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MONITORING HYDROLOGIC CONDITIONS IN THE VADOSE ZONE IN FRACTURED ROCKS, YUCCA MOUNTAIN, NEVADA

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Abstract. A 44.5-centimeter-diameter experimental borehole was drilled by a reverse-air vacuum-drilling technique to a depth of 387 meters to monitor hydrologic conditions in the vadose zone at Yucca Mountain, Nevada. This borehole was instrumented at 33 depth levels. At 15 of the levels, three well screens were embedded in coarse-sand columns. The sand columns were isolated from each other by thin layers of bentonite, columns of silica flour, and isolation plugs, consisting of expansive cement. Thermocouple psychrometers and pressure transducers were installed within the screens. Two of the screens at each level were equipped with access tubes to allow collection of pore-gas samples. At the remaining 18 depth levels heat-dissipation probes were installed within the columns of silica flour. Thermocouple psychrometers were installed together with the heat-dissipation probes at selected depth levels. After more than 2 years of monitoring, the majority of the instruments were still functioning and appeared to be producing reasonable data. A slow recovery from the disturbed state toward natural conditions was detected during the first 90 days of monitoring probably because of the large diameter of the borehole. The effect of the materials in the borehole was simulated to understand the physical phenomena that control the response of the instruments. Flow of water in an axisymetric section of the welded tuff, 100 meters in radius and 20 meters thick, was modeled with the borehole at the center. Results indicated that, after 25 days, the moisture conditions in the fracture are disturbed most severely (compared to the welded tuff matrix) by the porous material in the borehole; this disturbance may extend as far as several tens of meters away from the borehole. From this simulation and from monitoring the instruments in the borehole, the conclusion was made that the placement of material in boreholes drilled in fractured rocks could disturb the natural system severely. These results also indicate that in-situ matric potential may be monitored most effectively by psychrometric methods in empty cavities isolated in boreholes without emplacement of porous materials.

Introduction

Mechanisms of fluid flow through thick unsaturated zones consisting of heterogeneous fractured rocks are not well understood in part due to the difficulty in studying this complicated system at depth. New techniques are required in addition those established to monitor shallow unsaturated soils. Comprehensive understanding of the flow through such rocks in natural state requires: (1) Laboratory investigations, consisting of both fracture and matrix flow tests; (2) ground-surface infiltration experiments and natural infiltration monitoring; (3) borehole hydraulic and pneumatic testing; (4) in-situ intrumentation and long term monitoring of deep boreholes; (5) large-scale, in-situ hydraulic and pneumatic testing; and (6) hydrochemical characterization. All such investigations are hampered by the problems that result from the lack of established instrumentation techniques for these rocks. The purpose of this paper is to highlight some of the problems that exist with instrumentation and monitoring of the fractured rocks, and to describe a field example of borehole instrumentation and a numerical simulation.

Hydrologic instrumentation and monitoring of unsaturated fractured tuff in deep boreholes have not been attempted previously and testing of unsaturated fractured tuff have been hampered by the difficulties inherent in installation of equipment and interpretation of the results. Evans [1983] reviewed state-of-the-art instrumentation technology applicable to monitoring these types of rocks. Montazer [1982] discussed the problems associated with testing unsaturated fractured metamorphic rocks. Although, many investigators have begun research on characterization of unsaturated fractured tuff in the past few years, the author is unaware of other attempts to install instruments in unsaturated fractured rocks in deep boreholes.

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Measurement of Fluid Potential

Type of Sensors

Knowledge of the distribution of fluid potential (or potential energy) is needed to understand fluid flow in the unsaturated zone. Fluid potentials that are relevant in unsaturated-zone flow are: (1) Matric (or pressure) potential in the liquid phase; (2) liquid-phase gravitational potenial; (3) gas-phase pressure (or pneumatic) and gravitational potentials; (4) osmotic potential; and (5) thermal potential, or downhole temperature for a given fluid phase. Combined pressure and gravitational potential represent total potential; fluid movement occurs down the total potential gradient. Concepts of these potentials and methods for their measurements are described by Evans [1983], Morrison [1983], Stallman [1964], and Remson and Randolph [1962].

Matric potential commonly is measured directly using tensiometers or indirectly using heat-dissipation probes, porous blocks, or indirectly by thermocouple psychrometry. Psychrometry enables measurement of combined osmotic and matric potential. Osmotic potential is assumed to be insignificant and the psychrometric measurements is assumed to represent the matric potential in this paper. Tensiometers are difficult to install in deep boreholes, and their usefulness is limited to the very wet sections of the formation. All tensiometers have a fluid reservoir; its pressure needs to equilibrate with that of the formation. Fractured rocks commonly have a very low matrix porosity and permeability. The small quantity of fluid that may flow to or from the tensiometer reservoir for the equilibration between the rock and the tensiometer to take place could change the matric potential around the tensiometer substantially for a relatively long period of time after installation. In addition, hydraulic coupling of the tensiometer to the formation requires a porous medium that could cause disturbance of the in-situ matric potential (as will be discussed later). Also the air bubbles trapped in the tensiometer reservoir could affect the measurements.

Similar problems exist when using heat dissipation probes and porous blocks except that the fluid interchange with the formation is minimal. However, none of the three instruments can provide information about the potential energy in draulically coupling the instruments to the fractures exists.

Water potential can be obtained indirectly from psychrometric measurements, using Kelvin's relation [Morrison, 1983]. The advantage of this method in fractured rock is that the coupling of the instrument with the rock is through the vapor phase; therefore, a porous medium is not required for the coupling. In addition, because vapor diffusion and convection are much more rapid in the fractures than through the matrix, the potential energy in the fracture may be estimated almost separately from that in the matrix.

Pneumatic potentials are measured by either downhole or land-surface pressure transducers. The problem with the downhole emplacement of the transducers is that the calibration cannot be readily checked and the slightest drift in the transducer characteristics could result in substantial change in the readings. Downhole rather than land-surface measurements are made to avoid time lag and pressure loss through the access tubing, particularly if the borehole is designed for pneumatic withdrawal or injection tests. The transducers need to be aged before installation to minimize their inherent, exponentially decreasing drift. Methods of downhole calibration or removal of these instruments need to be devised to provide a possibility of periodically checking the calibration of the downhole instruments.

State-of-the-art thermal sensing is well-advanced, and a variety of choices for downhole temperature measurements are available. Thermocouples, although adequate for many purposes, are undesirable because of the length of high-resistance cables required for deep downhole emplacements.

Borehole Instrumentation

An experimental study was conducted to evaluate the feasibility of the installation and monitoring of equipment in a borehole drilled to a depth of 387 m in unsaturated fractured tuff. Matric potentials were measured using heat-dissipation probes (HDP); water potentials were measured by thermocouple psychrometers (TP). HDP were calibrated for matric potentials ranging from -0.1 to 15 bars. However, at pressures less than -5 bars, the calibration curve was flat and insensitive to pressure changes [Thamir and McBride, 1985]. TP were calibrated and used for measuring water potentials from -5 to -75 bars; temperature measurements also were made from the output of copper-constantan thermocouple junctions that are part of the TP.

Pneumatic potentials were measured downhole by semiconductor, pressure transducers. Periodically, fluctuations in total pneumatic potential were measured, using a differential-pressure transducer connected through a solenoid-valve manifold system to various access tubes at the land surface.

Emplacement of Instruments

After drilling and logging test borehole USW UZ-1 [Whitfield, 1985; Palaz, 1985], 15 depth zones were selected for installation of pressure transducers, TP, and access tubes. These depth locations were designated by instrument stations (IS) 1 through 15. At each IS, sensors were housed in one of three well screens (fig. 1), and

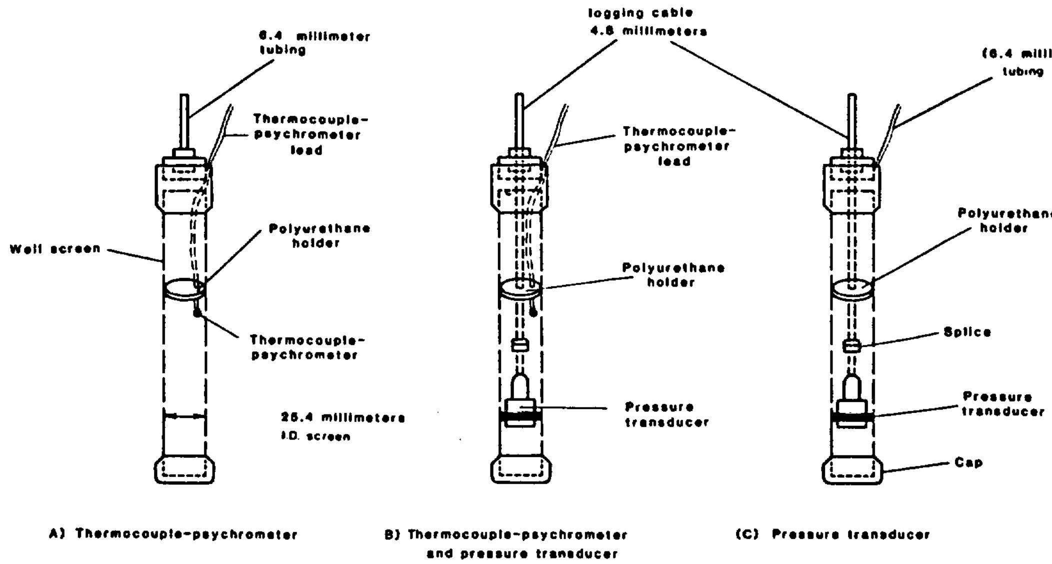


Fig. 1. Schematic diagrams of the well screens and the types of instruments installed in screens A, B, and C, test borehole USW UZ-1.

designated A, B, and C from top to bottom (with a few exceptions). The top well screen (A) contained a TP and was connected to the land surface by an access tube for gas sampling. The middle well screen (B) housed a TP and a pressure transducer. The bottom well screen (C) contained a pressure transducer and was connected to an access tube for gas sampling, and for checking calibration and proper functioning of the pressure transducer.

In addition to these IS, 18 different depths were selected for installation of HDP; TP also were installed at 5 of these depths. These HDP were designated as HDP-A or HDP-B depending on whether they were located above (HDP-A) or below (HDP-B) the nearby IS. The TP associated with these HDP were designated as HDP-TP.

Assembly and Installation of the Instruments

Prior to installation, the sensors were calibrated with cable lengths cut for the predesignated depths of installation in the borehole. After calibration, all cables with attached sensors were laid out, and instruments were inserted into the well screens and secured. The HDP ceramic tips were protected with fabric bags filled with saturated silica flour, but the bags were not placed in the well screens. The well screens and the HDP were adjusted, so that they would be located in predesignated-depth intervals. The entire assembly was transported to the test-borehole site as a bundle.

To emplace the filler material in the borehole, two tremie pipes were lowered into the borehole prior to installation of the bundle. After tremie-pipe installation, a television camera was lowered into the borehole to inspect it for obstructions. The bundle then was lowered into the borehole, attached to a 6.0-cm outside-diameter fiberglass access tube for geophysical logging. The wires and tubing of this assembly were encased in polyurethane-foam isolation plugs to prevent gas flow between instrument stations along the wires. The isolation plugs were situated so that they would be surrounded by grout during stemming. Standoffs also were installed on the fiberglass tube near each IS to prevent damage to the instruments by collision with the borehole wall during installation. The use of the polyurethane foam contaminated the borehole air with fluorocarbons and, therefore, eliminated the possibility of sampling for formation fluorocarbons.

Stemming Procedures

After the assembly was lowered into the borehole, dry materials (silica flour, sand, and bentonite) were poured through one tremie pipe, and wet materials (cement and water) were poured through the other tremie pipe to stem the hole. Final configuration of the stemmed borehole and the location of the IS and HDP are shown in figure 2. Actual location of the sensors and the contacts between different materials were determined by geophysical logs obtained inside the fiberglass tube.

Silica flour was selected as the filler material, instead of the crushed tuff that was produced during drilling, because of its uniformity, and therefore, predictability. The HDP were embedded in the silica flour. The silica flour used to stem the HDP at IS located in nonwelded and bedded tuff units was wetted, prior to installation, to a

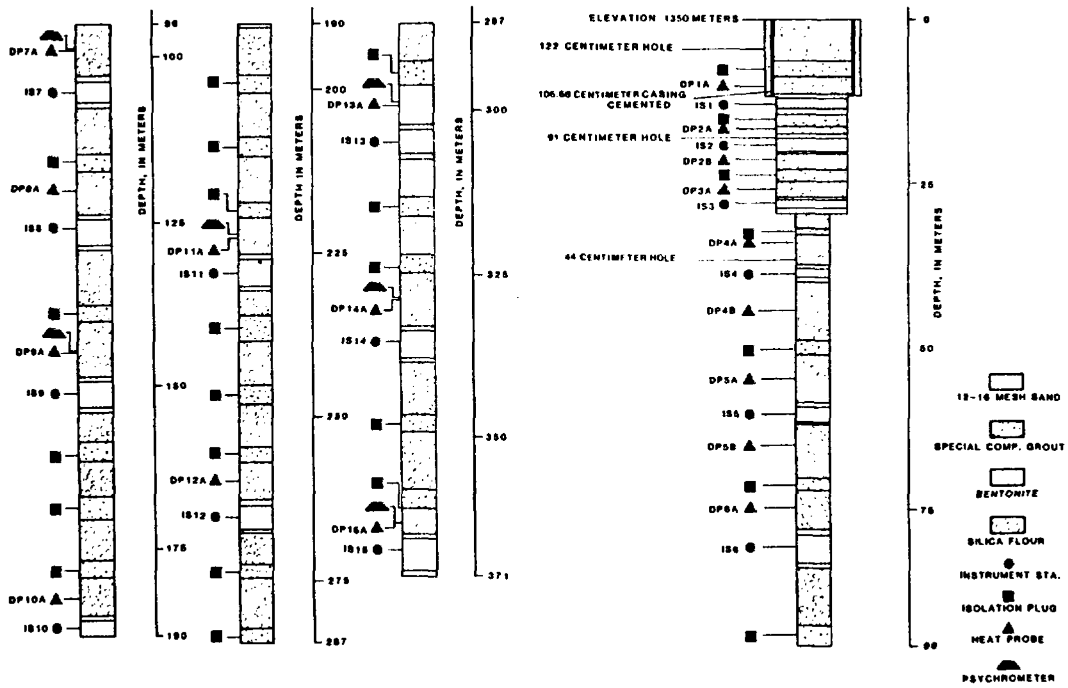


Fig. 2. Details of the stemming of test borehole USW UZ-1.

predetermined downhole matric potential slightly larger than that predicted for the formation. This procedure was done to prevent the HDP from drying to less than ambient-moisture content before rewetting. Such drying and rewetting would result in hysteresis; data collected under these conditions would not fit the drainage-calibration curve.

Where the silica flour was in contact with the matrix of densely welded tuff, a capillary barrier probably existed that retarded the flow of water from the formation into the silica flour. This retardation could result in additional delays in equilibration time. However, this condition probably did not exist where silica flour was in contact with fractures or with nonwelded units.

The silica flour was separated from the sand layers by a thin layer of bentonite to decrease further the possibility of gas flow from one depth zone to the other. The bentonite was emplaced dry and needed to become nearly saturated to establish equilibrium with the formation, thereby attaining minimum permeability to air.

The grout limited the movement of the gases between adjacent IS within the borehole. In addition, the grout layer supported the column of the silica flour, minimizing settlement of the flour, that could create large air cavities.

The well screens housing TP and transducers were embedded in coarse dry sand, because the sensors monitored the formation through the air phase. At the ambient matric potential of the formation, the sand attains very small saturation, and thereby retains large permeability to air.

Monitoring Fluid Potentials

Matric Potential

Examples of variations with time of the matric potential measured with HDP are shown in figure 3. Most of the HDP initially measured large matric potentials because the silica flour was wetter

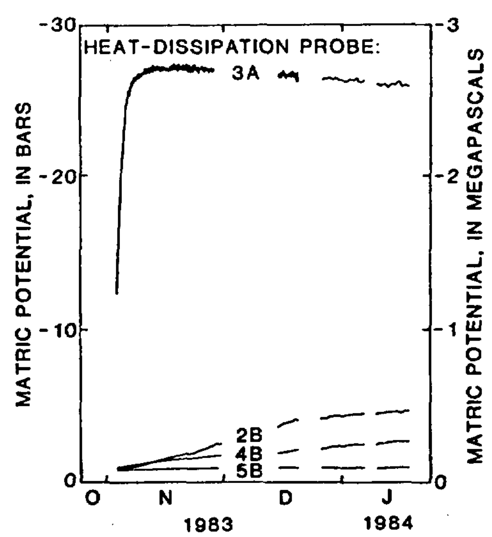


Fig. 3. Variations of matric potential with time in test boreholeUSW UZ-1 as measured with heat-dissipation probes.

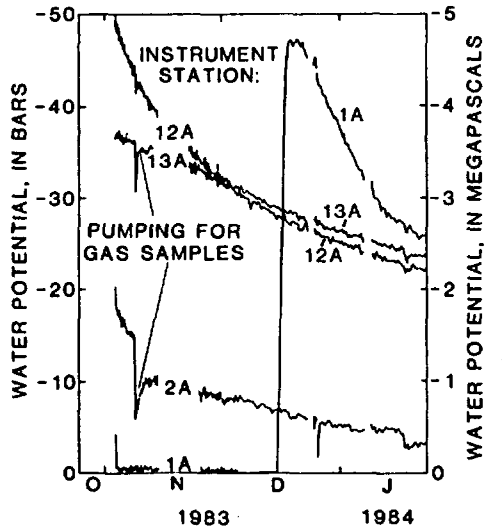


Fig. 4. Variations of water potential with time in test borehole USW UZ-1 as measured with thermocouple psychrometers installed in instrument stations.

around these probes than elsewhere in the silica-flour column either because of the added water and (or) the wet silica flour in the protecting porous fabric bag. The matric-potential measurements rapidly decreased as this water dissipated into the silica flour and possibly into the formation. Data for HDP-3A had a different trend. However, the calibration curve for the indicated range for the HDP was based on linear extrapolation from the -5-bar range, and the absolute values may not be reliable for matric potentials less than -5 bars. Examples of variation of the water potential with time measured by the TP are shown in figure 4. In this case, the water potentials initially were small; they rapidly increased during the first 90 d; then they increased more slowly. The TP were stemmed within initially dry screened sand. The unsaturated hydraulic conductivity of this sand was negligible at the presumed ambient-moisture tension in the surrounding medium. Consequently, vapor diffusion into the sand and subsequent sorption on the sand grains probably was the dominant transport process by which the moisture content of the sand backfill equilibrated with that in the formation. The rate at which this process progressed decreased exponentially with time. Three downward spikes in water potential measured by TP in IS 2A, 12A, and 13A occurred on November 8, 1983 (fig. 4). These increases in the water potentials occurred during pumping for gas samples; they probably resulted from the flow of nearly vapor-saturated air through the sand column. This vapor-saturated air increased the humidity around the TP. However, soon after pumping stopped, the normal trend resumed, as vapor condensed on the drier sand without materially changing its matric potential or diffused into the surrounding dryer sand. This phenomenon probably indicated that, under transient conditions, advection of nearly-saturated air could occur through a relatively dry medium without equilibrating with that medium. Another explanation for these spikes could be the flow of water droplets onto the material surrounding the TP. These droplets could have formed during pumping a warmer downhole air through a nylon tubing that was in equilibrium with geothermal gradient before pumping started. As the vapor-saturated air moved along the tube, a supersaturation temperature was attained in the tube and condensation occured. The condensate flowed along the tube wall until it fell on the material surrounding the TP. This latter explanation is unlikely because: (1) The responses to the pumping were almost immediate (within an hour); 2) both the wetting and drying cycles were indicated by relatively smooth curves that would not be expected in case of sudden and irregular fall of droplets; and 3) recent simultaneous pumping of IS-3A and IS-3C caused similar downward spike in water-potential trend of the TP in the IS-3B to which no tube is connected.

IS-1A initially measured large water potentials from October to December 1983 (fig. 4). In December 1983, this TP began measuring much smaller water potentials. This sudden reversal probably is the result of a single-point measurement technique, as discussed by Thamir and McBride [1985].

Temperature

Temperature records at various IS from November 1983 to April 1984 indicated that temperatures of the IS had nearly equilibrated with temperatures in the adjacent formation by mid-November. However, the temperatures at IS-1, IS-2, IS-3, and IS-4 indicated some variations with time. No seasonal changes would be anticipated at the depths of IS-3 and IS-4; the cause of variation was unknown. In addition, the temperature data for IS-1, IS-4, IS-7, and IS-8 indicate departures from the normal trend; the cause of these variations is not known at this time.

Pneumatic Potential

Data from the downhole-pressure transducers are shown in figure 5 for February 25-27, 1984. Diurnal-pressure changes occurred at most of the IS shown in this figure in response to more pronounced barometric changes at land surface. At greater depths, pressure responses to diurnal barometric fluctuations were damped out; however, long-term fluctuations (not shown) occurred.

These long-term fluctuations are characterized by broad lows and highs and do not seem to be directly correlated with the seasonal temperature changes. Rather, they reflect long term weather patterns with one to two month durations. The zero offset was shifted from that obtained during calibration, so that the positions of various

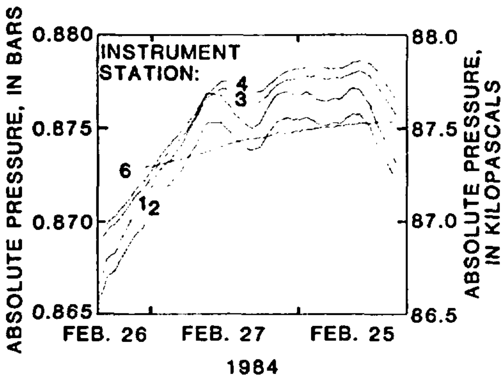


Fig. 5. Downhole-pressure variations at test borehole USW UZ-1, as measured with downhole-pressure transducers.

curves were not offset necessarily by an amount equal to the gravitational potential in the gas phase. However, these data can be adjusted to provide total pneumatic potential by subtracting the long-term mean pressure from each transducer record and adding the mean barometric pressure.

Fluctuations in total pneumatic potential were monitored during the same period using a differential-pressure transducer connected through a solenoid-valve manifold system to various access tubes at land surface. Data were obtained by opening the valves sequentially using a data-logger actuated multiplexer system; absolute pressure at the land surface was monitored using a digital barometer. Results of these measurements are shown in figure 6; these results, in terms of pressure fluctuations, agree well with results obtained using the downhole-pressure transducers.

Discussion and Results

Matric Potential and Flux

Interpretation of the data from TP and HDP in test borehole USW UZ-1 is complicated by the effect of the large volume of backfill material in which matric potential needs to equilibrate with the conditions in the formation before accurate measurements can be obtained. As noted before, the TP were installed in initially dry sand and the HDP were enclosed in fabric bags filled with saturated silica flour. The silica flour around the HDP installed in the nonwelded units was wetted. Therefore, the expected trend for the water potential measured by the TP would be from low to high (dry to wet) and the expected trend for the matric potential measured by the HDP would be from high to low (wet to dry). The wet zone created around the HDP in the silica flour was expected to become drier as the water dissipated. The drier sections of the column were expected to absorb water from the formation and, therefore, to attain equilibrium with the rest of the column.

Variations in average matric potential, as measured by HDP for the months indicated, are shown in figure 7. Seven of the HDP eventually became inoperative, so only a few data are shown for these probes. HDP 2A, 4A, 5A, and 5B, that were adjacent to alluvium or nonwelded tuff, initially dried a little and these virtually remained unchanged. HDP 3A showed a reverse response, becoming wetter throughout monitoring. HDP 8A, 9A, and 15A became progressively drier through 1984, then they became wetter in 1985. HDP 11A had two reversals. HDP 13A became drier, then it seemed to stabilize.

These results indicate that HDP adjacent to alluvium or nonwelded tuff generally dried for a short time before reaching some equilibrium, whereas HDP adjacent to welded tuff dried for a long time and then became wetter. Alluvium and nonwelded tuff contained larger moisture contents than did the welded units did therefore, more water was available to wet the silica-flour columns that were adjacent to alluvium and nonwelded tuff than was available to wet the columns adjacent to welded units. In addition, the alluvium and nonwelded tuff had larger matrix hydraulic conductivity than did the welded tuff. Also, the silica-flour columns adjacent to these alluvium and nonwelded-tuff intervals were much shorter than the silica-flour columns adjacent to the welded-tuff intervals. The combined effect of these differences probably resulted in the differences in trends detected between the probes placed adjacent to the two rock-type intervals. The HDP adjacent to the alluvium and nonwelded tuff probably have reached equilibrium with the formation. However, the HDP in the welded-tuff interval only recently have begun to indicate the movement of water from the formation into the silica flour; this condition is inferred from reversal of the trend from the deeper HDP-8A, HDP-9A, HDP-11A, HDP-13A, and HDP-15A. In conclusion,

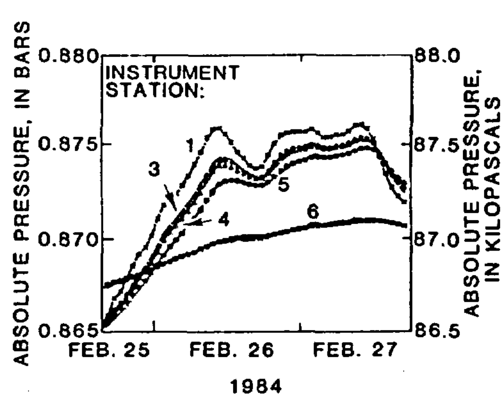


Fig. 6. Adjusted downhole-pressure variations in test borehole USW UZ-1. Differential pressures, measured with land surface transducers, were added to the calculated pneumatic-gravitational potential.

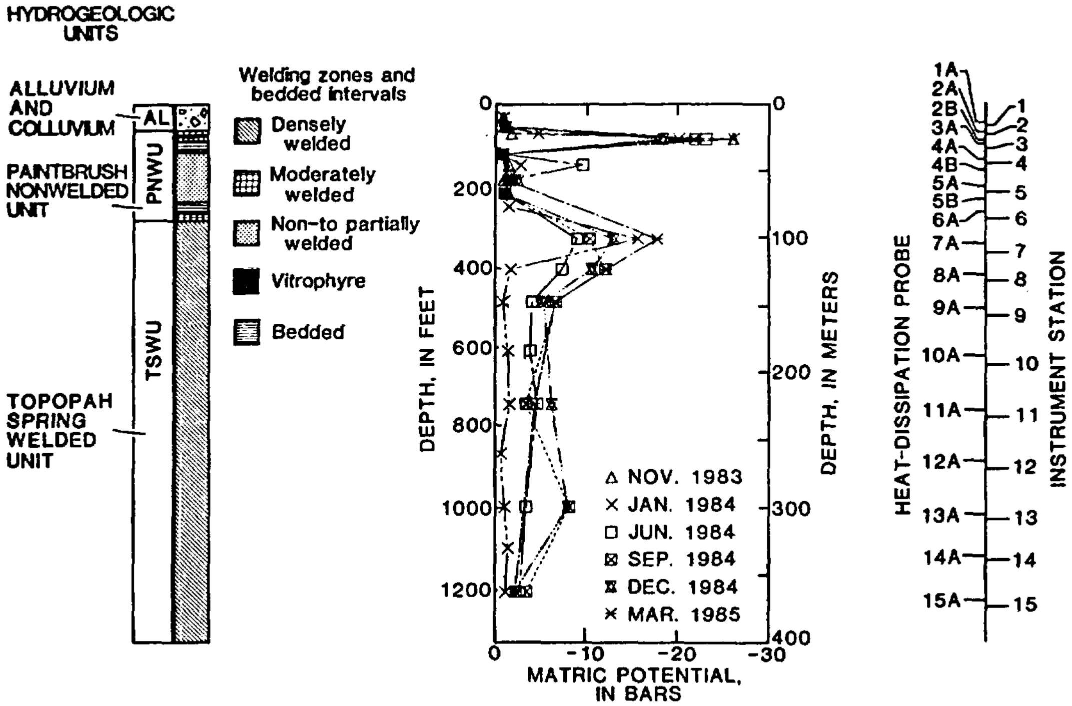


Fig. 7. Matric potential in test borehole USW UZ-1 based on data from heat-dissipation probes.

results of the HDP adjacent to alluvium and non-welded tuff probably represent the formation conditions. Deeper HDP probably are still in a non-equilibrium condition. It should be noted that these data are very noisy and these conclusions are reached on the basis of averaged and filtered data.

Variation of water potentials with depth, measured using TP in the A-screens, are shown for various times in figure 8. Initially, all TP except three showed expected trends of dry-to-wet conditions. These three TP (IS-3A, IS-6A, and IS-15A) fluctuated without any trend. IS-15A was located near the bottom of the borehole; the other two (IS-3A and IS-6A) were in bedded tuff in the upper part of the borehole. The TP in the two intervening stations (IS-4A and IS-5A) indicated trends similar to those of the majority of the TP. Individual measurements for the HDP -3A, -13A, and -15A and the three anomalous instrument stations and for IS-5 are compared in figures 9 and 10. For IS-3A and IS-6A, early measurements may have represented very dry, rather than very wet, conditions. This situation was possible because measurements by the TP could represent either very dry or very wet conditions equally well, as a result of measurement and calibration methods [Thamir and McBride, 1985]. If early data for IS-3A and IS-6a are interpreted as wetting trend (flipping the first one-third of the curves in figure 9 about -40 and -20 bars for IS-3A and IS-6A respectively), the trends would be similar to that of the IS-5A, from dry to wet.

Inspection of the long-term trends (not shown) indicated that a majority of the TP have stabilized and attained some mean value. Slight deviation from this mean valu+e occurred for some TP. Some deviations of the TP measurements (IS-1A, IS-2A, IS-14A, and IS-15A) consistently indicated gradual drying conditions; at other stations (IS-6A, IS-7A, IS-10A, and IS-13A), deviations of the TP measurements consistently indicated wetting conditions.

Trends for IS-14A and IS-15A (fig. 8) reflected the effects of a 15-m column of cement that was poured to plug the bottom part of the test borehole [Whitfield, 1985]. The recent tendency toward drying conditions probably indicated that, the formation was drier than the fill material at this depth. IS-1A and IS-2A also were affected by the water that was used to drill the first 17.7 m of the borehole [Whitfield, 1985]. The tendency toward drier conditions probably was indicative of the fact that conditions were dryer in the formation relative to the fill material. IS-3A, at a depth of 25.3 m, probably was not yet affected by this drilling water (figs. 8 and 10).

TP measurements probably are more reliable below depths of about 61 m because of the drier state of the formations below this depth. In addition, the TP in the A screen pumped several times for gas samples; therefore, they were more

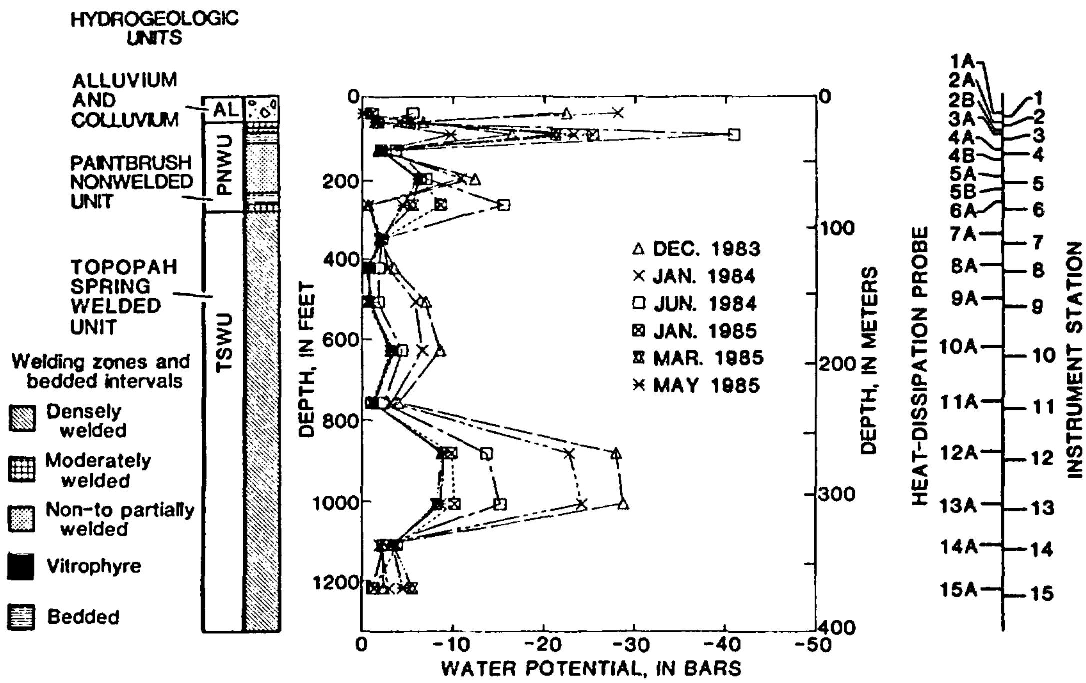
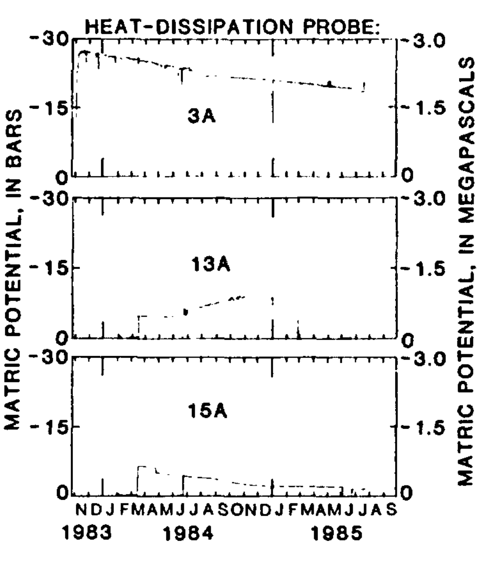


Fig. 8. Water potential in test borehole USW UZ-1 based on data from thermocouple psychrometers.

nearly equilibrated with the formation than TP in the B screensThe TP installed adjacent to some of the HDP did not perform well probably because of the ceramic tip that was chosen to minimize contamination from direct contact with silica flour.

Simulation of the Effects of Stemming Material

Disturbance of the in-situ matric potential by the emplacement of the material in the borehole was evaluated by an axisymetric simulation of the



Breaks in data line indicate no data

Fig. 9. Variations of matric potentials with time for selected instrument stations in test borehole USW UZ-1.

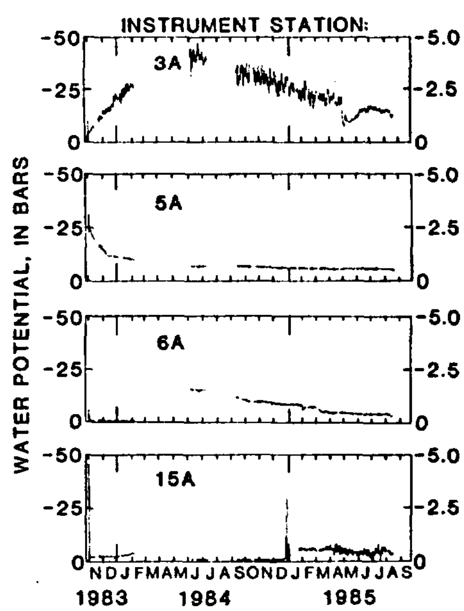


Fig. 10. Variations of water potential with time for selected instrument stations in test borehole USW UZ-1.

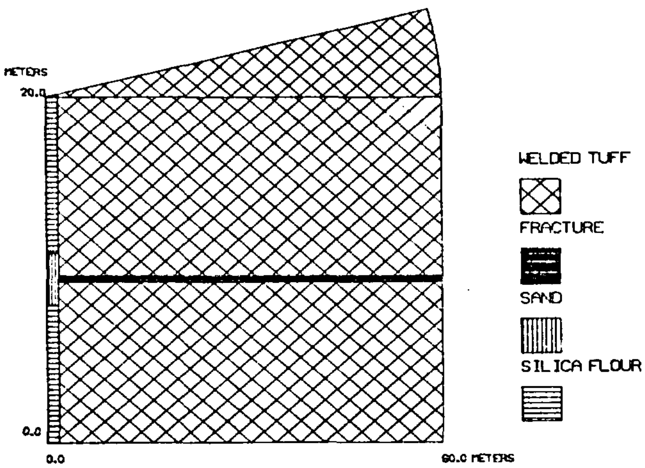


Fig. 11. A slice of the region simulated, 20 meters thick and 100 meters in radius; horizontal fracture is 0.3 meter thick.

problem (fig. 11). Flow through a 20-m thick section of the welded tuff with a 0.3-m thick horizontal fracture zone in the middle and a borehole along the center of a 100-m radius cylinder was simulated using the UNSAT2 code [Neuman, 1973]. The borehole is filled with silica flour except for the middle 3-m, which is filled with medium to coarse washed sand. The characteristic unsaturated properties of these materials are shown in figure 12. Properties of the welded tuff were from laboratory measurements. The material properties of the sand were from Davis and Newman [1983] and properties of the silica flour properties were provided by D.P. Hammermeister (U. S. Geological Survey, written commun. 1984): The fracture properties were estimated using the method described by Montazer and Harrold [1985].

A 0.5 mm/yr flux was applied to the upper surface of the model to simulate the perceived insitu conditions and to prevent gravity from draining the model. Initially, the welded tuff was set at -20 m of pressure head, and the borehole materials were set at -100 m of pressure head.

Results of this simulation are summarized in figures 13 and 14. The pressure history at various locations within the model is shown in figure 13. The center of the sand column becomes wetter after about 1 d; however, after about 10 d, the sand begins to dry again. A point in the fracture, 3m away from the borehole wall begins to dry rapidly and approaches the same matric potential as that of the sand column. The fracture at a point 50 m away from the borehole wall also has been affected in the same manner, but with a smaller magnitude. The silica flour, in the center of the borehole, remains almost unaffected, with a slight wetting trend.

This phenomenon can be explained by the fact that the fracture has substantial saturated permeability, and drains rapidly because of the steep potential gradient towards the borehole. However, the storage in the fracture is so small compared to that in the sand column that the effect in the fracture is sensed 50 m away, but the sand column is disturbed only slightly. The later drying trend in the sand column is the result of the gradient toward the silica-flour column. The conditions simulated here are not as severe as those that existed onsite in the actual field conditions because the dry silica flour and sand could have had pressure heads much lower than 1000 m when they were placed in the borehole. One way to minimize this disturbance would be by wetting the stemming material so that the matric potentials in the stemming material and the formation are almost identical. However, precisely predicting the matric potential of the formation usually is difficult. Nevertheless, slightly wetter conditions of the stemming material could change the matric potential in the fracture substantially for long distances away from the borehole for relatively long times. These problems possibly could be avoided by not using stemming

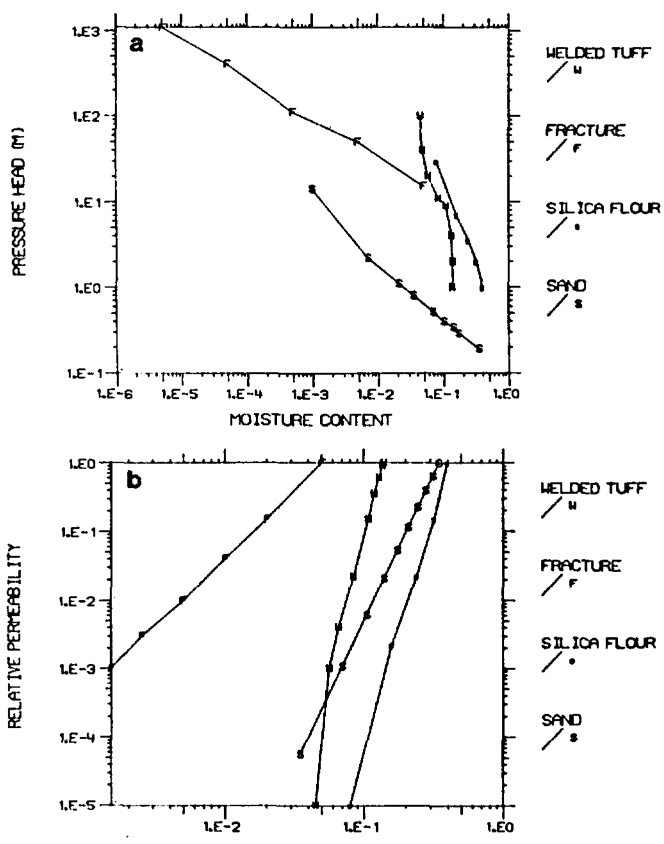


Fig. 12. Characteristic properties of the materials used in the simulation of; a) moisture-characteristic curves; and b) relative permeability versus moisture content. Values of saturated hydraulic conductivity, in meters per day, were: welded tuff, 0.3x10^{-3}; fracture, 1.0; silica flour, 1.0x10^{-2}; and sand, 5.5.

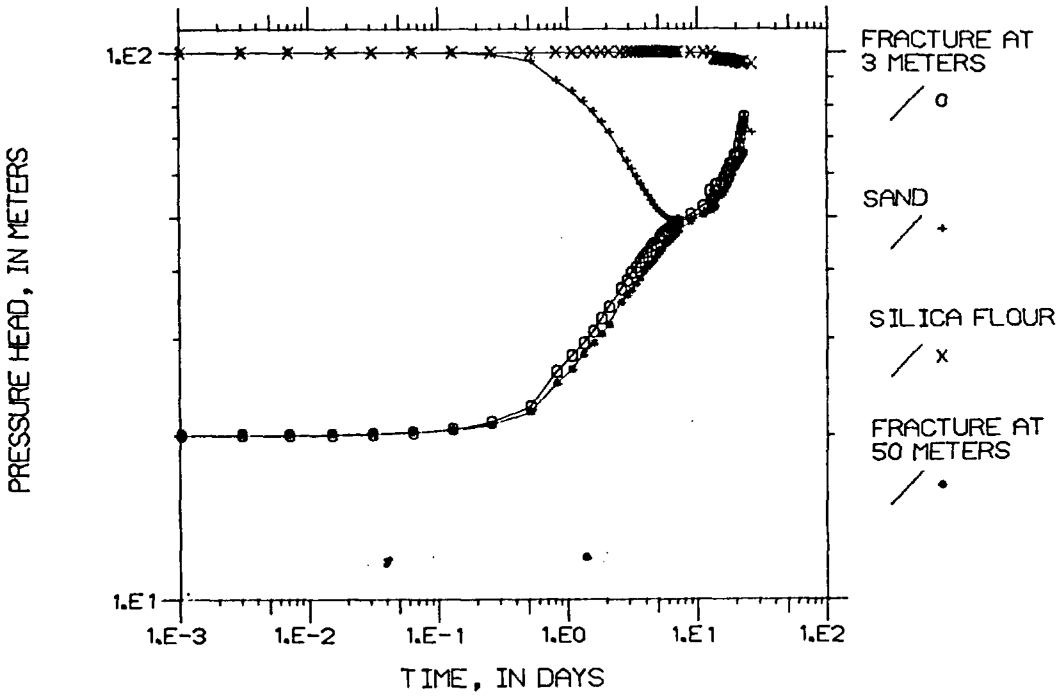


Fig. 13. Variation of pressure head with time at points in the fracture 3 and 50 meters away from the borehole compared with variations in pressurehead of points at the center of the sand column and at a point in the silica flour 7.5 meters above the fracture.

material but instead relying on psychrometric measurements in packed-off air-filled cavities. This approach needs to be tested. Existing measurements indicate that the psychrometers emplaced in screens surrounded by sand that are pumped periodically produce more reliable data than those in unpumped screens or in silica flour.

The complexities that exist in the borehole and the formation cannot be simulated realistically with a simple model, such as the model depicted here. Nevertheless, the results of this simulation indicate that a long period of time is required for any disturbance in the formation to dissipate. The small matrix permeability , the large fracture permeability, and the small fracture porosity makes the fractured rocks susceptible to disturbances. In some cases, this susceptibility could result in almost irreversible conditions. Such phenomena need to be considered when instrumenting and monitoring of unsaturated fractured rocks.

Summary and Conclusions

Fifteen depth intervals were selected in a 44.5-cm-diameter experimental borehole, drilled in tuff, to evaluate the emplacement and operation of thermocouple psychrometers, and for monitoring hydrologic conditions in the vadose zones of fractured vocus HDP in silica-flour columns. The TP and pressure transducers were housed in well screens and were embedded in coarse sand. After more than 2 years of monitoring, a majority of the instruments were still functioning. HDP that were placed adjacent to nonwelded tuff and alluvium attained equilibrium faster than those that were placed adjacent to welded tuff. TP produced more reliable data for welded tuff than for nonwelded tuff and alluvium. Numerical simulation of the effect of the stemming materials on the matric potential of the formation indicated that the fractures are most susceptible to the disturbance caused by emplacement of the dry materials in the borehole. Fractures are drained rapidly and the effect of draining was noticable tens of meters away from the borehole. Monitoring the in-situ matric potentials indicated that, in stemmed boreholes, the most reliable results may be obtained when the instrument station is pumped for a relatively long of time and the matric potential is psychrometrically monitored. However, because of disturbances of matric potential caused by the stemming materials, attempts need to be made to develop methods for obtaining psychrometric measurements in isolated sections of a borehole without any porous filler materials.

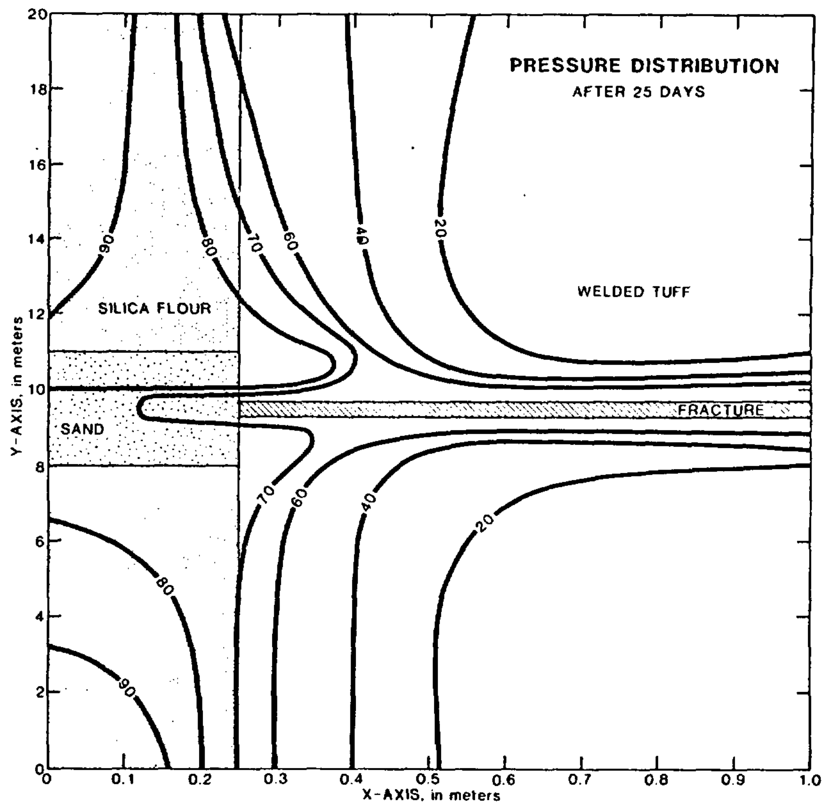


Fig. 14. Contour diagram of the pressure head distribution in the vicinity of the borehole after 25 days; slight wetting of the sand column and severe drying of the fracture are evident.

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