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NEVADA OPERATIONS OFFICE
U.S. DEPARTMENT OF ENERGY
Interagency Agreement DE-AI08-97NV12033

Use of Temperature, Pressure, and Water Potential Data to Estimate Infiltration and Monitor Percolation in Pagany Wash Associated with the Winter of 1997–98 El Niño Precipitation, Yucca Mountain, Nevada

Water-Resources Investigations Report 02–4035

U.S. Department of the Interior
U.S. Geological Survey

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By Gary D. LeCain, U.S. Geological Survey, Denver, Colorado
Ning Lu, Colorado School of Mines, Golden, Colorado
Mark Kurzmack, S.M. Stoller Corporation, Lafayette, Colorado

U.S. GEOLOGICAL SURVEY

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U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

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For additional information write to:

Chief, Earth Science Investigations Program
Yucca Mountain Project Branch
U.S. Geological Survey
Box 25046, Mail Stop 421
Denver Federal Center
Denver, CO 80225–0046

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
cubic meter (m^3)	35.341	cubic foot
joule per kilogram, °C (J/kg °C)	2.39×10^{-4}	British thermal unit per pound, °F
British thermal unit per pound, °F	1.0	watt per meter, °C
kilogram (kg)	2.205	pound
kilogram per cubic meter (kg/m^3)	0.062	pound per cubic foot
kilometer (km)	0.6214	mile
kilopascal (kPa)	0.145	pound-force per square inch
meter (m)	3.281	foot
meter per day (m/d)	3.281	foot per day
square meter (m^2)	10.765	square foot
meter per second (m/s)	196.850	foot per minute
millimeter (mm)	0.0394	inch
pascal (Pa)	1.45×10^{-4}	pound-force per square inch

Temperature in degree Celsius (°C) can be converted to degree Fahrenheit (°F) as follows:

$$°F = 1.8\ (°C) + 32$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets across the United States and Canada, formerly called Sea Level Datum of 1929.

In this report, the term "standard" means a measurement taken at a temperature of 0 degree Celsius and atmospheric pressure of 101.3 kilopascals.

Use of Temperature, Pressure, and Water Potential Data to Estimate Infiltration and Monitor Percolation in Pagany Wash Associated with the Winter of 1997–98 El Niño Precipitation, Yucca Mountain, Nevada

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Abstract

Temperature, pressure, and water potential monitoring in two vertical boreholes at Pagany Wash near Yucca Mountain in Nevada indicated infiltration and deep percolation through the alluvium. Temperature data indicated that the annual temperature wave was measurable to a depth of 12.2 meters. Water potential values ranged from –3 to –1 bars. Temperature, pressure, and water potential disruptions were measured at a depth of 35.2 meters. The disruptions were interpreted to be the result of the percolation of infiltrated water associated with the winter of 1997–98 El Niño precipitation. The pressure differences between stations indicated that the wetting front had migrated deeper than 35.2 meters and that the Yucca Mountain Tuff may have retarded the downward movement of the wetting front. Analytical modeling indicated that the 1997–98 El Niño precipitation resulted in a percolation flux through the alluvium of about 1,130 millimeters. Numerical models indicated that the infiltration flux was between 1,000 to 2,000 millimeters.

INTRODUCTION

The Yucca Mountain Project (YMP) is a scientific study by the U.S. Department of Energy (DOE) to evaluate the potential for geologic disposal of high-level radioactive waste in an unsaturated-zone desert environment. The potential repository site at Yucca Mountain is about 130 km northwest of Las Vegas, Nevada, near the DOE Nevada Test Site (NTS) (fig. 1).

The thickness of the unsaturated zone at the potential repository site ranges from 300 to 600 m. The U.S. Geological Survey (USGS) has been conducting geologic and hydrologic studies of the potential repository site for the DOE. The studies included downhole testing in surface boreholes and underground testing in the tunnels and alcoves of the Exploratory Studies Facility. These studies are to quantify the geologic and hydrologic characteristics of Yucca Mountain and to conceptualize and model gas and liquid flow at the potential repository site.

One of the Yucca Mountain scientific studies was the USGS Surface-Based Monitoring Program (SBMP). The SBMP used vertical boreholes instrumented with thermistors, pressure transducers, and thermocouple psychrometers to provide data on the temperature, pressure, and water potential of the unsaturated zone and how these values change with depth and time. The overall goal of the SBMP was to gain a better understanding of the distribution and transfer of heat, pressure, and moisture in the unsaturated zone. Two of the SBMP boreholes are the Underground Exploratory, Area 25, unsaturated zone boreholes #4 and #5 (UZ #4 and UZ #5). Boreholes UZ #4 and UZ #5 were instrumented in July 1995. Borehole UZ #4 is located in the alluvial deposits of Pagany Wash, a stream-carved, dry channel northeast of Yucca Mountain and the potential repository site (fig. 2). Borehole UZ #5 is located about 37 m south of borehole UZ #4 on a hillside 3.9 m above Pagany Wash. One goal of the SBMP was to provide some insight on infiltration

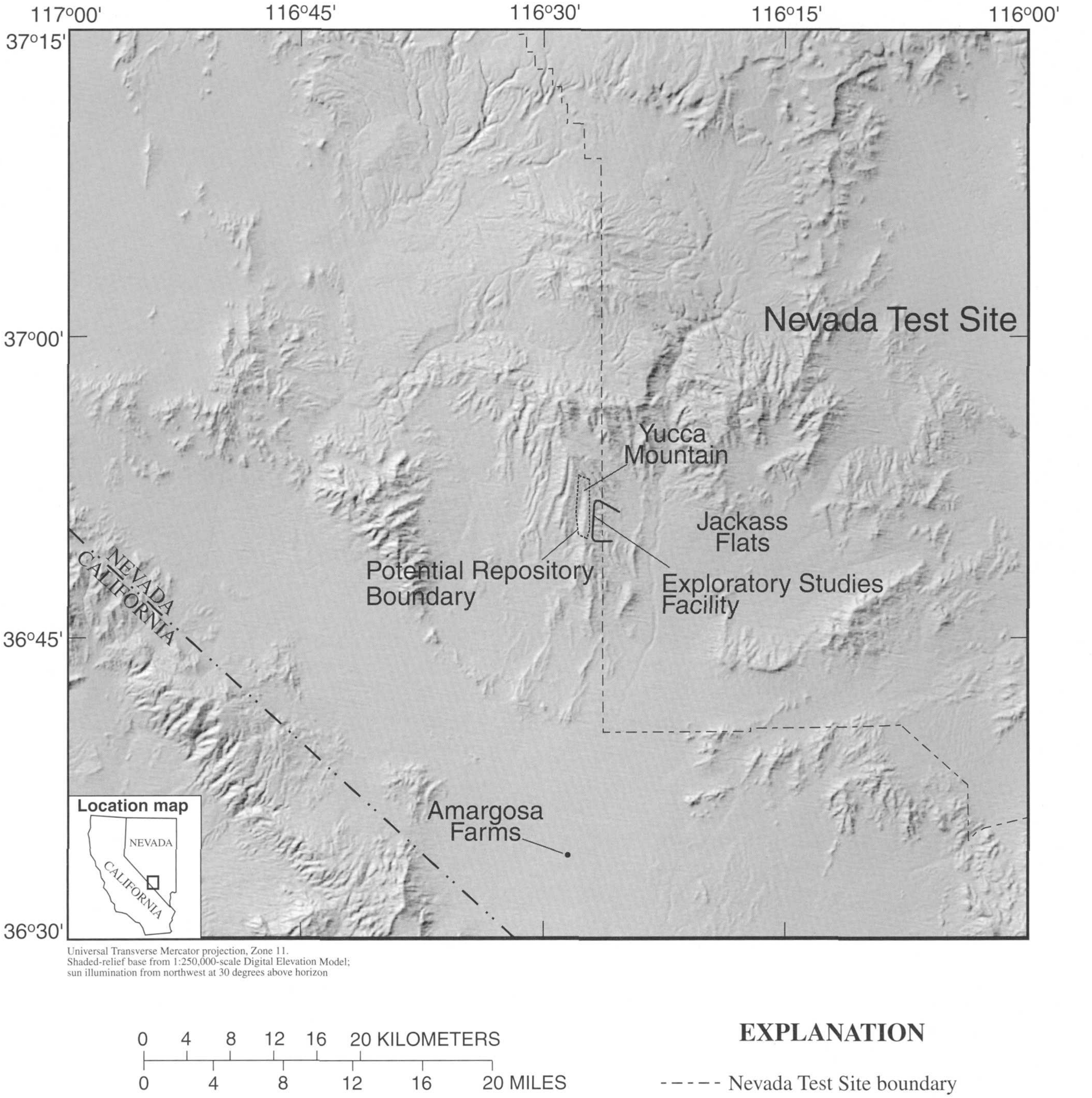


Figure 1. Location of the Nevada Test Site, Exploratory Studies Facility, and the potential repository at Yucca Mountain, Nevada.

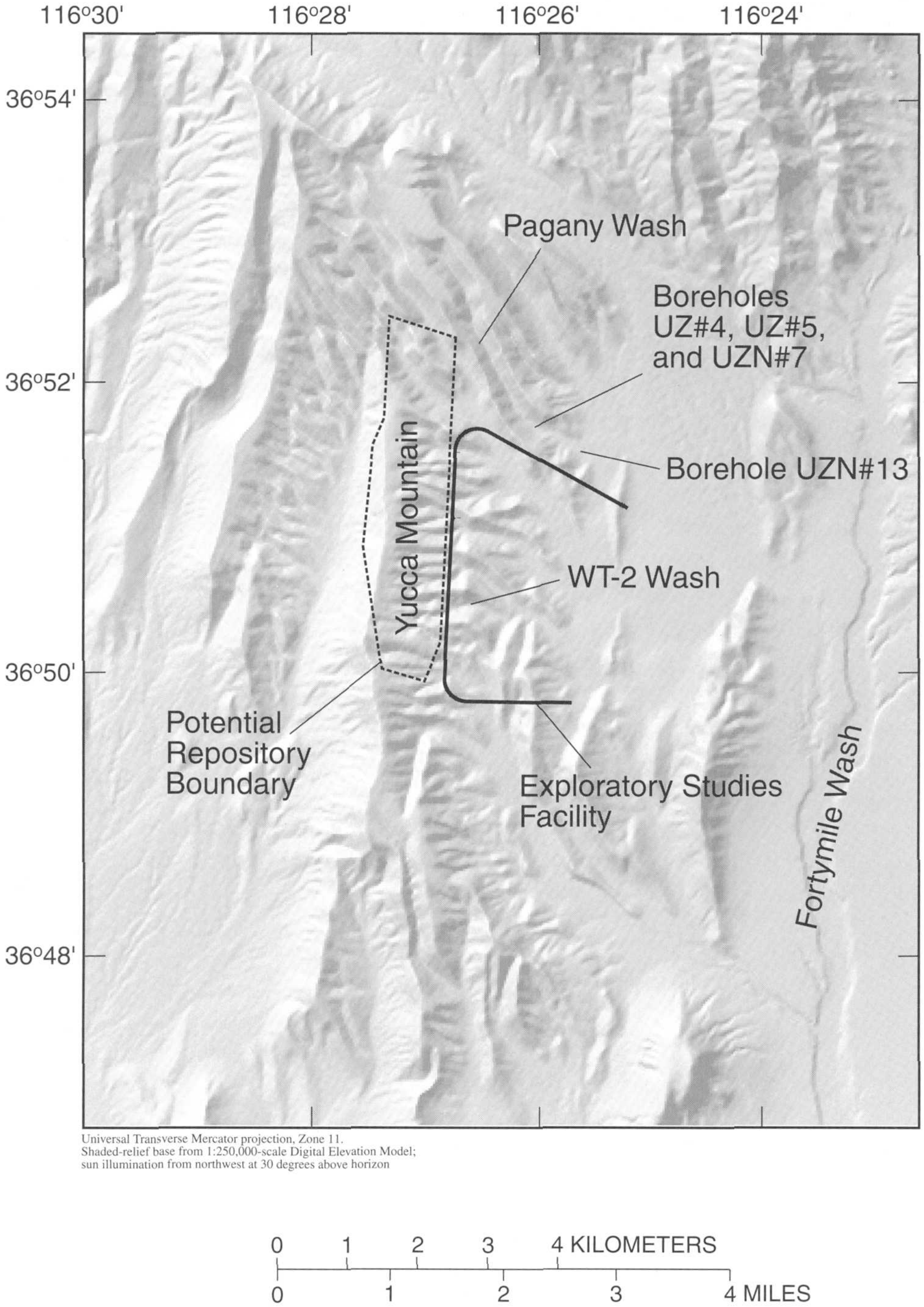


Figure 2. Location of Unsaturated Zone Boreholes UZ #4 and UZ #5, Pagany Wash, and neutron boreholes UZN #7 and UZN #13.

and percolation through the alluvial deposits of the usually dry stream channels. This potential source of infiltration and ground-water recharge may be significant because in areas of low precipitation "infiltration of runoff in channels is often the largest source of recharge" (Stephens, 1996, p. 115).

The winter of 1997–98 was an El Niño winter and therefore was wetter than normal. A plot of the 1990–99 monthly precipitation at Amargosa Farms, Nevada, is presented in figure 3 (Western Regional Climate Center, 2000). The Amargosa Farms are located at Garey, Nevada, about 30 km south of Yucca Mountain. Figure 3 shows several periods of increased precipitation that were associated with the El Niño events of 1991–92, 1993, 1994, and 1997–98. During the winters of 1994–95 and 1997–98, flowing water was seen and measured in some of the usually dry channels at Yucca Mountain (C.S. Savard, U.S. Geological Survey, written commun., 1999). Surface-water temperature values measured at Wren Wash, Pagany Wash, and Yucca Wash during the February 1998 El Niño precipitation ranged from 3.4° to 5.7°C (Savard, 1999). The average annual precipitation at Yucca Mountain ranges from 130 mm over the southern part of the mountain to 250 mm at the higher elevations in the north (Flint, 1999, p. 10). Rain-gage data from WT–2 Wash and Jackass Flats (figs. 1 and 2) had precipitation values of 173.2 and 134.6 mm respectively, for the period February 3, 1998, to February 25, 1998 (W.J. Davies, U.S. Geological Survey, written commun., 1999). These large precipitation events can result in surface runoff and concentrated flow in the washes, resulting in a high potential for infiltration beneath the washes. Because the winter precipitation is generally much cooler than the subsurface temperature, the infiltrated water can cause temperature decreases in the subsurface.

The instruments installed in boreholes UZ #4 and UZ #5 provided data on the temperature, pressure, and water potential disruptions associated with infiltration and percolation of the wetting front through the alluvium in Pagany Wash. This report presents temperature, pressure, and water potential data from boreholes UZ #4 and UZ #5 that relate to the 1997–98 winter El Niño precipitation. This report also presents analytical and numerical estimates of the associated infiltration and percolation flux.

BOREHOLE GEOLOGY

Borehole UZ #4 has a total depth of 127.7 m and penetrates the alluvium/colluvium of Pagany Wash, the Tiva Canyon Tuff, the Paintbrush Tuff nonwelded unit, and the upper Topopah Spring Tuff. The volcanic- and volcaniclastic-origin rocks are of Miocene age (Buesch and others, 1996). Borehole UZ #5 has a total depth of 123.5 m and also penetrates the Tiva Canyon Tuff, the Paintbrush Tuff nonwelded unit, and the upper Topopah Spring Tuff.

The upper 12.1 m of borehole UZ #4 penetrates alluvium/colluvium of Quaternary age. The alluvium/colluvium is composed of subangular to subrounded silt to pebble-sized gravel, cobbles, and boulders. The alluvium/colluvium was formed from moderately to densely welded tuffs of the Tiva Canyon

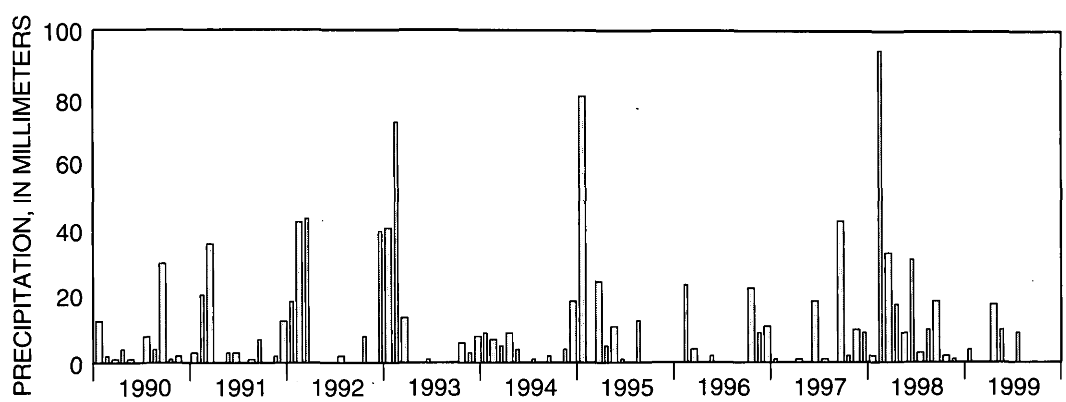


Figure 3. Monthly precipitation at Amargosa Farms, Garey, Nevada, for the period 1990–99.

Tuff (Loskot and Hammermeister, 1992). Both boreholes penetrate the lower nonlithophysal zone of the Tiva Canyon Tuff (Tpcpln), a moderately to densely welded devitrified, crystal poor, nonlithophysal ash-flow tuff. This lower section of the Tpcpln is referred to as the "columnar unit" due to the high density of columnar fractures. Below the Tpcpln the boreholes penetrate the crystal-poor vitric zone of the Tiva Canyon Tuff (Tpcpv). Loskot and Hammermeister (1992) classify the vitric zone as a nonwelded, slightly argillic ash-flow tuff. Below the Tpcpv the boreholes penetrate the bedded tuff #4 of the Paintbrush Tuff nonwelded unit (Tpbt4). The Tpbt4 is a vitric, poorly to moderately consolidated, ash-fall tuff. Below the Tpbt4 the boreholes penetrate the Yucca Mountain Tuff member of the Paintbrush Tuff nonwelded unit (Tpy). The Tpy is a nonwelded to partially welded, vitric, ash-flow tuff. Below the Tpy the boreholes penetrate the bedded tuff #3 of the Paintbrush Tuff nonwelded unit (Tpbt3). The Tpbt3 is a vitric, poorly to moderately consolidated, ash-fall tuff. Figure 4 presents a geologic cross section of the upper 50 m of boreholes UZ #4 and UZ #5. The data presented and analyzed in this report were collected in the upper 50 m of boreholes UZ #4 and UZ #5.

BOREHOLE INSTRUMENTATION

Boreholes UZ #4 and UZ #5 were instrumented in June 1995. The surface equipment consists of an instrument shelter and two wellhead boxes (fig. 4). The temperature-controlled instrument shelter contains the data-acquisition equipment. The borehole wellhead boxes are connected to the instrument shelter through PVC pipe containing the borehole instrument

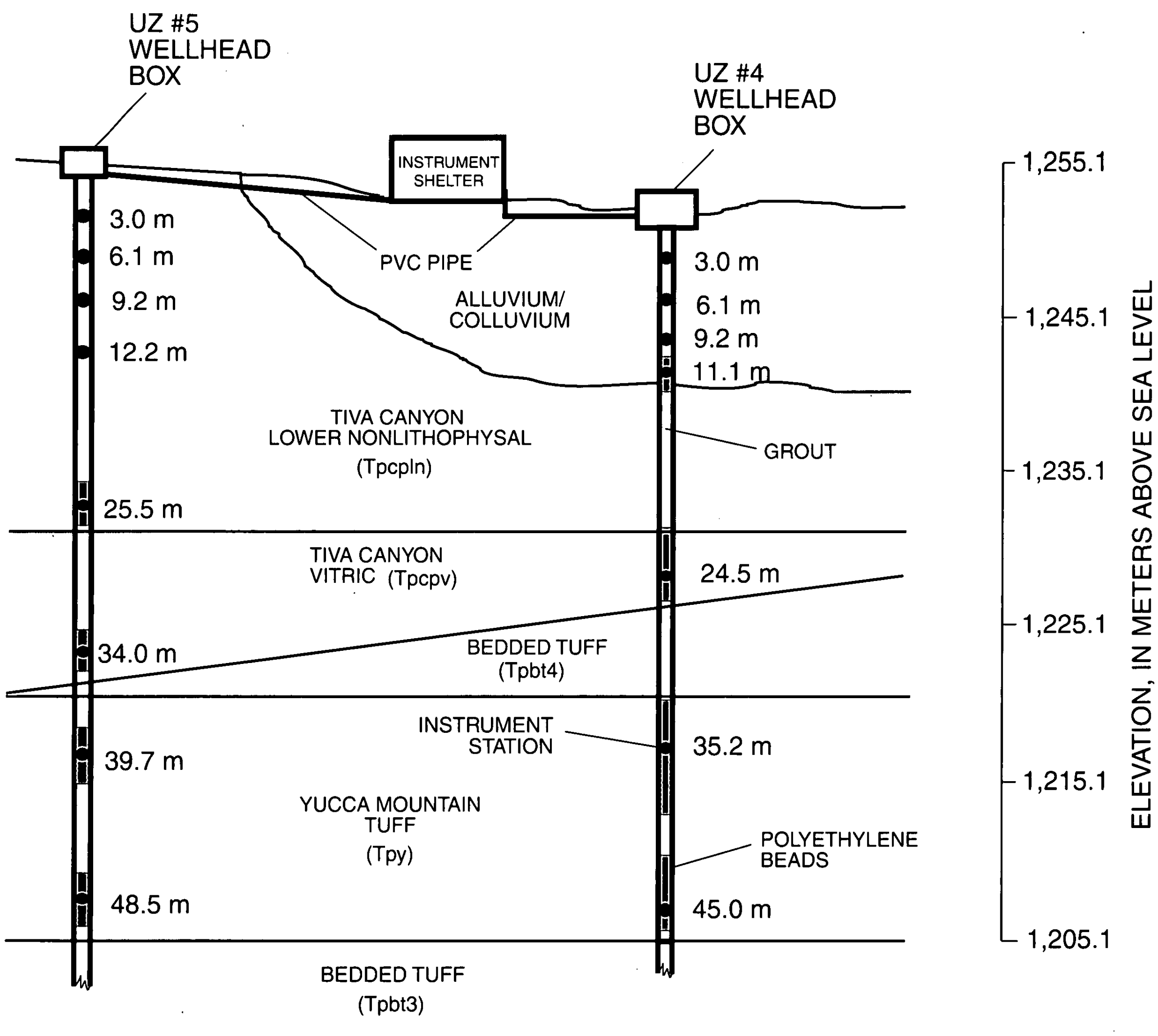


Figure 4. Boreholes UZ #4 and UZ #5 instrument stations and generalized geology.

cables. The PVC pipe is buried about 1 m deep. The wellhead boxes are about 2 m in diameter and 2 m in height, are made of steel with a steel lid, and are buried about 1.7 m deep. Borehole UZ #4 had a total of 11 instrument stations ranging in depth from 3.0 to 111.9 m, and borehole UZ #5 had a total of 12 instrument stations ranging in depth from 3.0 to 111.6 m. The boreholes were uncased with the exception of the upper 18.4 m of borehole UZ #4 where casing was required to keep the hole open through the alluvium. The three shallowest stations in borehole UZ #4 (3.0, 6.1, and 9.2 m in depth) and the four shallowest stations in borehole UZ #5 (3.0, 6.1, 9.2, and 12.2 m in depth) were instrumented with thermistors to measure temperature. The deeper stations were instrumented with thermistors to measure temperature, pressure transducers to measure absolute pressure, and thermocouple psychrometers to measure water potential. Thermistors and pressure transducers also were installed in the wellhead boxes and the PVC pipe. The downhole sensors were operated with constant current to eliminate the resistance effects of the variable-length electrical wires.

Figure 4 presents a schematic diagram of the generalized borehole geology and the relative locations of the instrument stations in the upper 50 m of boreholes UZ #4 and UZ #5. The upper four stations of borehole UZ #4 were located in the alluvium/colluvium of Pagany Wash. Borehole UZ #4 station 24.5 m was located in the welded Tiva Canyon Tuff lower vitric zone, and stations 35.2 m and 45.0 m were located in the nonwelded Yucca Mountain Tuff. Stations 3.0 m, 6.1 m, and 9.2 m, were installed in the cased interval of the borehole and grouted in place with gypsum grout. The casing was slotted to ensure a good connection between the instrument stations and the surrounding rock. The deeper stations (11.1 m, 24.5 m, 35.2 m, and 45.0 m) were installed in protective shells and suspended in a medium of polyethylene beads. The lengths of the station intervals ranged from 3.7 to 5.2 m, and the sensors were located near the center of the intervals. The stations were separated by infilling the remainder of the borehole with gypsum grout.

The upper five stations of borehole UZ #5 were located in the welded Tiva Canyon Tuff lower nonlithophysal zone, station 34.0 m was located in the welded Tiva Canyon Tuff vitric zone and stations 39.7 m and 48.5 m were located in the nonwelded Yucca Mountain Tuff. The thermistors at stations 3.0 m, 6.1 m, 9.2 m, and 12.2 m were grouted in place with gypsum grout. The deeper stations (25.5 m, 34.0 m, 39.7 m, and 48.5 m) were installed in protective shells and suspended in a medium of polyethylene beads. The lengths of the station intervals were about 3 m, and the sensors were located near the center of the intervals. The stations were separated by infilling the remainder of the borehole with gypsum grout.

The station sensors were calibrated over a narrow operational range to maximize precision and accuracy. The thermistors were accurate to ±0.005°C (95 percent confidence) with a sensitivity of 0.0005°C. The pressure transducers were accurate to ±20.0 pascals (Pa) with a sensitivity of 1.0 to 3.0 Pa. (Kume and Rousseau, 1994). The thermocouple psychrometers were accurate to ±2 bars with a sensitivity of 0.05 bar (Rousseau and others, 1999, p. 144) The computer-controlled data-acquisition program allowed automated reading of the downhole sensors.

RESULTS FROM BOREHOLE TEMPERATURE MONITORING

Borehole UZ #4

Figure 5 presents the borehole UZ #4 temperature data for the period July 1, 1995 through July 1, 2000, for the four instrument stations in the Pagany Wash alluvium. The temperature data showed that the annual temperature wave was measurable at station 11.1 m. Figure 5 shows an abrupt temperature decrease at station 3.0 m on February 24, 1998, and a less pronounced but discernible decrease at station 6.1 m on March 2, 1998. Figure 5 also shows that the 1998 annual temperature highs and lows at all four stations were depressed compared to the July 1, 1995 to 1997 monitoring period. Figure 6 presents the temperature data for the period of April 1, 1996 to April 1, 2000 for stations 24.5 m and 35.2 m. The long-term steady increase in temperature indicated stations 24.5 m and 35.2 m were still stabilizing following the borehole construction and instrumentation. Figure 6 shows that on April 17, 1998 station 35.2 m had an abrupt temperature decrease followed by a period of instability. Figure 6 also shows that on March 22, 1998 station 24.5 m had an increase in temperature and then restabilized.

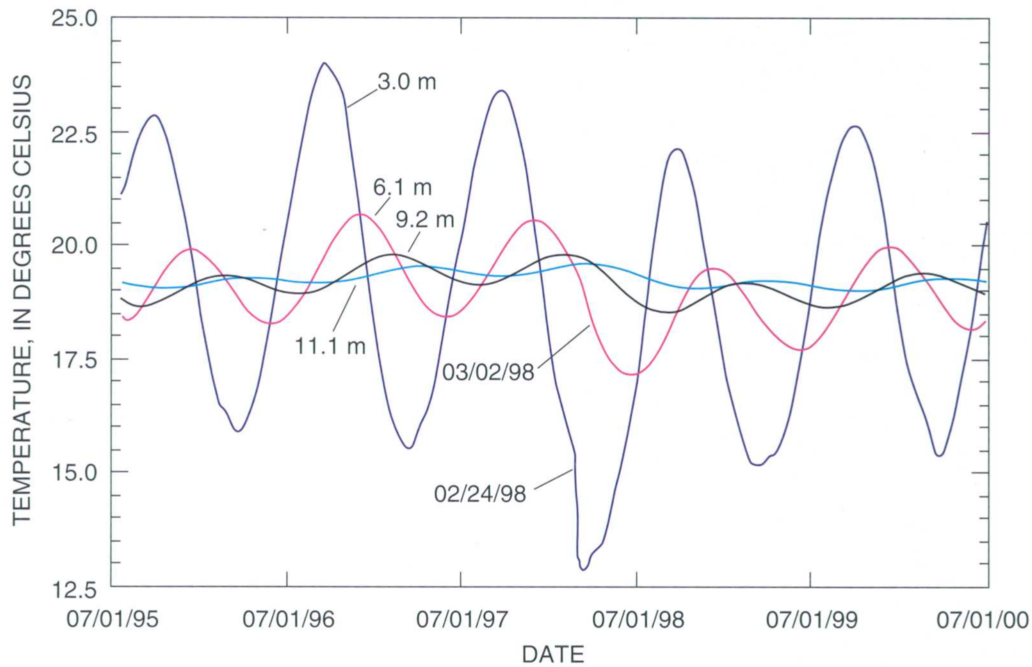


Figure 5. Temperatures at borehole UZ #4 stations 3.0 m, 6.1 m, 9.2 m, and 11.1 m for July 1, 1995, through July 1, 2000.

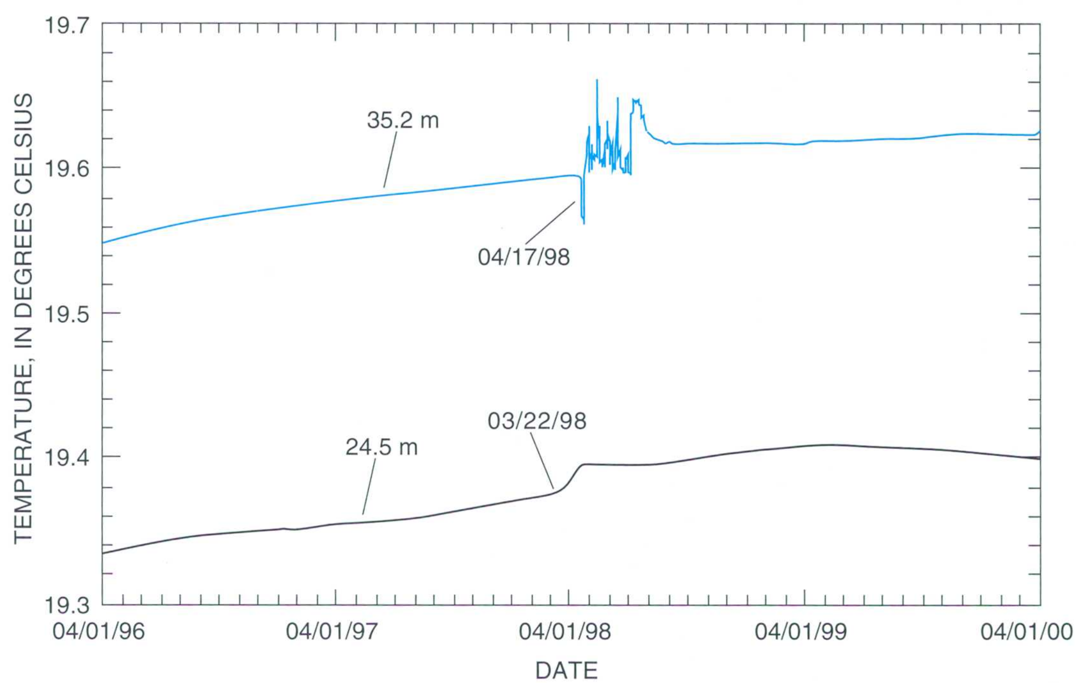


Figure 6. Temperatures at borehole UZ #4 stations 24.5 m and 35.2 m for April 1, 1996, through April 1, 2000.

Figure 7 presents a more detailed view of the temperature responses at stations 3.0 m, 6.1 m, 9.2 m and 11.1 m for the period November 1, 1997 to June 1, 1998. Figure 7 shows that the February 24, 1998 temperature decrease measured at station 3.0 m was about 2.6°C. The temperature decrease was interpreted to be the result of cooler water percolating through the alluvium and was a direct result of the infiltration of water associated with the February 1998 El Niño precipitation. The smaller, yet still discernible, temperature decrease at station 6.1 m (March 2, 1998) was interpreted to be the continued downward movement of the wetting front. Although stations 9.2 m and 11.1 m did not show the abrupt temperature decreases measured at stations 3.0 m and 6.1 m, examination of the long-term record showed depressions of the annual temperature wave associated with the continued downward percolation of the wetting front (fig. 5). The percolation theory agrees with the neutron data from the unsaturated zone neutron borehole #13 (UZN #13). Borehole UZN #13 is located in the alluvium in the active channel at the mouth of Pagany Wash; neutron logging during the winter of 1984–85 showed evidence that a pulse of water percolated through 13.4 m of alluvium and reached bedrock (Flint and Flint, 1995, p. 11).

Figure 8 presents a more detailed view of the temperature responses of stations 24.5 m and 35.2 m for the period January 1, 1998 to July 1, 1998 (note the different scales for the two stations). The 0.02°C temperature increase at station 24.5 m occurred over the period of March 22 to April 17, 1998 and may be partially due to the downward movement of warmer, shallower water. The presence of warmer shallow water is possible because the time lag of the annual temperature wave increases with depth; therefore, the shallow stations will have annual reversals of the normal temperature gradient. Figure 8 shows that on March 22, 1998 the temperature at station 24.5 m was about 19.38°C and rising, whereas figure 7 shows that during March 1998 the temperature at station 11.1 m was about 19.6°C. The temperature increase at station 24.5 m is discussed further in the section "Results from Borehole Pressure Monitoring." Figure 8 also shows a 0.04°C temperature decrease at station 35.2 m on April 17, 1998 followed by an unstable period with abrupt temperature increases and decreases that never dipped below the initial baseline temperature of about 19.6°C. During the unstable period, the temperatures at station 35.2 m spiked to as high as 19.67°C. These temperature spikes were associated with barometric pressure lows and are discussed further in the section "Results from Borehole Pressure

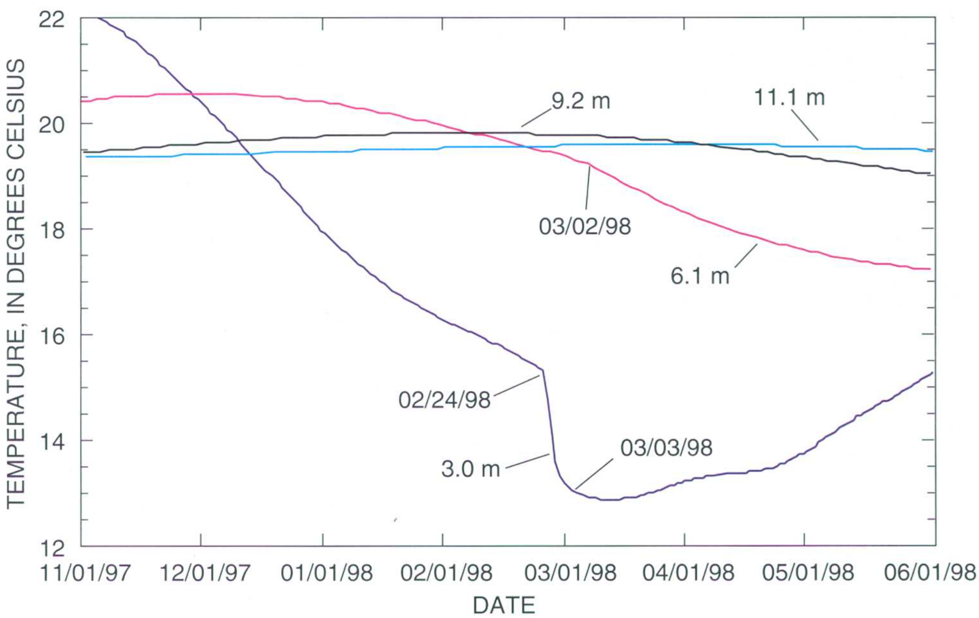


Figure 7. Temperatures at borehole UZ #4 stations 3.0 m, 6.1 m, 9.2 m, and 11.1 m for November 1, 1997, through June 1, 1998.

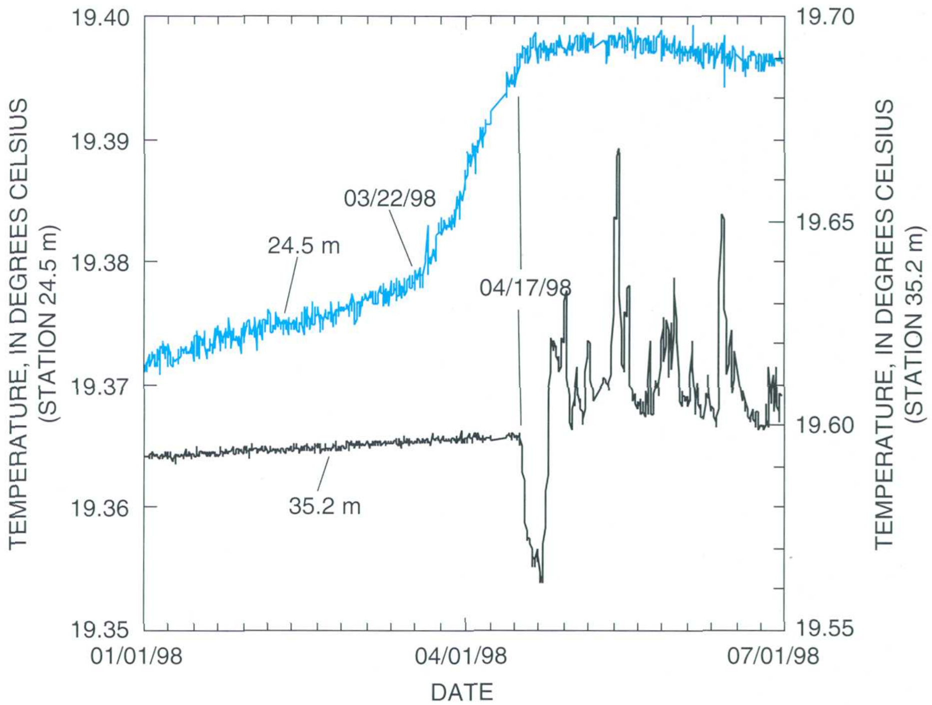


Figure 8. Temperatures at borehole UZ #4 stations 24.5 m and 35.2 m for January 1, 1998, through July 1, 1998.

Monitoring." Any causal relation between the station 24.5 m April 17, 1998 temperature stabilization and the station 35.2 m April 17, 1998 temperature decrease has not been determined.

Borehole UZ #5

Figure 9 presents the borehole UZ #5 temperature data for the period July 1, 1995 through July 1, 2000, for the five instrument stations located in the welded Tiva Canyon Tuff lower nonlithophysal zone. The data showed that the annual temperature wave was measurable at station 12.2 m. Figure 9 shows abrupt temperature disruptions at stations 3.0 m, 6.1 m, 9.2 m, and 12.2 m during February 1998. Figure 10 provides a more detailed view of the temperature responses at stations 3.0 m, 6.1 m, 9.2 m, 12.2 m and 25.5 m for the period February 1, 1998 to March 8, 1998 (note the different scales). Figure 10 shows that station 3.0 m had six abrupt temperature decreases during February 1998; station 6.1 m had five. The temperature decreases were interpreted to be the result of shallow, cooler water percolating down through the fractures of the Tiva Canyon Tuff lower nonlithophysal zone and were a direct result of the infiltration of water associated with the February 1998 El Niño precipitation. Figure 10 shows that station 9.2 m had three abrupt temperature increases and two abrupt temperature decreases and station 12.2 m had five abrupt temperature increases. The temperature increases and decreases were interpreted to be the result of the downward movement of water associated with the infiltration and percolation of the El Niño precipitation. The temperature decreases are the result of the downward movement of shallow, cooler water while the temperature increases are the result of the downward movement of shallow, warmer water. The existence of both shallow, cooler and shallow, warmer water is because the time lag of the annual temperature wave increases with depth; therefore, at shallow depths there are annual reversals of the normal temperature gradient. The temperature increases at stations 9.2 m and 12.2 m are due to the downward movement of shallow, warmer water associated with the annual reversal of the normal temperature gradient. Figure 10 shows a temperature decrease at station 25.5 m of about 0.007°C for the period February 18–28, 1998. Station 25.5 m is located below the reversal of the thermal gradient. The temperature decrease was interpreted to be the result of shallow, cooler water perco-

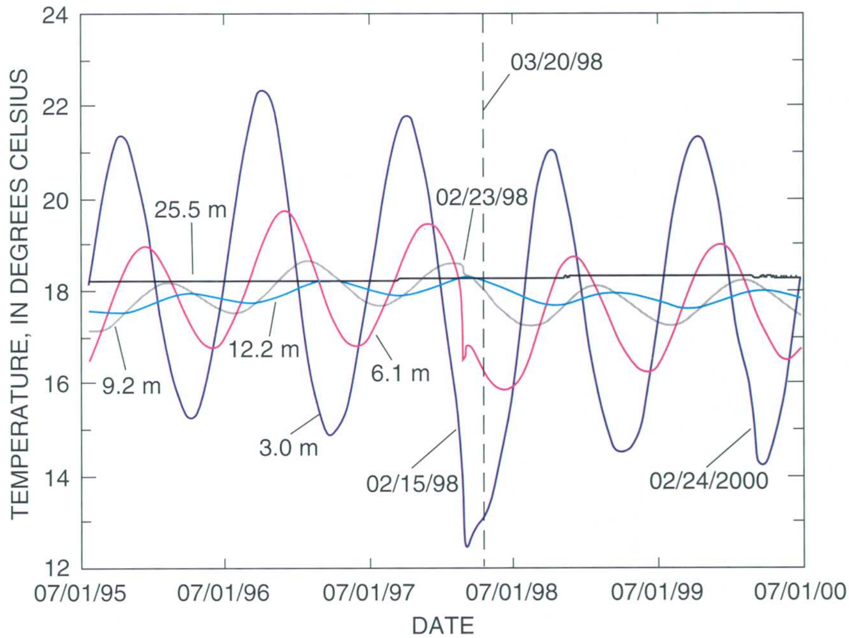
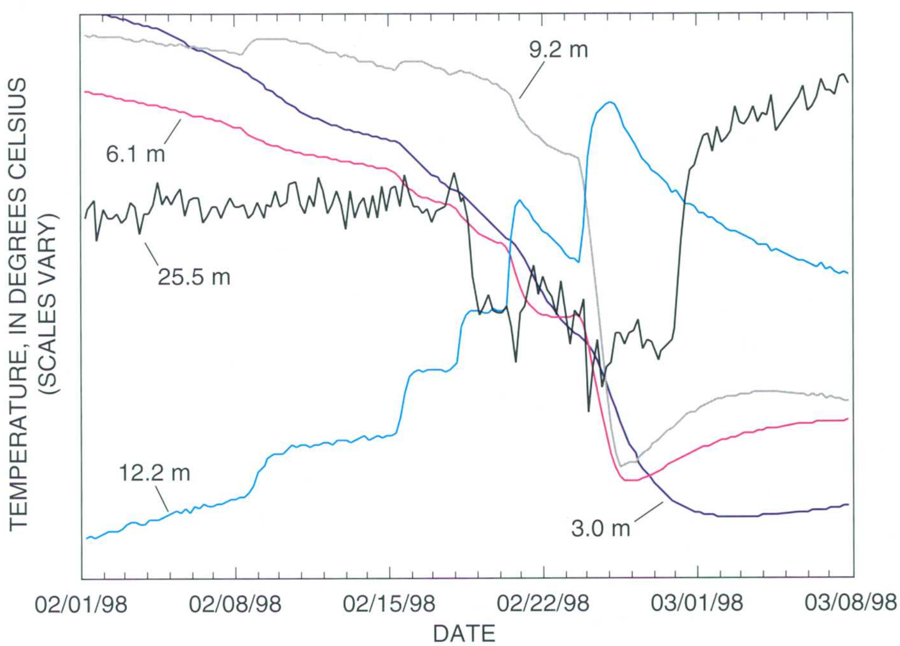


Figure 9. Temperatures at borehole UZ #5 stations 3.0 m, 6.1 m, 9.2 m, 12.2 m, and 25.5 m for July 1, 1995, through July 1, 2000.



EXPLANATION

Station	Temperature, in degrees Celsius	Full scale value in degrees Celsius
3.0 m	12.07–16.07	4.0
6.1 m	16.31–19.31	3.0
9.2 m	18.20–18.40	0.2
12.2 m	18.20–18.40	0.2
25.5 m	18.25–18.28	0.03

Figure 10. Temperatures at borehole UZ #5 stations 3.0 m, 6.1 m, 9.2 m, 12.2 m, and 25.5 m for February 1, 1998, through March 8, 1998.

lating down through the fractures of the Tiva Canyon Tuff lower nonlithophysal zone and was a direct result of the infiltration and percolation of precipitation associated with the February 1998 El Niño precipitation. Borehole UZ #5 station 34.0 m showed a very small (less than 0.001°C) temperature decrease on March 8, 1998, indicating that some water had percolated to the bottom of the Tiva Canyon Tuff vitric zone. Stations 39.7 m and 48.5 m, both located in the Yucca Mountain Tuff, had no temperature changes.

Figure 10 shows that the temperature responses measured at borehole UZ #5 are different than those measured at borehole UZ #4 (fig. 7). The temperature responses measured at the shallow stations in borehole UZ #5 are separated into numerous individual events that occurred throughout the precipitation period of February 1998. In contrast, the borehole UZ #4 temperature responses were single events. The difference is because the infiltration and percolation at borehole UZ #5 is dominated by fracture flow through the welded Tiva Canyon Tuff while the infiltration and percolation at borehole UZ #4 were buffered by the Pagany Wash alluvium. The borehole UZ #5 fracture flow resulted in higher flow velocities, less storage, and faster response times to individual precipitation events. The six distinct temperature decreases measured at borehole UZ #5 station 3.0 m probably represent six high-intensity rainstorms.

Comparison of the temperatures at the same or similar elevations in the upper 25 m of boreholes UZ #4 and UZ #5 for February and March 1998 showed that, on average, the temperatures at borehole UZ #5 were more than 1°C cooler. The cooler temperatures at borehole UZ #5 were because the Tiva Canyon Tuff lower nonlithophysal zone has a higher thermal conductivity than the Pagany Wash alluvium. Figure 9 shows that on March 20, 1998, the temperatures at borehole UZ #5 stations 3.0 m, 6.1 m, 9.2 m, 12.2 m, and 25.5 m were 13.2, 16.3, 18.0, 18.2, and 18.2° Celsius, respectively. Figure 8 shows that on March 20, 1998, the temperature at borehole UZ #4 station 24.5 m was 19.38°C. The cooler temperatures in borehole UZ #5 indicate that the March 22–April 17, 1998 temperature increase at borehole UZ #4 station 24.5 m could not have been due to lateral flow from the borehole UZ #5 hillside. The temperature gradients indicate that the March 22 to April 17, 1998 temperature increase at borehole UZ #4 station 24.5 m was the result of percolation through the alluvium of Pagany Wash. Comparison of the temperature response at borehole UZ #4 station 24.5 m to the temperature response at borehole UZ #5 station 25.5 m can provide some insight on the relative flux volumes. The higher flow velocities at borehole UZ #5 should result in larger temperature changes for a given percolation flux. The 0.02°C temperature disruption at borehole UZ #4 station 24.5 m compared to the smaller 0.007°C temperature disruption at borehole UZ #5 station 25.5 m indicates that, despite the rapid-flow velocities at borehole UZ #5, the percolation flux was larger at borehole UZ #4.

RESULTS FROM BOREHOLE PRESSURE MONITORING

Borehole UZ #4

Figure 11 presents the pressure data from borehole UZ #4 stations 11.1 m and 24.5 m, the pressure differences between the two stations, and the temperature at station 24.5 m for the period February 11, 1998 to May 6, 1998. Because the stations are at different altitudes, the pressure difference is normally 15.0 to 20.0 Pa. Annual variations at both stations are normally less than 0.9 kPa. Figure 11 shows that for the period March 22, 1998 to April 2, 1998 (11 days), the pressure difference between the two stations increased to more than 2.0 kPa. During this period, the pressure at station 11.1 m closely followed the ground-surface barometric pressure (not shown), which was decreasing, while the pressure at station 24.5 m increased. The pressure differences indicate that for the 11-day period station 24.5 m was pneumatically isolated from station 11.1 m. One possible interpretation is that the wetting front had moved below station 11.1 m, and the pressure increase at station 24.5 m may have been due to the compression of air ahead of the downward-moving wetting front. This interpretation assumes that the permeability of the tuff at station 24.5 m (Tpcpv) is relatively small and that the area coverage of the wetting front was large enough to minimize the effect of any constant-head lateral flow boundaries. Figure 11 also shows the temperature data from station 24.5 m previously presented in figure 8. The temperature at station 24.5 m showed an abrupt increase on or near March 22, 1998 and continued to increase until April 17, 1998; ultimately the

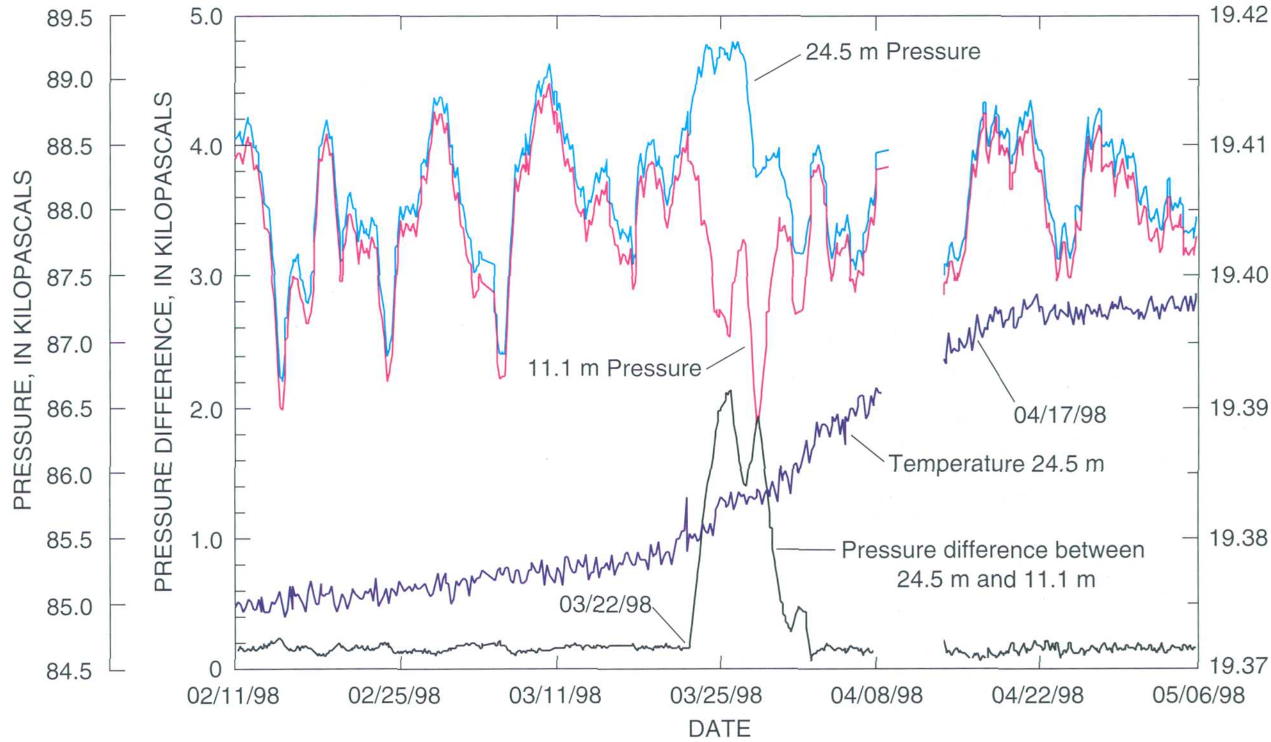


Figure 11. Pressures at borehole UZ #4 stations 11.1 m, and 24.5 m, the pressure differences between stations 11.1 m and 24.5 m, and the temperatures at station 24.5 m for February 11, 1998, through May 6, 1998.

temperature restabilized after a total increase of about 0.02°C. The timing of the station 24.5 m pressure and temperature increases indicated that the initial temperature increase might have been due to the heat of compression or the heat of condensation associated with compression of air ahead of the wetting front. The continued temperature increase at station 24.5 m, after the pressure had dissipated, indicated that the temperature increase was due to the downward movement of warmer, shallow water. As discussed earlier, the reversal of the temperature gradient is caused by the time lag of the annual temperature wave; on March 22, 1998 the temperatures at stations 11.1 m and 24.5 m were about 19.6°C and about 19.4°C, respectively. It is possible that the heat of compression, heat of condensation, and the downward movement of warmer, shallower water all contributed to the station 24.5 m temperature increase.

Figure 12 presents the ground-surface barometric pressure, the pressure at station 35.2 m, and the temperature at station 35.2 m for the period March 2, 1998 through September 28, 1998. As discussed earlier, beginning on April 17, 1998 station 35.2 m had a 0.04°C temperature decrease followed by an unstable period (April 26 to July 6, 1998) with abrupt temperature increases and decreases that never dipped below the initial baseline temperature of 19.6°C. Figure 8 showed that on April 17, 1998 the temperature at station 24.5 m was about 19.4°C and the temperature at station 35.2 m was about 19.6°C. The temperature difference between the stations and the abruptness of the station 35.2 m temperature fluctuations indicated that the April 17, 1998 temperature decrease at station 35.2 m was due to the downward movement of cooler air. Figure 12 also shows a correlation between barometric fluctuations and the April 26 through July 6, 1998 unstable-period temperature fluctuations. The unstable-period temperature increases may have been the result of deeper, warmer air moving upward in response to barometric low pressure (barometric pumping effect). One possible explanation is that air moving ahead of the wetting front passed through station 35.2 m and opened air-flow pathways below the station. Above station 35.2 m, the downward-moving wetting front would have filled most or all of the pore spaces with water. The open air-

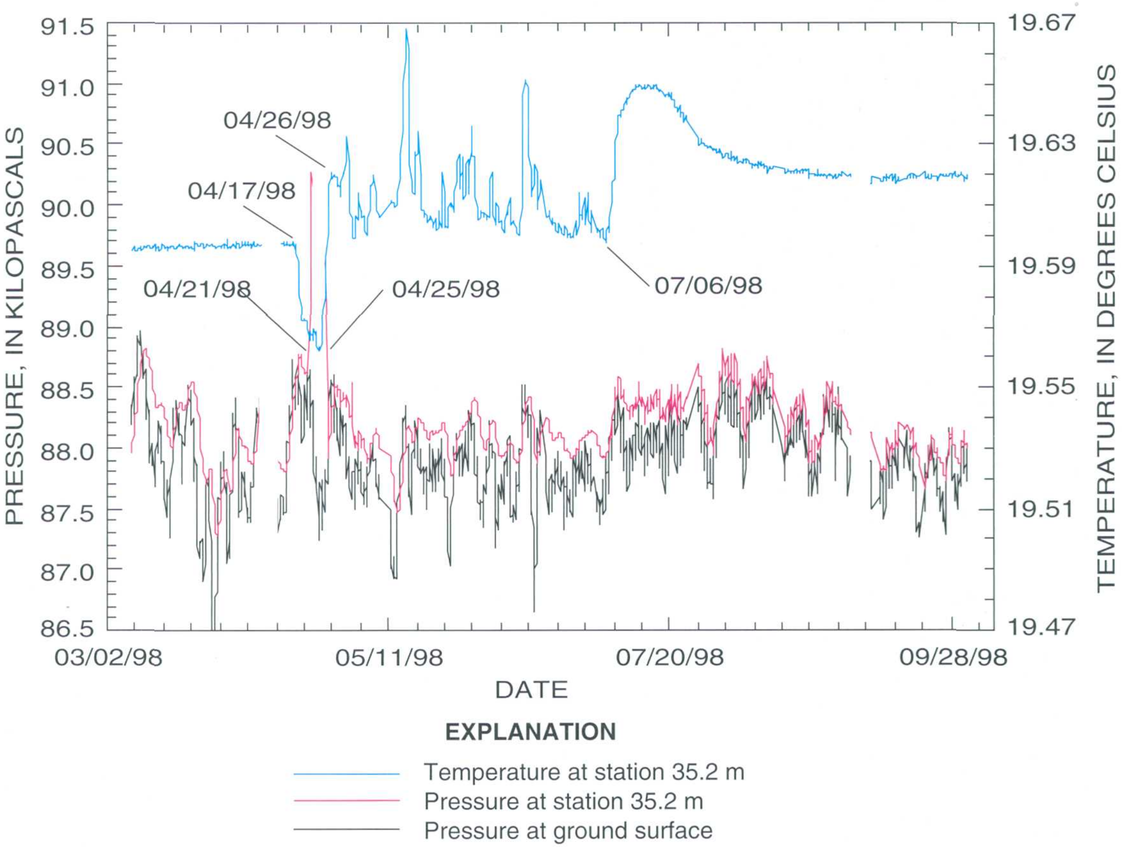


Figure 12. Temperatures and pressures at borehole UZ #4 station 35.2 m, and the surface barometric pressures for March 2, 1998, through September 28, 1998.

flow pathways below the station would have allowed deeper, warmer air to move up and laterally in response to barometric lows, whereas the water-filled pore spaces above the station would have prevented the downward movement of shallow, cooler air. Figure 12 shows that the pressure measurements at station 35.2 m for the period April 20 to July 6, 1998 were dampened. The dampened pressure signals support the concept of increased moisture above the station. The post-July 6, 1998 equilibration period was very smooth compared to the abrupt temperature responses of the April 26 through July 6, 1998 unstable period. This smooth transition indicated that the wetting front had reached the instrument station shortly after July 6, 1998. The wetting front filled in the open pore spaces, isolated the station from the deeper, warmer air, and stabilized the station temperature.

Station 35.2 m did not have a pressure increase associated with the compression of air ahead of the wetting front. The absence of a pressure increase indicated that the permeability of the Yucca Mountain Tuff at station 35.2 m was larger than the permeability of the Tiva Canyon Tuff vitric zone at station 24.5 m. Figure 12 shows that the pressure transducer located at station 35.2 m malfunctioned from April 20 to 24, 1998 (gap in data). Experience gained from the SBMP indicated that the 4-day malfunction was probably due to liquid water in the transducer electronics. The water may have been from condensation associated with the April 17, 1998 temperature decrease.

Figure 13 presents the July 1, 1995 through July 1, 2000 pressure differences between stations 24.5 m and 35.2 m and between stations 35.2 m and 45.0 m, and the temperature at station 35.2 m. Figure 13 shows that the pressure differences between stations 24.5 m and 35.2 m were initially in the 1.2 to 3.8 kPa range and that on or about July 1, 1998 the pressure differences decreased to the 0.2 to 0.8 kPa range. The decrease in the pressure differences indicated an improved pneumatic connection and(or) a decrease in the barometric time lag between the stations. One

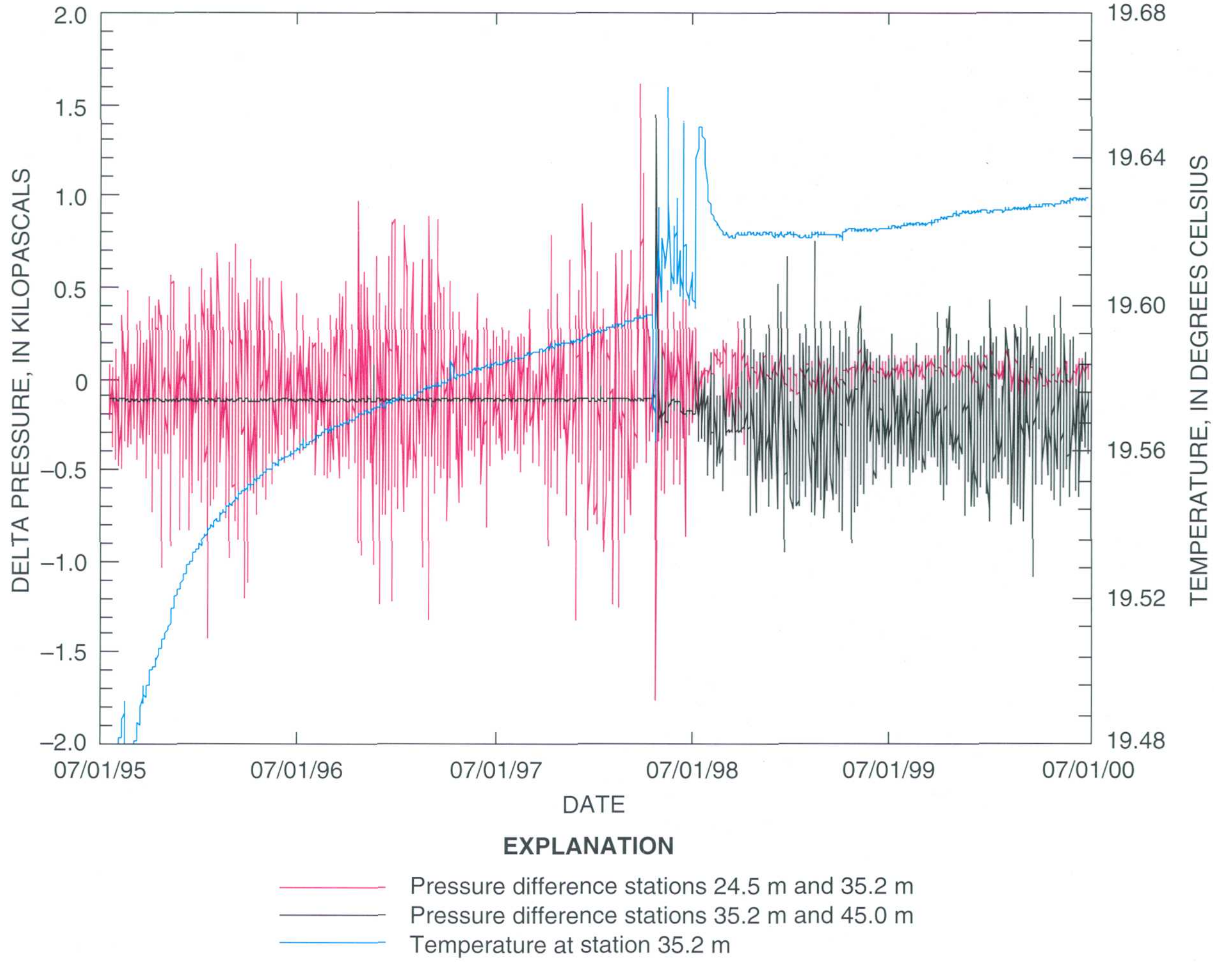


Figure 13. Pressure differences between borehole UZ #4 stations 24.5 m and 35.2 m, and between stations 35.2 m and 45.0 m, and the temperatures at station 35.2 m for July 1, 1995, through July 1, 2000.

possible explanation is that water from the wetting front filled in some of the air-filled pores above station 24.5 m, resulting in a smaller time lag between stations. Figure 13 also shows that as of July 1, 2000 the pressure differences had not returned to their pre-July 1998 levels.

Figure 13 also shows that the pressure differences between stations 35.2 m and 45.0 m were initially very small (less than 0.1 kPa) and that on or about July 1, 1998 the pressure difference between stations 35.2 m and 45.0 m increased. The temporary increase in the pressure differences between stations 35.2 m and 45.0 m in late April and early May 1998 was due to the April 20–24, 1998 transducer malfunction and equilibration. The July 1, 1998 increase in the pressure differences indicated that station 35.2 m had become pneumatically isolated from station 45.0 m. One possible interpretation is that the wetting front had moved below station 35.2 m, deeper into the Yucca Mountain Tuff, and was now located between station 35.2 m and station 45.0 m. This interpretation is supported by the station 35.2 m temperature data discussed earlier. Figures 12 and 13 show that on or about July 6, 1998 the temperature at station 35.2 m began to stabilize; this is also consistent with the movement of the wetting front below station 35.2 m. Figure 13 shows that as of July 1, 2000 the pressure differences between stations 35.2 m and 45.0 m had not returned to their pre-July 1, 1998 values. The continued presence of the large pressure differences indicated that the Yucca Mountain Tuff may have retarded the downward movement of the wetting front.

Borehole UZ #5

Figure 14 shows the pressure and temperature at borehole UZ #5 station 25.5 m for January 1, 1998 through June 1, 1998 (the temperature data are the same as presented in figures 9 and 10). The pressure monitoring identified two abrupt pressure increases during the period February 18 to 28, 1998. Figure 14 shows that the average barometric pressure at station 25.5 m was about 88.0 kPa and that the abrupt pressure increases reached values of 98.3 and 103.0 kPa. Figure 14 also shows that the pressure increases and the temperature decrease occurred at the same time. Recall that a similar, although smaller, pressure response was measured in borehole UZ #4 station 24.5 m (fig. 11). Here again the pressure buildup is at the contact with the Tiva Canyon Tuff vitric zone. As discussed earlier, one possible interpretation is that the pressure increase at station 25.5 m may have been due to the compression of air ahead of the downward-moving wetting front. This interpretation assumes that the permeability of the Tiva Canyon Tuff vitric zone is relatively small and that the area coverage of the wetting front was large enough to minimize the effect of any constant-head lateral flow boundaries.

RESULTS FROM BOREHOLE WATER POTENTIAL MONITORING

Borehole UZ #4

Figure 15 presents the water potential values measured at borehole UZ #4 stations 11.1 m, 35.2 m, and 45.0 m for January 1, 1998 through May 1, 1998; the thermocouple psychrometers at station 24.5 m had failed several years earlier. The water potentials ranged from –2 to –1 bars and were generally stable with the exception of station 35.2 m. Figure 15 shows

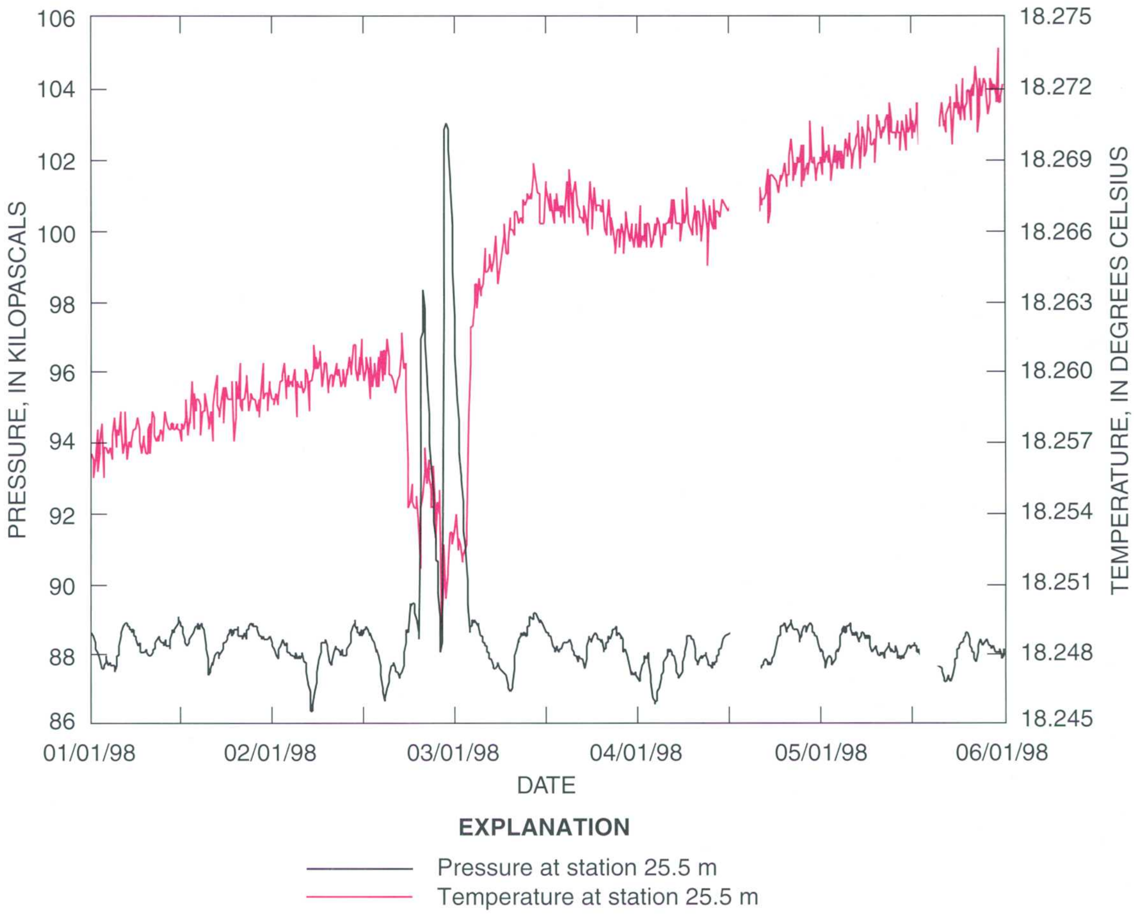


Figure 14. Pressure and temperature at borehole UZ #5 station 25.5 m for January 1, 1998, through June 1, 1998.

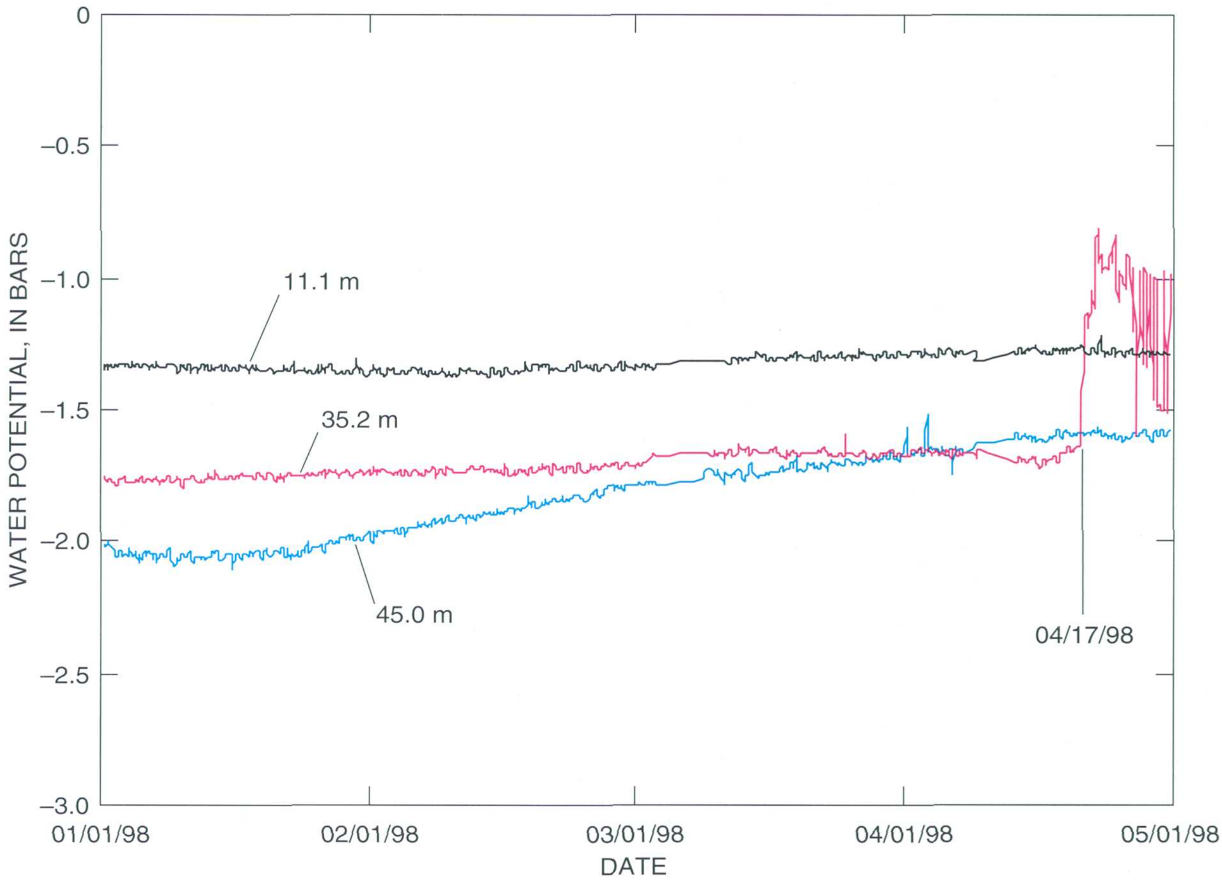


Figure 15. Water potentials at borehole UZ #4 stations 11.1 m, 35.2 m, and 45.0 m for January 1, 1998, through May 1, 1998.

that on or about April 17, 1998 the thermocouple psychrometer at station 35.2 m failed. The failure is indicative of liquid water in the unit. April 17, 1998 is the same date that the thermistor at station 35.2 m measured an abrupt temperature decrease of 0.02°C (fig. 8). The timing of the thermocouple psychrometer failure supports the earlier interpretation that the temperature response was due to the wetting front reaching station 35.2 m. The failure of the thermocouple psychrometer probably was not due directly to the increased moisture of the wetting front but to the associated sudden drop in temperature shown in figure 8. A sudden drop in temperature will result in water condensing on the thermocouple and not evaporating, which leads to failure of the unit. The absence of a response at station 45.0 m supports the theory that the wetting front had not reached station 45.0 m and that the Yucca Mountain Tuff may have retarded the downward percolation of the wetting front. As of March 1, 2001 the station 45.0 m thermocouple psychrometer was still operational. The absence of a response at station 11.1 m is probably due to the limited sensitivity of the thermocouple psychrometers. Neutron logging in a borehole located in the channel alluvium at Yucca Mountain indicated that as the wetting front percolated through the alluvium the change in the moisture content at 10- to 12-m depth will be in the 2 to 5 percent range (Flint and Flint, 1995, p. 13). The characteristic curves for gravel and sand (Stephens, 1996, p. 9) show that for a water content of 10 to 30 percent, a 2 to 5 percent change in the moisture content corresponds to a 0.01–0.02 bar change in the water potential; less than the 0.05 bar sensitivity of the thermocouple psychrometers.

Borehole UZ #5

Figure 16 presents the water potential values measured at borehole UZ #5 stations 25.5 m, 34.0 m,

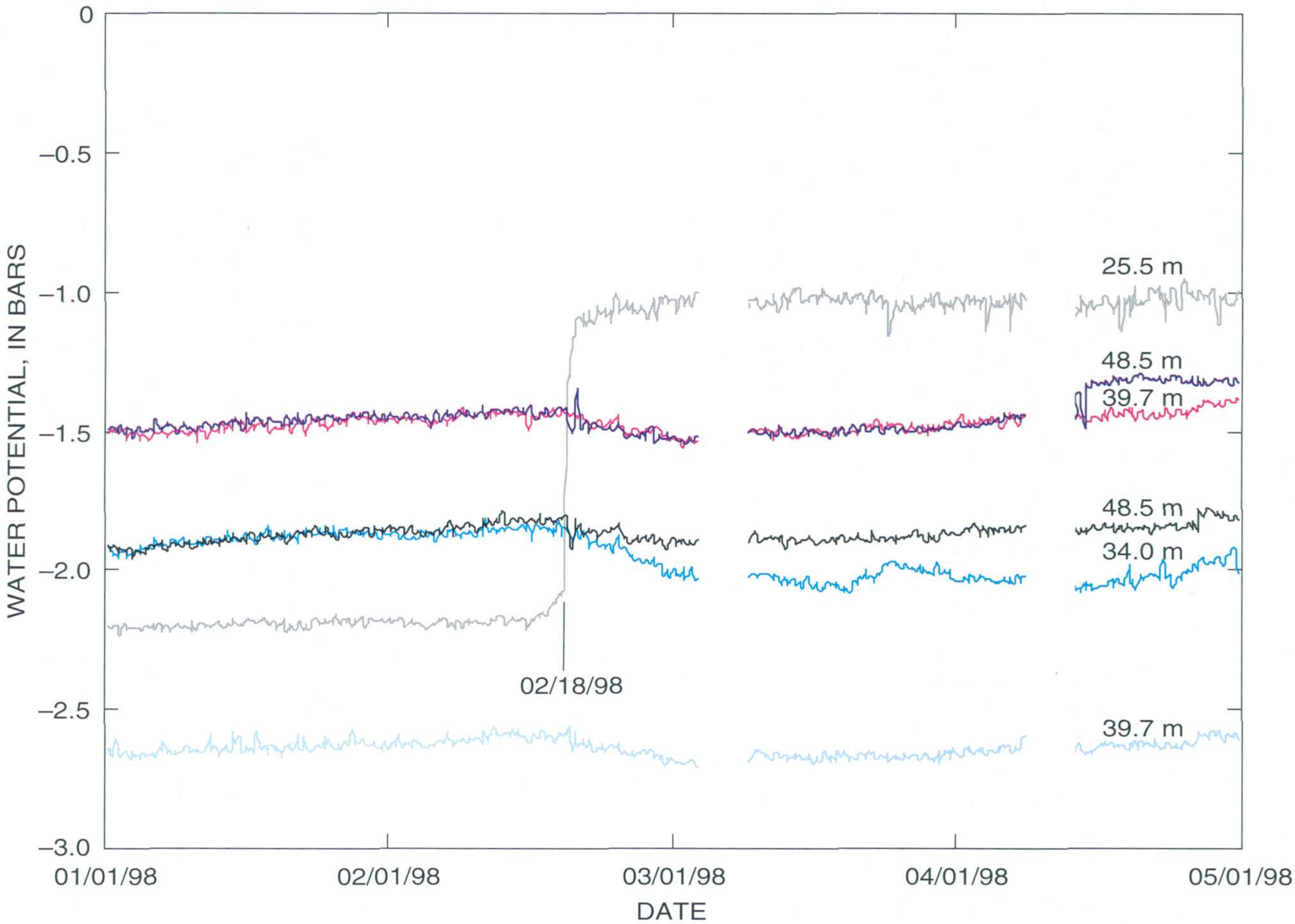


Figure 16. Water potentials at borehole UZ #5 stations 25.5 m, 34.0 m, 39.7 m, and 48.5 m for January 1, 1998, through May 1, 1998.

39.7 m, and 48.5 m for January 1, 1998 through May 1, 1998. Stations 39.7 m and 48.5 m each had two operational thermocouple psychrometers. The water potentials ranged from –3 to –1 bars. Figure 16 shows that station 25.5 m had a sudden increase in water potential on or about February 18, 1998. Recall that February 18, 1998 is the date the sensors at station 25.5 m measured an abrupt temperature decrease of 0.007°C and the date of the start of an abrupt pressure increase (see fig. 14). As with borehole UZ #4 station 35.2 m, the reaction of the thermocouple psychrometer was probably due to the temperature decrease associated with the wetting front. The 0.007°C temperature decrease at borehole UZ #5 station 25.5 m was smaller than the 0.02°C temperature decrease measured at borehole UZ #4 station 24.5 m. The smaller temperature decrease would mean a smaller increase in the relative humidity and may explain why the borehole UZ #5 thermocouple psychrometer recovered and continued to function. Figure 16 also shows that after February 18, 1998 all the other thermocouple psychrometers showed small decreases in water potential. A causal relation with the February 18, 1998 temperature and pressure disruptions at station 25.5 m is unclear but may be associated with the pressure increase and(or) the infiltration of water in to the Tiva Canyon Tuff vitric zone. A change in the Tiva Canyon Tuff vitric zone air permeability could cause a change in the air movement at borehole UZ #5 and result in a new equilibration of the thermocouple psychrometers.

INFILTRATION ESTIMATES USING AN ANALYTICAL METHOD

Estimates of infiltration and percolation flux through the alluvium were made using the temperature disruptions and the vertical distance between the sensors. The velocity of the infiltrating water was estimated by using equation 1:

$$V = D/\Delta T \qquad (1)$$

where

V = velocity, in meters per second;
D = distance between stations, in meters; and
ΔT = traveltime, in seconds.

Because the data from a single borehole are one dimensional, the flow is assumed to be vertical, gravity driven, and the hydraulic gradient is unity. Equation 2 used the velocity estimate from equation 1 to estimate a hydraulic conductivity assuming a unit gradient:

$$K = V \times \phi \qquad (2)$$

where

K = hydraulic conductivity, in meters per second; and
ϕ = porosity, in cubic meters per cubic meter.

The vertical infiltration flux was estimated by using equation 3:
where

$$F = K \times T \qquad (3)$$

F = infiltration flux, in meters; and
T = duration of the event, in seconds.

The input parameters for equations 1, 2, and 3 were derived from figure 7. The temperature decreases at borehole UZ #4 stations 3.0 m and 6.1 m were interpreted to indicate the arrival of the wetting front. The traveltime (ΔT) between station 3.0 m and station 6.1 m was estimated to be 155.1 hours (5.58×10^5 seconds). The distance between the stations was 3.1 m. The porosity of the alluvium was assumed to be 0.31 (Guertal and others, 1994). The time required for all the water to pass by station 3.0 m was estimated to be 7.6 days (6.57×10^5 seconds, see fig. 7). This estimate is the time elapsed between the arrival of the wetting front at station 3.0 m (abrupt temperature decrease on February 24, 1998) and the start of the recovery period (March 3, 1998). The duration was estimated from station 3.0 m because it had the largest thermal disruption and, therefore, provided the best opportunity to identify the initial temperature decrease and the start of the recovery period (fig. 7). Using the input parameters from stations 3.0 m and 6.1 m, the downward percolation flux between station 3.0 m and station 6.1 m for the February 1998 El Niño rainstorm was estimated to be 1,130 mm. The input parameters for equations 1, 2, and 3, and the estimated percolation flux are presented in table 1.

INFILTRATION ESTIMATES USING A NUMERICAL METHOD

The USGS computer program VS2DH (Healy and Ronan, 1996) and its graphical user interface (Hsieh and others, 2000) were used to estimate the infiltration flux and to model the observed downhole temperatures in borehole UZ #4. A two-dimensional model was developed to represent the conceptual fluid flow and heat transfer in Pagany Wash. The model simulations calculated fluid flow in the unsaturated alluvium attributed to surface infiltration, subsurface temperature as a result of surface temperature variation, heat conduction of unsaturated alluvium, and heat convection induced by percolation.

Table 1. Input parameters for equations 1, 2, and 3 and percolation flux estimate using borehole UZ #4 stations 3.0 m and 6.1 m

[m, meters; s, seconds; m^3, cubic meters; mm, millimeters]

Upper station (m)	Lower station (m)	Distance (m)	Traveltime (s)	Velocity (m/s)	Porosity (m^3/m^3)	Hydraulic conductivity (m/s)	Duration (s)	Percolation flux (mm)
3.0	6.1	3.1	5.58×10^5	5.56×10^{-6}	0.31	1.72×10^{-6}	6.57×10^5	1,130

Previous studies on soil temperature variation (Wierenga and others, 1970; Osterkamp and others, 1995; Silliman and others, 1995; Constantz and Thomas, 1997) identified several distinct features: (1) convective heat transfer is required to disrupt the annual sinusoidal wave at depths greater than 1 m; (2) convective heat transfer will generally disturb the subsurface sinusoidal temperature waves, depending on the surface infiltration rate and the temperature of the infiltrated water; and (3) convective heat signals can travel much faster than conductive signals, depending on the permeability, porosity, and thermal conductivity of soils. The modeling strategy was to use these features to constrain the subsurface temperature predictions and to identify the controlling factors.

The VS2DH model was based on an idealized cross section of Pagany Wash. The model represented the alluvium of Pagany Wash as a grid with dimensions of 50-m width (x) and 12.1-m height (z); cell width was 1 m and cell height ranged from 0.2 to 2.1 m. The model assumed an active channel width of 5 m. The upper boundary was defined as a specified vertical flux boundary, the sides as no-flow boundaries, and the lower boundary as a seepage face. The saturated hydraulic conductivity of the alluvium was based on an infiltration test conducted at the UZN #7 located next to borehole UZ #4. The infiltration test was conducted during September 23 to 26, 1994. A volume of 61.3 m^3 of water was ponded over an area of about 5.0 m^2 during a 62-hour period giving a hydraulic conductivity of 4.7 m/d. The 4.7 m/d hydraulic conductivity value is very close to the 4.3 m/d hydraulic conductivity value derived by Hofmann and others (2000) from an infiltration test conducted at unsaturated zone neutron borehole #14 (UZN #14). Neutron borehole UZN #14 is located at the mouth of Pagany Wash on a terrace about 1 m above the active channel. Based on these two tests, the initial saturated hydraulic conductivity value of the alluvium was set at 5.0 m/d. The model assumed that the individual model layers were isotropic and that the specific storage was zero. The model porosity values (ϕ) were based on an average porosity value of 0.31 from laboratory analysis of terrace alluvium at unsaturated zone neutron borehole #85 (UZN #85) (Guertal and others, 1994). The residual moisture contents (RMC) were derived from the September 23, 1994, UZN #7 neutron log; the log preceded the September 23 to 26, 1994 infiltration test and represents a baseline dry period for the alluvium of Pagany Wash. The alluvium alpha value of 10.0 m^{-1} was also based on the laboratory work by Guertal and others (1994). Their laboratory measurements showed an average value of 8.9 m^{-1} for the borehole UZN #85 terrace alluvium. Laboratory estimates of beta ranged from 1.17 to 1.33 with an average of 1.22 (Guertal and others, 1994). These beta values seemed to be on the low side compared to estimates presented by Carsel and Parrish (1988) for sand (2.68) and a sandy loam (1.89) so the initial beta value for the alluvium was set at 2.0. Longitudinal and transverse dispersivity (α_L, α_T) were assumed to be relatively unimportant at this small scale and were set at 0.5 for computational efficiency. The initial thermal conductivity and heat capacity values for water and rock were from Hillel (1982, p. 161–162).

Neutron logs conducted during the September 1994 UZN #7 infiltration test identified a low-permeability zone at a depth of about 5.6 m. The neutron logs indicated that the wetting front reached 5.6 m in about 6 hours, yet required an additional 6 days to reach 10 m. To account for this change in velocity, a low permeability zone extending from 5.0 to 5.6 m was assumed in the model. The model used the VS2DH default parameters of a silt to represent the saturated hydraulic conductivity, alpha, and beta values of the low-permeability zone.

The first phase of the modeling effort was to create a baseline model and to calibrate the model to the measured annual temperature wave for the period July 30, 1996 to February 1, 1998. The baseline model could then be used to simulate the expected temperatures for the period February 1, 1998 to December 31, 1999 without the El Niño infiltration. The baseline model assumed no infiltration; therefore, the subsurface temperature variation was dominated by heat conduction. The temperatures at the model upper boundary were based on the monthly average temperatures for the period July 30, 1996 to February 1, 1998 as measured by a thermistor located in the buried PVC pipe that connected borehole UZ #4 to the data acquisition trailer. Because the baseline model assumed that all the heat flow was conductive, the downhole temperatures were dominated by the thermal conductivity values. The thermal conductivity parameters (K_{Tr} and K_{Ts}) for the alluvium were adjusted until the model prediction matched the measured temperatures of the annual temperature wave for the period July 30, 1996 to February 1, 1998.

After the thermal properties were selected, the model was run to December 31, 1999 to provide a baseline model without the El Niño infiltration. Once the baseline model was completed, variable quantities of infiltration water were added to the alluvium to determine the water flux required to match the measured temperature responses. The hydraulic conductivity values were then adjusted to match the measured arrival times of the wetting front. Lastly, the alpha and beta values were adjusted to match the UZN #7 March 11, 1998 neutron log RMC. The simulation included a 20-day prewetting period of 10-mm/d infiltration across the upper boundary to represent the February 2–22, 1998 El Niño rainfall. The temperature of the infiltrating water was assumed to be 5°C, and the infiltration event was assumed to have occurred over a 24-hour period on February 23, 1998. The model parameters that resulted in the best match to the measured data are presented in table 2.

Figure 17 presents the measured and simulated temperatures at station 3.0 m for a theoretical infiltration flux of 1,000 mm at 5°C on February 23, 1998. Figure 17 shows that the model provides a good match to both the pre-El Niño conduction-dominated period and the convection-dominated infiltration period. The conceptual model assumes that as the infiltration flux increases, the temperature disruption will increase because convective heat transfer becomes more dominant. The measured and simulated temperature decreases for borehole UZ #4 stations 3.0 m, 6.1 m, 9.2 m, and 11.2 m using infiltration fluxes of 500, 1,000, 1,500, and 2,000 mm are presented in table 3. The temperature decreases are all relative to the baseline model that assumed no El Niño infiltration.

Table 3 shows that different stations best match different infiltration fluxes. The simulated infiltration fluxes that best match the measured temperature disruptions at the four station depths were: station 3.0 m, 1,000 mm; station 6.1 m, 2,000 mm; station 9.2 m, 2,000 mm; and station 11.1 m, 1,500 mm. The model simulations indicated that the temperature decreases were due to water percolation and the associated convective heat transfer. The model simulations indicated that the February 23, 1998 infiltration flux in Pagany Wash at borehole UZ #4 was between 1,000 and 2,000 mm.

Table 2. Summary of hydrologic and thermal properties used in the VS2DH numerical simulations of infiltration and flow in the Pagany Wash alluvium

[K_{hh}, saturated hydraulic conductivity; K_{zz}/K_{hh}, ratio of vertical to horizontal hydraulic conductivity; S_s, specific storage; ϕ, porosity; θ_r, residual moisture content; Alpha, van Genuchten parameter for characteristic pore size; Beta, van Genuchten parameter for pore-size distribution; α_L, longitudinal dispersivity; α_T, transverse dispersivity; K_{Tr}, thermal conductivity at residual moisture content; ; K_{Ts}, thermal conductivity at saturation; C_s, heat capacity of alluvium; C_w, heat capacity of water; m, meter; m/d, meter per day; J/d/m^3 °C, joules per day per cubic meter degree Celsius; J/m^3 °C, joules per cubic meter degree Celsius]

Depth (m)	Geologic unit	K_{hh} (m/d)	K_{zz}/K_{hh}	S_s	ϕ	θ_r	Alpha (m^{-1})	Beta	α_L (m)
0 – 2.0	Upper alluvium	5.0	1.0	0.0	0.31	0.05	10.0	1.5	0.5
2.0–5.0	Middle alluvium	5.0	1.0	0.0	0.31	0.10	10.0	1.5	0.5
5.0–5.6	Low-permeability zone	0.005	1.0	0.0	0.31	0.10	1.6	1.37	0.5
5.6–12.1	Lower alluvium	20.0	1.0	0.0	0.31	0.13	10.0	2.5	0.5

Depth (m)	Geologic unit	α_T (m)	K_{Tr} (J/d/m^3 °C)	K_{Ts} (J/d/m^3 °C)	C_s (J/m^3 °C)	C_w (J/d/m^3 °C)
0 – 2.0	Upper alluvium	0.5	3.0×10^4	1.4×10^5	2.0×10^6	4.2×10^6
2.0–5.0	Middle alluvium	0.5	3.0×10^4	1.4×10^5	2.0×10^6	4.2×10^6
5.0–5.6	Low-permeability zone	0.5	3.0×10^4	1.4×10^5	2.0×10^6	4.2×10^6
5.6–12.1	Lower alluvium	0.5	3.0×10^4	1.4×10^5	2.0×10^6	4.2×10^6

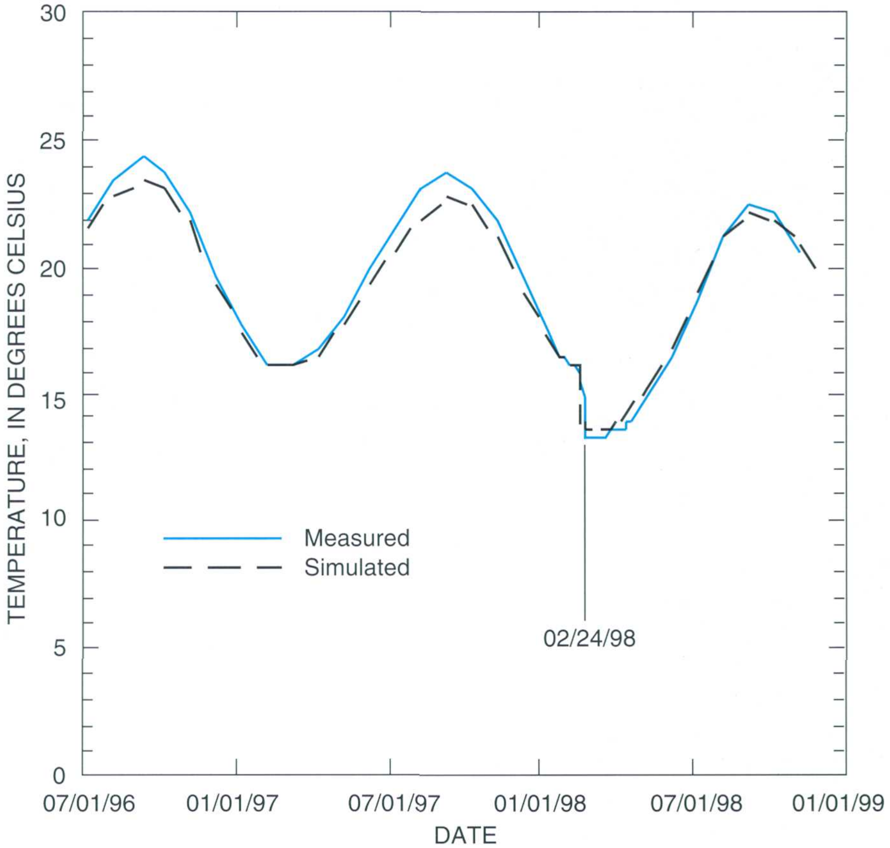


Figure 17. Temperatures measured at borehole UZ#4 station 3.0 m and the numerical model temperature simulations for station 3.0 m for the period July 1, 1996 through January 1, 1999, assuming a February 23, 1998 infiltration flux of 1,000 millimeters at 5 degrees Celsius.

Figure 18 presents the measured borehole UZN #7 neutron log moisture contents for September 23, 1994 (baseline) and March 11, 1998. Figure 18 also shows the simulated moisture contents for February 1, 1998 (baseline) and March 11, 1998 assuming infiltration fluxes of 1,000, 1,500, and 2,000 mm. Overall, the model does a reasonable job of replicating the measured moisture contents. The simulated moisture contents tend to be slightly higher than the measured moisture contents, but the relative change in moisture contents is a good match. Figure 18 also shows that the simulated moisture

Table 3. Measured and simulated temperature decreases in borehole UZ #4 for 500-, 1,000-, 1,500-, and 2,000-millimeter infiltration fluxes

[m, meters; °C, degrees Celsius; mm, millimeters]

Station depth (m)	Measured (°C)	Simulated 500-mm Infiltration	Simulated 1,000-mm infiltration	Simulated 1,500-mm infiltration	Simulated 2,000-mm infiltration
3.0	2.6	1.0	2.5	3.9	5.4
6.1	1.2	0.1	0.50	0.80	1.2
9.2	0.55	0.0	0.30	0.45	0.55
11.1	0.21	0.0	0.16	0.25	0.36

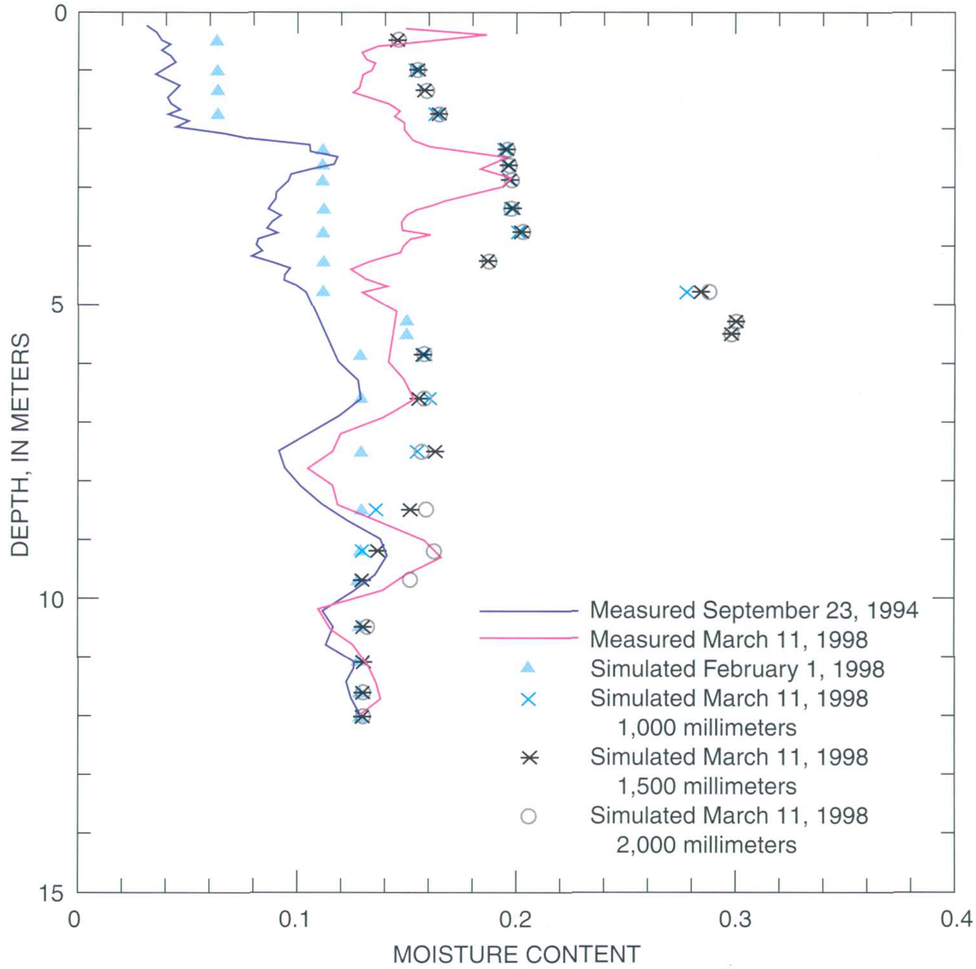


Figure 18. Moisture content measured in borehole UZN #7 on September 23, 1994, and March 11, 1998, and the numerical model predicted moisture content for February 1, 1998, and March 11, 1998, for 1,000-, 1,500-, and 2,000-millimeter infiltration fluxes.

contents are not very sensitive to the different infiltration fluxes. The elevated moisture content value of 0.3 is located just above the low-permeability zone (5.0–5.6 m). The elevated value is because the model simulated perched water at the contact. The measured data do not indicate perched water at this contact.

It is possible that winter infiltration might be cooler than the 5.0°C water temperature used in the model. To assess the potential effect of cooler water, a sensitivity simulation was run using 1,000 mm of infiltration at 2.0°C. The sensitivity simulation indicated that the temperature decrease at station 3.0 m would be 3.0°C compared to the 2.5°C temperature decrease shown in table 3. The sensitivity simulation does indicate that cooler water temperatures could indicate smaller infiltration fluxes, but the simulation shows that the sensitivity of the model to small changes in the water temperature is relatively small.

The simulations indicated that the measured temperature decreases were due to convective heat transfer associated with an infiltration flux of between 1,000 to 2,000 mm of water. Both the magnitude of the temperature decreases and the arrival times support the convective heat-transfer hypothesis. When comparing the measured and simulated values, it is important to realize that the shallow stations have less uncertainty because they are closer to the surface boundary and therefore are more sensitive to convective heat transfer. The deeper stations have increased uncertainty because the heat conduction time is proportional to the power of the depth; therefore, deeper stations require longer boundary variable time-series data to constrain the model.

SUMMARY

The Yucca Mountain Project (YMP) is a scientific study by the U.S. Department of Energy (DOE) to evaluate the potential for geologic disposal of high-level radioactive waste in an unsaturated-zone desert environment. The potential repository site at Yucca Mountain is about 130 km northwest of Las Vegas, Nev. As part of the study, the Area–25, Unsaturated Zone, Underground Exploratory boreholes #4 and #5 (UZ #4 and UZ #5) were instrumented with thermistors, pressure transducers, and thermocouple psychrometers. The goal was to gain a better understanding of the distribution and transfer of heat, pressure, and moisture in the unsaturated zone. Borehole UZ #4 is located in the alluvial deposits of Pagany Wash, a stream-carved, dry channel northeast of Yucca Mountain and the potential repository site. Borehole UZ #5 is located about 37 m south of borehole UZ #4 on a hillside 3.9 m above Pagany Wash.

The borehole UZ #4 temperature data indicated that the annual temperature wave was measurable to a depth of 11.1 m. Abrupt temperature decreases were measured at stations located in the alluvium of Pagany Wash at 3.0, and 6.1 m below land surface. Depressions of the annual temperature wave were measured at stations located in the alluvium of Pagany Wash at 9.2, and 11.1 m below land surface. Temperature disruptions also were measured at stations located 24.5 and 35.2 m below land surface in the Tiva Canyon Tuff vitric zone and the Yucca Mountain Tuff. The temperature disruptions were interpreted to be the result of infiltration and subsequent percolation associated with the February 1998 El Niño precipitation.

The borehole UZ #5 temperature data indicated that the annual temperature wave was measurable to a depth of 12.2 m. Abrupt temperature disruptions were measured at stations located in the Tiva Canyon Tuff lower nonlithophysal zone at depths of 3.0, 6.1, 9.2, and 12.2 m below land surface. The temperature disruptions were interpreted to be the result of infiltration and subsequent percolation associated with the February 1998 El Niño precipitation. Thermistors located at stations 9.2 m and 12.2 m measured abrupt temperature increases and decreases during February 1998. Station 34.0 m showed a very small (less than 0.001°C) temperature decrease on March 8, 1998 indicating that some water had percolated to the bottom of the Tiva Canyon Tuff vitric zone. Stations located in the Yucca Mountain Tuff (39.7 m and 48.5 m) had no temperature changes.

The temperature responses at borehole UZ #5 are different than those at borehole UZ #4. The difference is because the infiltration and percolation at borehole UZ #5 is dominated by fracture flow while the flow at borehole UZ #4 is buffered by the alluvium of Pagany Wash. Comparison of the temperatures at similar elevations in boreholes UZ #4 and UZ #5 for February and March 1998 showed that the temperatures at borehole UZ #5 were more than 1°C cooler. The cooler temperatures in borehole UZ #5 indicate that the March 22 to April 17, 1998 temperature increase measured at borehole UZ #4 station 24.5 m could not have been due to lateral flow but was the result of downward percolation through the alluvium of Pagany Wash.

For the period March 22, 1998 to April 2, 1998 (11 days), the differential pressure between borehole UZ #4 stations 11.1 m and 24.5 m increased significantly. The pressure data indicated that station 24.5 m was temporarily pneumatically isolated from station 11.1 m. One possible interpretation is that the wetting front had moved below station 11.1 m, and that the increase in pressure at station 24.5 m may have been due to the compression of air ahead of the downward-moving wetting front. The pressure data also indicated that the permeability of the Tiva Canyon Tuff vitric zone is relatively small and that the area coverage of the wetting front must have been large enough to minimize the effect of any constant-head lateral flow boundaries.

Borehole UZ #4 station 35.2 m had a 0.04°C temperature decrease followed by a period of instability where temperatures spiked to higher levels but never dropped below the initial baseline temperature of 19.6°C. Pressure monitoring indicated a correlation between barometric low pressures and the temperature spikes. The correlation indicated that low barometric pressure resulted in deeper, warmer air moving upward and warming station 35.2 m (barometric pumping effect). One possible explanation is that air moving ahead of the wetting front passed through station 35.2 m and opened air-flow pathways below the station. The open air-flow pathways below the station allowed deeper, warmer air to move upward and laterally in response to barometric lows, whereas the water-filled pore space above the station prevented shallow, cooler air from moving downward.

Pressure differences between borehole UZ #4 stations 24.5 m and 35.2 m indicated that on or about July 1, 1998 there was an improved pneumatic connection and/or decrease in the time lag between the two stations. One possible explanation is that water from the wetting front filled in some of the air-filled flow paths above station 24.5 m, thereby decreasing the barometric time lag between the stations. Pressure monitoring also indicated that on or about July 6, 1998, the pressure differences between stations 35.2 m and 45.0 m increased. The increase in the pressure differences indicated that the wetting front had moved below station 35.2 m, deeper into the Yucca Mountain Tuff, and was located between station 35.2 m and station 45.0 m. Pressure monitoring through June 2000 shows that the large pressure differences are still present and indicates that the Yucca Mountain Tuff may have retarded the downward movement of the wetting front.

Pressure monitoring in borehole UZ #5 station 25.5 m identified two abrupt pressure increases during the period February 19 to 28, 1998. The average barometric pressure at station 25.5 m was about 88.0 kPa; the abrupt pressure increases reached values of 98.3 and 103.0 kPa. A similar, although smaller, pressure response was measured in borehole UZ #4 station 24.5 m. Here again, the pressure buildup is at the contact with the Tiva Canyon Tuff vitric zone. One possible interpretation is that the pressure increase at station 25.5 m may have been due to the compression of air ahead of the downward-moving wetting front.

The water potentials at borehole UZ #4 stations 11.1 m, 35.2 m, and 45.0 m ranged from –2 to –1 bars and were generally stable. On or about April 17, 1998 the thermocouple psychrometer at station 35.2 m failed. The failure is indicative of liquid water in the unit. April 17, 1998 is the same date that station 35.2 m had a sudden temperature decrease of 0.02°C. The timing of the thermocouple psychrometer failure supports the earlier interpretation that the temperature response at station 35.2 m was due to the wetting front. The absence of a response at station 45.0 m supports the theory that the wetting front had not reached station 45.0 m and that the Yucca Mountain Tuff may have retarded the downward percolation of the wetting front

Water potential values measured at borehole UZ #5 stations 25.5 m, 34.0 m, 39.7 m, and 48.5 m ranged from –3 to –1 bars. On February 18, 1998 station 25.5 m had a sudden increase in water potential. February 18, 1998 is also the date that station 25.5 m had a sudden temperature decrease of 0.007°C. The reaction of the thermocouple psychrometer was probably due to the temperature decrease and condensation of water. The causal relation between the February 18, 1998 temperature and pressure disruptions at station 25.5 m is unclear but may be associated with the pressure increase and(or) the infiltration of water into the Tiva Canyon Tuff vitric zone.

Analytical and numerical methods were used to estimate the infiltration flux associated with the 1998 El Niño precipitation. The analytical method indicated that the infiltration flux through the alluvium of Pagany Wash was 1,130 mm. Numerical simulations using the USGS computer code VS2DH indicated that the measured temperature disruptions were due to convective heat transfer associated with an infiltration flux of between 1,000 to 2,000 mm of water.

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LeCain and others—Use of Temperature, Pressure, and Water Potential Data to Estimate Infiltration and Monitor Percolation in Pagany Wash Associated with the Winter of 1997–98 El Niño Precipitation, Yucca Mountain, Nevada

USGS/WRIR 02–4035

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