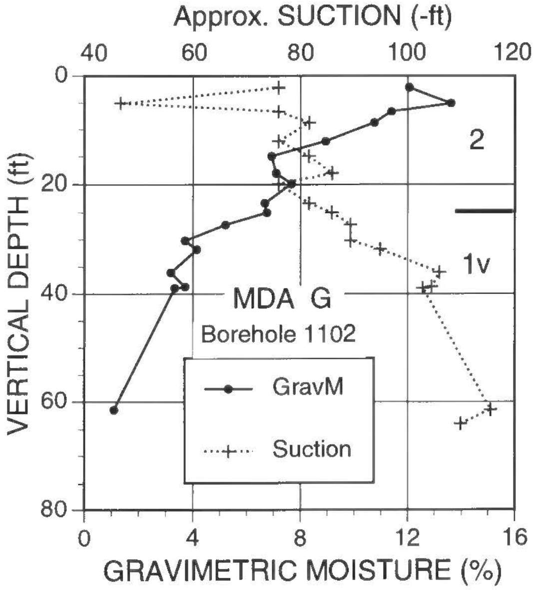

FIGURE 7. Profile of moisture and suction in borehole 1102, slanted beneath an asphalt-covered pit.

of the Colonnade, these peaks may also be due to abrupt changes in matrix properties.

MATRIC SUCTION AND HYDRAULIC BARRIERS

Knowledge of the physical and hydraulic properties of the Bandelier Tuff is important for estimating water and contaminant transport beneath

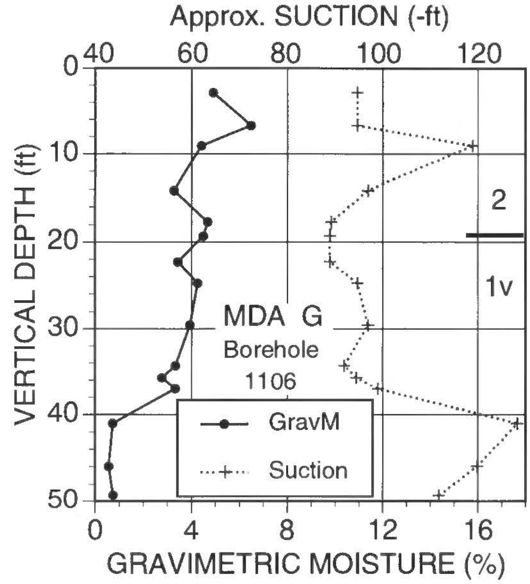

FIGURE 8. Profile of moisture and suction in borehole 1106, slanted beneath a grass-covered pit.

waste disposal sites at LANL. Rogers and Gallaher (1995) summarized the unsaturated hydraulic properties of the Bandelier Tuff. Measurement of the vertical profiles of moisture content, matric suction, and hydraulic head are fundamental to understanding the direction and rate of liquid water movement through the unsaturated tuff.

Most profiles of hydraulic head indicate downward flow of water

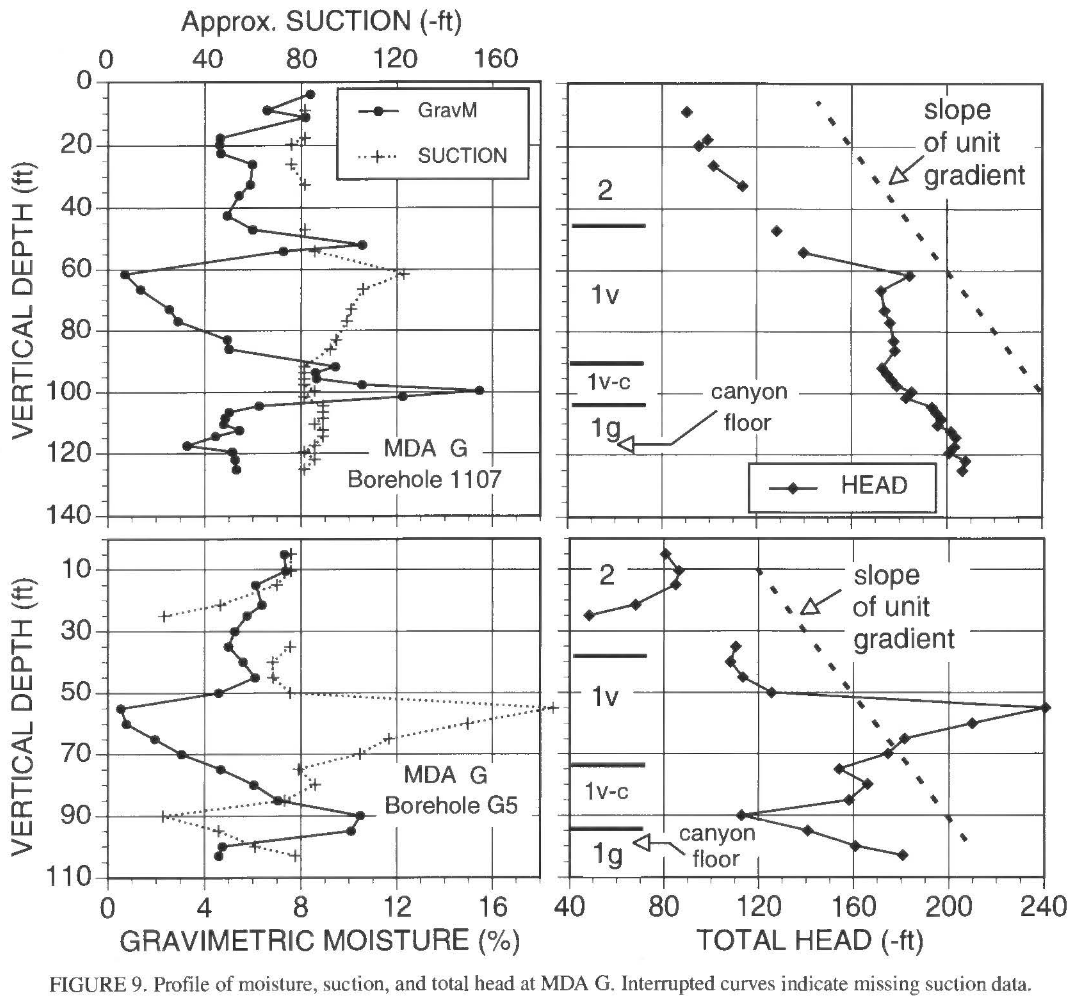

FIGURE 9. Profile of moisture, suction, and total head at MDA G. Interrupted curves indicate missing suction data.

through the unsaturated tuff. An important finding at some boreholes is the presence of hydraulic gradient reversals at discrete depth intervals where high values of matric suction occur. The gradient reversals indicate upward flow of water toward the high matric suction. The top of the interval of upward water flow is referred to here as a "hydraulic barrier". A hydraulic barrier forms an obstacle to downward migration of aqueous contaminants beneath disposal sites. The existence of hydraulic barriers was described by Rogers and Gallaher (1995) and in a report of measurements on core from boreholes located at MDA G (Gallaher et al., unpubl. report to LANL, Environmental Restoration Project technical session, October 19, 1994). The dynamics of hydraulic barriers are discussed in the following sections.

Suction measurements

The matric suction values shown in Figures 7-9 are approximate measurements obtained in the field with a chilled mirror psychrometer (AquaLab Model CX-2, Decagon Devices Inc.), an instrument used by the U.S. Geological Survey at the Yucca Mountain Project. Data from the chilled mirror psychrometer were compared with laboratory measurements on collocated samples from MDA G. At absolute values of suction greater than 65 ft (2000 cm), the chilled mirror psychrometer systematically indicated larger suction values than the laboratory values. Bandelier Tuff has a low specific surface area, and it may be that the process of measurement with the chilled mirror instrument either removes a significant fraction of the moisture content of the driest samples, or that the sample fails to equilibrate with the mirror. Accordingly, the field measurements of the chilled mirror psychrometer were scaled to agree with laboratory measurements, and are therefore labeled as approximate. For Bandelier Tuff, we regard the chilled mirror psychrometer as a reliable indicator of the trend of matric suction, but not as a quantitative device at high suction. The matric suction data at TA-49 and at MDA L, discussed below, were obtained by laboratory measurements on core samples, and are therefore not labeled as approximate. The term "laboratory measurements" means that the original moisture content and the initial drainage curve of each sample were measured, and the original matric suction was derived from interpolation on the drainage curve of that sample.

Evidence of hydraulic barriers

The boreholes represented in Figure 9 are located more than 300 ft from the canyon walls of MDA G. Both boreholes show a decrease in moisture and a peak in matric suction at a depth near 60 ft, which corresponds to the bottoms of the nearby shafts. Figure 9 also shows the total hydraulic head, which is the sum of matric suction and depth below an arbitrary zero at ground surface. The slope of a unit gradient is shown for comparison. In each borehole, the hydraulic gradient is reversed (causing upward flow of moisture) beneath the peak of matric suction. We regard the horizon at which the direction of moisture flow changes from downward to upward as a hydraulic barrier. It is an imaginary surface across which the downward movement of liquid water is prevented by the underlying reversed hydraulic gradient.

Figure 10 presents moisture, matric suction, and total head derived from laboratory measurements on samples from the 700-foot borehole at TA-49. Hydraulic barriers are apparent across two short intervals. The barriers appear small on the plot of total head, due to the scale of the graph. However, the steep changes in the suction values indicate that the barriers are significant. The horizon of the upper barrier is exposed in an unnamed shallow canyon about 800 ft from the borehole, and the horizon of the lower barrier is about 1700 ft from exposure in Water Canyon (Fig. 2). The data also indicate a possible barrier with a slightly reversed gradient in the interval between 500 and 560 ft Unfortunately, all samples in this interval became disaggregated and were repacked before the moisture and drainage curves were measured, so the data are not reliable.

We have insufficient data to trace a complete profile of matric suction beneath the undisturbed ground near MDA L. Representative profiles of hydraulic head, derived from laboratory measurements, are shown in Figure 11. Borehole 1006 has a reversed gradient between 60 and 120 ft. The data of nearby borehole 1002 also indicate a reversed gradient within that interval, although the data do not extend to the top of the interval. We note that the evidence for a barrier in Figure 11 is composed of only a few data points; therefore, the existence of an hydraulic barrier beneath MDA L must be confirmed by additional measurements.

Origin of a hydraulic barrier

A hydraulic barrier is a horizon below which the hydraulic gradient is in the direction to cause upward flow of moisture. In most circumstances, moisture above the barrier will be moving downward. Our fragmentary evidence (e.g., Figs. 9–11) indicates that, within a mesa, a barrier extends across horizontal distances of at least hundreds of feet. Because barriers exist at several locations, they may be a common feature of the Pajarito Plateau. What could initiate, or maintain, such a barrier? In principle, a hydraulic barrier might be a remnant of an ancient event that left the tuff very dry. In that case, a current barrier represents the confluence of two wetting fronts, one descending from above and one rising from below. We suggest a second hypothesis, that a barrier is caused by removal of moisture from within a mesa.

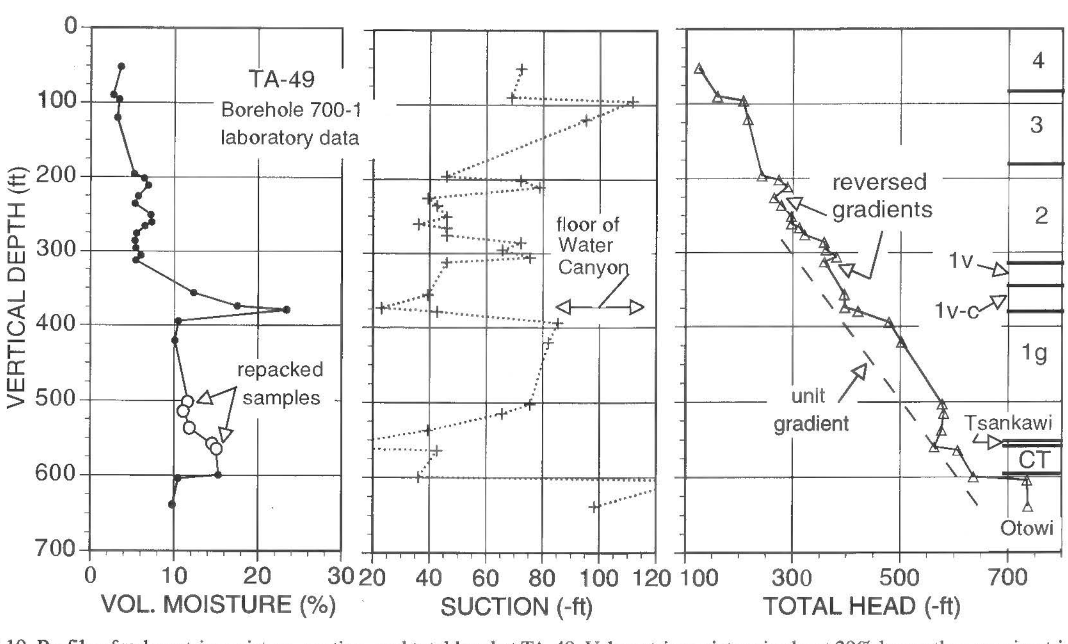

FIGURE 10. Profile of volumetric moisture, suction, and total head at TA-49. Volumetric moisture is about 20% larger than gravimetric moisture.

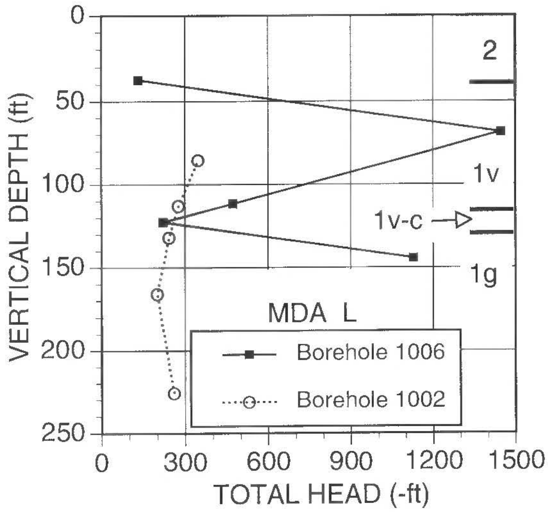

FIGURE 11. Profiles of total hydraulic head near MDA L.

The atmosphere is the only apparent sink for removal of moisture from the subsurface, and the following argument shows that the atmosphere is thermodynamically capable of removing moisture from even the driest tuff that we have observed. The annual average dewpoint at MDA G is near 30°F (Bowen, 1990). If the matrix were brought into equilibrium with the average atmospheric moisture, the matric suction would exceed -33,000 ft (-1000 bars), and the gravimetric moisture would be 0.1% or less. Matric suction of this magnitude has not been observed in the tuff. Therefore, on average, moisture will be transferred from the tuff to any atmospheric air with which it comes into contact. It is not clear how atmospheric air could cause evaporation within a mesa, rather than only at the surfaces. It may be that air moves into the subsurface along fractures, joints, or other high-permeability paths. The barometric pumping mechanism would enhance the removal of moisture via these paths.

Barometric pumping

In daily barometric cycles, fresh air penetrates the matrix about 1 ft from a mesa surface, or from the surfaces of a large open fracture or joint within the mesa. The back-and-forth motion of air within the matrix penetrates to a much greater depth. Oscillatory air motion supplied to the matrix by a fracture can greatly increase the removal of a vapor (Nilson and Lie, 1990; Nilson et al, 1991; Auer et al, Los Alamos National Laboratory internal report LA-UR-95-3303, 1995). With other colleagues, we are conducting measurements of in situ air permeability, the subsurface propagation of barometric variations, and measurements of the CO_2 concentration in the pore gas. One goal of this investigation is to determine whether natural or engineered venting can create or maintain a hydraulic barrier. Confirmation of significant water removal by barometric pumping will require careful analysis that includes a model of high-permeability conduits (such as boreholes, joints, fractures, or surge beds) and the concurrent effect of temperature cycles on unsaturated aqueous flow and vapor diffusion.

CONCLUSIONS

Abnormal accumulation of subsurface moisture was found beneath asphalt-paved surfaces at three sites, at depths below the seasonal wetting front. Although not conclusive, the evidence suggests that the moisture may accumulate in part due to the reduced respiration associated with the pavement. Hydraulic barriers, in which upward and downward unsaturated gradients meet at an interval of large matric suction, provide additional indirect evidence for atmospheric removal of moisture from deep within a mesa. Barometric pumping is a candidate mechanism for atmospheric removal of moisture via fractures or other high-permeability paths. The existence of hydraulic barriers is of interest because they suggest that either natural or engineered subsurface venting may be employed to prevent downward aqueous transport of contaminants beneath waste disposal units.

ACKNOWLEDGMENTS

Laboratory measurements of soil hydraulic properties were performed by the Daniel B. Stephens and Associates, Inc., of Albuquerque, NM. Mark Ankeny of the Stephens firm served as a valuable resource on vadose zone hydrology. Vincent Trujillo, Ken Kisiel, Jon Marin, and Steven Limback performed field measurements and data analysis. Bill Lowry designed and operated supporting tests. Donathan Krier and Bill Lowry provided helpful reviews of this manuscript. Thoughtful guidance was provided by Keith Woloshun and Cheryl Rofer.

REFERENCES

Bowen, B. M., 1990, Los Alamos climatology: Los Alamos National Laboratory, Report LA-11735-MS.

Broxton, D. E. and Reneau, S. L., 1995, Stratigraphic nomenclature of the Bandelier Tuff of the Environmental Restoration Project at Los Alamos National Laboratory: Los Alamos National Laboratory, Report LA-13010-MS.

Gee, G. W., Wierenga, P. J., Andraski, B. J, Young, M. H., Fayer, M. J. and Rockhold, M. L., 1994, Variations in water balance and recharge potential at three western desert sites: Soil Science Society of America Journal, v. 58, p. 63–72.

Griggs, R. L., 1964, Geology and ground water resources of the Los Alamos area, New Mexico, U.S. Geological Survey, Water Supply Paper 1753, 107 p.

Nilson, R. H. and Lie, K. H., 1990, Double-porosity modelling of oscillatory gas motion and contaminant transport in a fractured porous medium: International Journal for Numerical and Analytical Methods in Geomechanics, v. 14, p. 565–585.

Nilson, R. H., Peterson, E. W., Lie, K. H., Burkhard, N. R. and Hearst, J. R., 1991, Atmospheric pumping: a mechanism causing vertical transport of contaminated gases through fractured permeable media: Journal of Geophysical Research, v. 96 (B13), p. 21,933–21,948.

Purtymun, W. D. and Kennedy, W. R., 1971, Geology and hydrology of Mesita del Buey: Los Alamos Scientific Laboratory, Report LA-4660.

Rogers, D. B. and Gallaher, B. M., 1995, The unsaturated hydraulic characteristics of Bandelier Tuff: Los Alamos National Laboratory, Report LA-12968-MS.

Scotter, D. R. and Raats, P. A. C., 1968, Dispersion of water vapor in soil due to air turbulence: Soil Science, v. 108, p. 170–176.