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CONTINUED INVESTIGATIONS OF THE OCCURRENCE OF WATER IN PAHUTE MESA EMPLACEMENT HOLES

Prepared by

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Water Resources Center
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ABSTRACT

Periodically, water has been observed in emplacement boreholes drilled for underground testing of nuclear weapons at Pahute Mesa, Nevada Test Site, and is often at levels elevated above the predicted local water table. Water which may provide a means to transport residual radionuclides away from weapon tests may originate as fluids introduced during drilling, from naturally perched groundwater draining into the borehole, or from penetration of the local groundwater table. Lithium-bromide (Li-Br) tracer is being used to evaluate both the origin and movement of these borehole waters.

The drilling fluid used to drill the final 100 meters of borehole U-19bh was chemically labeled with LiBr tracer. Lack of significant increase in borehole Br inventory over time indicates that standing water in U-19bh is not returned drilling fluid. Possible sources for the standing water are drilling fluid infiltrated above the bottom 100 m or natural water from a perched or shallower-than-expected saturated zone. Br mass in U-19bh has changed little since fluid levels stabilized in the borehole in late summer 1991 indicating little or no movement of water out of the borehole. Given known precision limitations in determining Br-ion concentration ($\pm 5\%$), small velocities might remain undetected in this experiment. The minimum detectable Darcy velocity of water passing through U-19bh is 0.3 m/yr.

Borehole U-19bk has a water level approximately 50 m above the predicted pre-drilling water level. Initial water samples were collected from U-19bk to characterize the borehole water quality prior to adding the tracer. The major-ion analytical results of U-19bk along with historical water quality analyses of Water Well 20 and water well UE-19c show that all three waters are similar in character and therefore the water in U-19bk may be either residual drilling fluids originating from Water Well 20 and UE-19c or naturally occurring Pahute Mesa groundwater. LiBr tracer was added to the U-19bk borehole and samples for tracer analysis were collected one month later. For the one month period, no detectable loss of Br was observed. Over this short time period, the minimum detectable Darcy velocity is 10.6 m/yr.

Although Pahute Mesa is widely considered to be a recharge area for the Oasis Valley and Alkalai Flat-Furnace Creek hydrologic subbasins, the experiments described above have so far been unable to find evidence of significant groundwater fluxes in known perched water bodies. Preliminary results suggest that minimal horizontal and vertical movement of groundwater is taking place above the local water table where investigated at Pahute Mesa. In effect, the shallow hydrologic system of Pahute Mesa appears to consist of isolated, relatively stagnant bodies of water; therefore, any contamination found in this shallow system may be immobile in most cases. Continued monitoring of tracer concentrations at the two sites discussed here can further constrain observed groundwater velocities, and will be important in confirming the surprising lack of mobility so far observed for perched water bodies at Pahute Mesa

CONTENTS

FIGURES

TABLES

INTRODUCTION

Periodically, water has been observed in emplacement boreholes drilled for underground testing of nuclear weapons at Pahute Mesa, Nevada Test Site (NTS), and is often at levels elevated above the predicted local water table. Water which may provide a means to transport residual radionuclides away from weapon tests may originate as fluids introduced during drilling, from naturally perched groundwater draining into the borehole, or from penetration of the local groundwater table. If the observed water originates as either perched or local groundwater, the potential for the migration of radionuclides away from an underground test is greatly increased. Lithium-bromide tracer is being used to evaluate both the origin and movement of these borehole waters. Final results at one site and preliminary results at another indicate a surprising lack of groundwater movement within known perched water bodies. This suggests that the potential for radionuclide migration at many Pahute Mesa weapon-test sites may be minimal.

Large volumes of water are introduced during drilling of emplacement boreholes. One hundred meters of water in the borehole are usually maintained above the drill bit during drilling, but, in certain formations, it is often impossible to maintain this amount of water in the borehole even with optimal water supply. This suggests that more than four-million liters (one-million gallons) may be added to the geologic formations during the course of drilling a typical emplacement borehole at Pahute Mesa (Gardner and Brikowski, 1993). Draining of these drilling fluids from the geologic formations back into the borehole may provide an ample source for this borehole water.

Pahute Mesa is one of the higher areas within the NTS boundaries (elevation ranges from 1,280 to 1,480 meters above mean sea level). It can receive significant precipitation and is considered a groundwater recharge area. Perched groundwater (a saturated zone separated from an aquifer by unsaturated rock, Figure 1) is common in recharge areas, as infiltrating precipitation encounters rocks of lower hydraulic conductivity and its downward percolation is restrained. Perched groundwater is known to occur within the bedded-tuff aquitards of Pahute Mesa (Blankennagel and Weir, 1973). If a perched groundwater aquifer is penetrated during drilling, this water can drain from the perched aquifer into the borehole. These perched aquifers can hold significant quantities of water and could provide a medium for the transport of weapon-test radionuclides.

Pahute Mesa emplacement holes are usually drilled so their total depth is above the predicted local groundwater table. The water-table map constructed by Blankennagel and Weir (1973) and more recent water-level information are used to predict the elevation of the groundwater table at a proposed emplacement hole. This predicted water-table elevation is based on sparse data covering a very large geographic area. Also, the geology at Pahute Mesa is very complex, with many inter-fingered layers of different volcanic rock types. These rock layers may be highly faulted and fractured, and have widely varying permeabilities. All of these situations contribute to the possibility that the elevation of the local groundwater table may be higher that predicted. Thus, the water observed in an emplacement hole may be the result of drilling into the local water table where water levels in the borehole are well above the predicted level. Any radionuclides introduced into a groundwater aquifer are susceptible to migration away from the underground nuclear test.

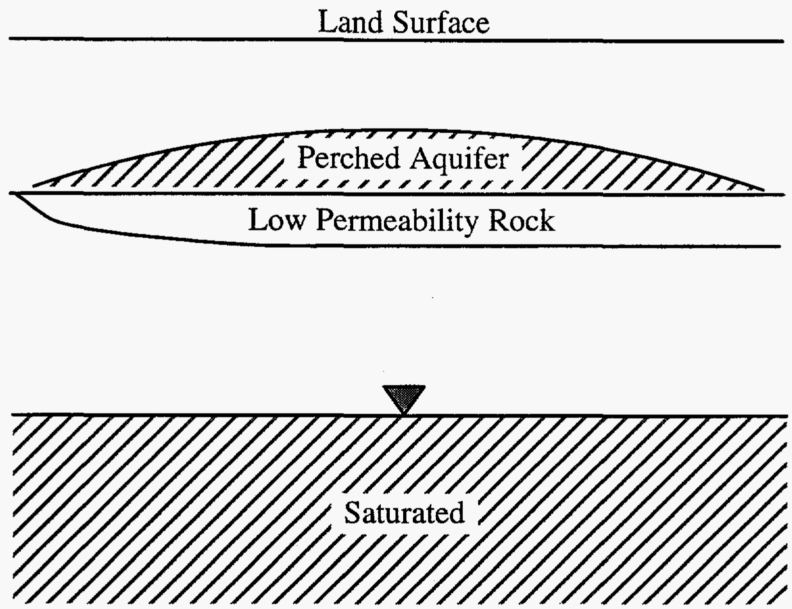

Figure 1. Idealized drawing of a perched aquifer.

Winograd (1970) suggested that drilling fluids lost in fractured rocks above the water table can reenter the borehole if the formations above the water table are not cased and cemented. Brikowski *et al.* (1993) evaluated the chemical composition of water in one borehole and conducted chemical tracer experiments in two other boreholes to evaluate the origin of borehole waters. They concluded that observed water in Pahute Mesa emplacement boreholes originated from the drainage of small-volume, naturally perched groundwater aquifers, and not from drilling fluids flowing back into the borehole from the geologic formations. Gardner and Brikowski (1993) compared numerical models of return flow to a borehole from both infiltrated drilling fluids and from a perched aquifer with the observed post-drilling water-level history of an actual emplacement borehole (U-19ba). The modeled duration and volume of return flow into a borehole from drilling fluids could not replicate the observed water-level history of an actual emplacement borehole. The return flow of drilling fluids back into the borehole is limited because the volume of saturated rock next to the borehole is small and the modeled hydraulic gradients indicate unsaturated flow away from the borehole wall toward rock of lower saturation. The modeled drainage of a naturally perched aquifer readily replicated the observed water-level history.

To further evaluate the origin and movement of these waters, emplacement boreholes continue to be investigated in Area 19 at Pahute Mesa by the Desert Research Institute. Boreholes presently being investigated are U-19bh and U-19bk (Figure 2).

CONTINUED ACTIVITIES AT U-19bh

The U-19bh emplacement borehole was completed to a depth of 654.7 meters (m), approximately 60 m above the predicted local water table. The hole intersects volcanic welded tuffs,

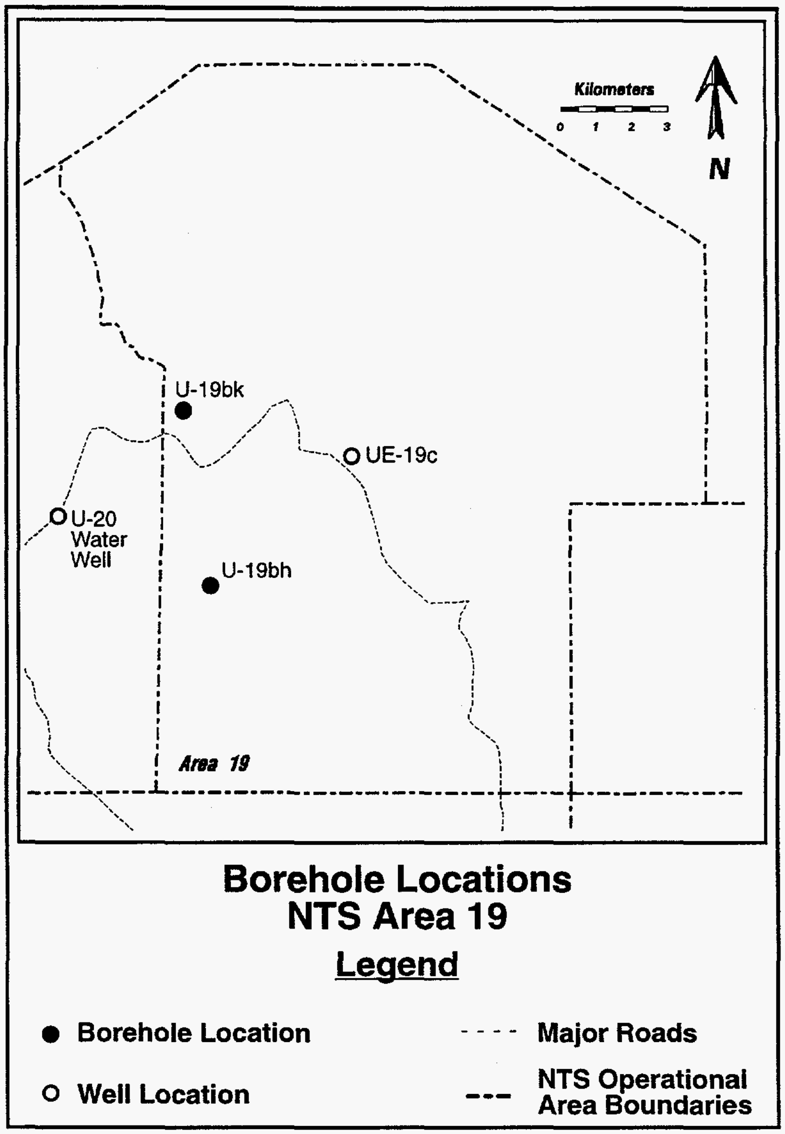

Figure 2. Location map of boreholes and wells discussed in this report.

tuffs, lavas, and welded ash-flow tuffs. Early studies of the dependence of transmissivity on lithology at Pahute Mesa found that transmissivities in rhyolite flows averaged an order of magnitude or more greater than transmissivities for welded tuffs, and another order of magnitude greater for bedded and zeolitized tuffs (Blankennagel and Weir, 1973). Sharp contrasts in hydraulic conductivity are generally required to form perched aquifers and the lithologic contact between lavas and underlying welded tuff may provide such a perching zone at U-19bh.

To evaluate the hydrologic impact of drilling-fluid leakage into the formation during emplacement-hole drilling, fluids used in the final 100 m of U-19bh were labeled with lithium bromide (LiBr). Ten liters (L) of an approximately 20-molar solution of LiBr were introduced into the inner drill string. Drilling continued with no further addition of water or tracer until the planned total depth (TD) was reached on June 18, 1991, at which time the hole was dewatered. Samples taken at the beginning, middle, and end of dewatering showed that relatively uniform concentrations of Br-ion were present throughout the standing column of water (approximately 4 mg/L). Water levels have risen steadily in the borehole since then, and as of September 1, 1994, 17 m of water were standing in the hole (Figure 3). Samples were collected at increasing intervals after the hole was completed (Table 1).

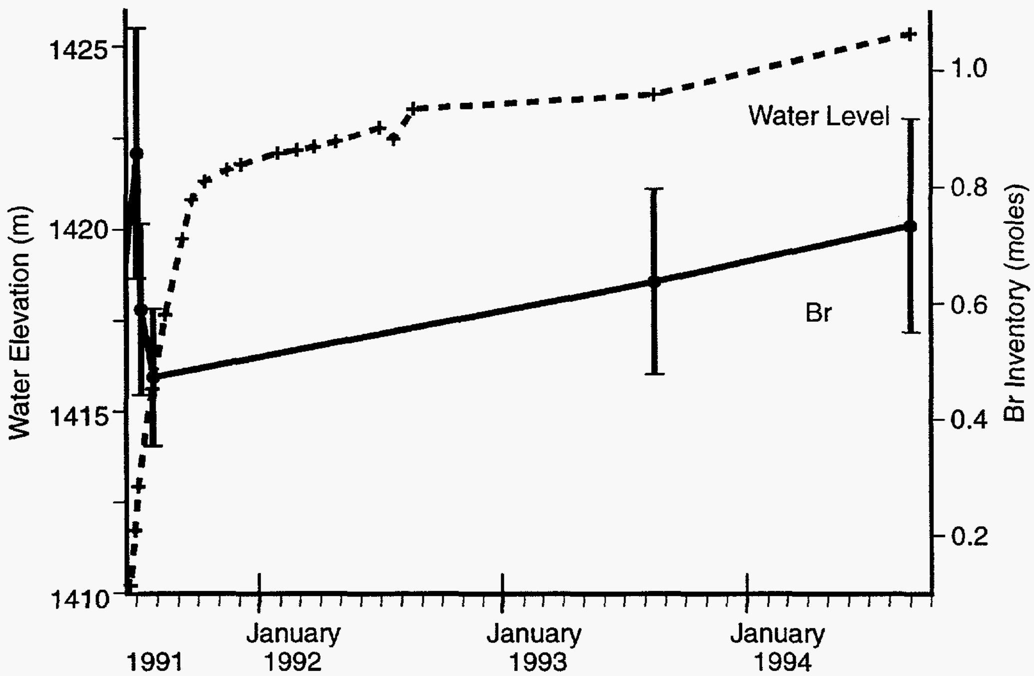

Figure 3. Bromide tracer inventory and water levels vs. time in borehole U-19bh, Pahute Mesa, Nevada Test Site.

TABLE 1. RESULTS OF CHEMICAL ANALYSES FROM U-19bh DRILLING FLUID LABELING EXPERIMENT. Maximum analytical error is five percent, detection limit for Br-ion is 0.02 mg/L.

Date Collected	Water Level Elevation (meters)	Li (mg/L)	Br (mg/L)	Description
6/18/91	1499.0	0.135	4.0	Begin borehole dewatering
6/18/91	1454.8	0.132	4.0	Mid borehole dewatering
6/18/91	1410.6	0.135	4.2	End borehole dewatering
7/2/91	1413.1	0.087	1.7	USGS sample U-19bh-183
7/8/91	1414.3	0.083	1.4	USGS sample U-19bh-189
7/26/91	1416.1	0.405	1.02	USGS sample U-19bh-207
8/9/93	1424.0	0.38	0.70	Collected at depth 647 m
9/1/94	1425.3	0.34	0.72	Collected at depth 647 m

Approximately 100 moles, or 60 percent, of the initial LiBr tracer was injected into the formation during drilling. Since borehole dewatering, Br-ion concentrations have declined in the standing fluids in the borehole, but total Br *mass* or inventory remained essentially constant (Table 2 and Figure 3). The increased fluids in the hole, coupled with the decrease in Br-ion concentrations, indicate that fluids entering the borehole were not labeled drilling fluid. Lack of significant increase in borehole Br inventory indicates that fluid standing in U-19bh is not returned drilling fluid from the final 100 m of drilling. Possible sources for the standing water are drilling fluid infiltrated above the bottom 100 m, or natural water from a perched or shallower-than-expected saturated zone.

The increase in water level and lack of change in Br-ion concentration since 1992 may result from sloughing of borehole wall material. Sloughing of borehole wall material may have filled in some of the bottom of the borehole, effectively raising the water level but not changing the total volume of water within the borehole. Total depth of U-19bh has not been measured since 1991; therefore, it is assumed to have remained constant in the calculations below. Any errors resulting from this assumption are within the error bars depicted in Figure 3.

TABLE 2. CALCULATION OF Br INVENTORY, U-19bh. TD on 6/19/91 was approximately 654.7 m. Column Height is water elevation from Table 1 minus TD. Column Volume is $\pi r^2 h$, where r is 1.22 m and h is Column Height. The inventory is Column Volume multiplied by Br concentration (divided by 1000 for grams and divided again by 79.904 for moles).

Date	Column Height (m)	Column Volume (L)	Br (mg/L)	Inventory	
				Br (gm)	Br (moles)
6/18/91	2.44	1.141×10^4	4.0	45.6	0.57
7/2/91	4.88	2.282×10^4	3.0	68.5	0.86
7/8/91	6.10	2.852×10^4	1.65	47.1	0.59
7/26/91	7.92	3.703×10^4	1.02	37.8	0.47
8/9/93	15.55	7.271×10^4	0.7	50.9	0.64
9/1/94	17.08	7.987×10^4	0.72	57.5	0.72

Long-term access to this borehole has allowed extension of the experiment to a point-dilution type study. Given a known concentration of tracer in a constant volume of water in a borehole which is exchanging with its surroundings, the specific discharge or Darcy velocity (q) of water flowing past the borehole can be computed using

$$q = -\frac{W}{\alpha A t}\ln\left(\frac{C}{C_o}\right) \qquad (1)$$

where W is the volume and A is the cross-sectional area of the column of water in the well, α is a geometry factor, C/C_o is the ratio of final to initial tracer concentration, and t is the elapsed time (Freeze and Cherry, 1979, p. 428-430).

Br mass in U-19bh has changed little since fluid levels stabilized in the borehole in late summer 1991 indicating little or no movement of water out of the borehole (q in equation (1) is zero). Given known precision limitations in determining Br-ion concentration ($\pm 5\%$), small velocities might remain undetected in this experiment. The minimum detectable velocity can be calculated as follows. The water column is considered to have remained at its current height throughout the experiment (allowing the maximum possible undetected velocity). Relative concentration (C/C_o) is assumed to be $1.0 \pm 5\%$. Assuming W is 79.87 m^3, A is 41.68 m^2, t is 1172 days, α is 1, the smallest recognizable Darcy velocity of water passing through U-19bh to date is 0.3 m/yr.

This experiment was designed to trace the contributions of the most recently infiltrated drilling fluids and their contribution to standing water in U-19bh was determined to be minor. Extended access and further sampling have shown that little dissolved Br is leaving the borehole and therefore groundwater flux through the borehole is small.

NEW ACTIVITIES AT U-19bk

Borehole U-19bk was completed to a depth of 670 m in tuffs and rhyolite lavas at Pahute Mesa on December 12, 1991. The predicted pre-drilling water level was approximately 655 m below land surface (bls) based on Blankennagel and Weir's (1973) water elevation map of Pahute Mesa. On June 8, 1994, the measured water level in the borehole was 605 m bls (Raytheon Services Nevada) or 50 m above the predicted pre-drilling water level. Because of the large difference in predicted vs. actual observed water level in the borehole, U-19bk was selected to conduct another single-hole, point-dilution study.

On July 29, 1994, U-19bk was visited to add LiBr tracer to the borehole. Prior to adding the tracer, the water in the borehole was logged for temperature and electrical conductivity (EC) variations, and water samples were collected. The temperature and EC profile of the water column was consistent throughout the water column with a temperature of 30°C and an EC of 160 µS/cm (Figure 4). The measured natural Br-ion concentration of the water sample at 638.6 m bls was 0.02 mg/L. Table 3 lists the analytical results of the water samples collected. Approximately 25 kilograms of anhydrous LiBr (288 moles of Br) were added to 63.7 m of standing water in the 2.44-m-diameter borehole. The LiBr was packed into a 1.5-m section of 15-cm-diameter PVC well screen, which was then lowered into the well on a wireline and raised and lowered through the water column several times to disperse the tracer. The average Br-ion concentration in the labeled water column was calculated to be 77 mg/L. The borehole was then logged again to examine the dispersal of the tracer within the water column. Figure 4 shows the results of the EC log and indicates that mixing of the tracer in the water column was inconsistent with most of the tracer dissolving in the upper portion of the water column and no tracer in the lower few meters. The EC of the water column ranged from approximately 400 µS/cm at the top of the water column to 160 µS/cm at the bottom. A second water sample for Br-ion content was then collected at a depth of 627.9 m bls with a resulting 139 mg/L. On September 1, 1994, another water sample for Br-ion content was collected at the same depth with an analytical result of 73 mg/L.

TABLE 3. RESULTS OF CHEMICAL ANALYSES FROM U-19bk AT PAHUTE MESA, NEVADA TEST SITE.

Sample Date	July 24, 1994	July 24, 1994	September 1, 1994
Sample Name	U-19bk before tracer 638.6 m below land surface	U-19bk after tracer 627.9 m below land surface	U-19bk 627.9 m below land surface
EC	175 μS/cm		
pH	7.90		
	mg/L	mg/L	mg/L
Na	102		
K	5.78		
Ca	19.9		
Mg	1.80		
HCO_3	86.9		
Cl	5.5		
SO_4	9.28		
NO_3	0.97		
SiO_2	66.8		
Li	0.040	10.7	6.12
Br	0.02	139	73
F	0.22		
Ba	0.007		
Be	<0.001		
Cd	<0.005		
Co	<0.01		
Cu	<0.005		
Fe	0.13		
Mn	<0.01		
Mo	<0.01		
Pb	<0.05		
Sr	0.023		
V	<0.02		
Zr	0.016		

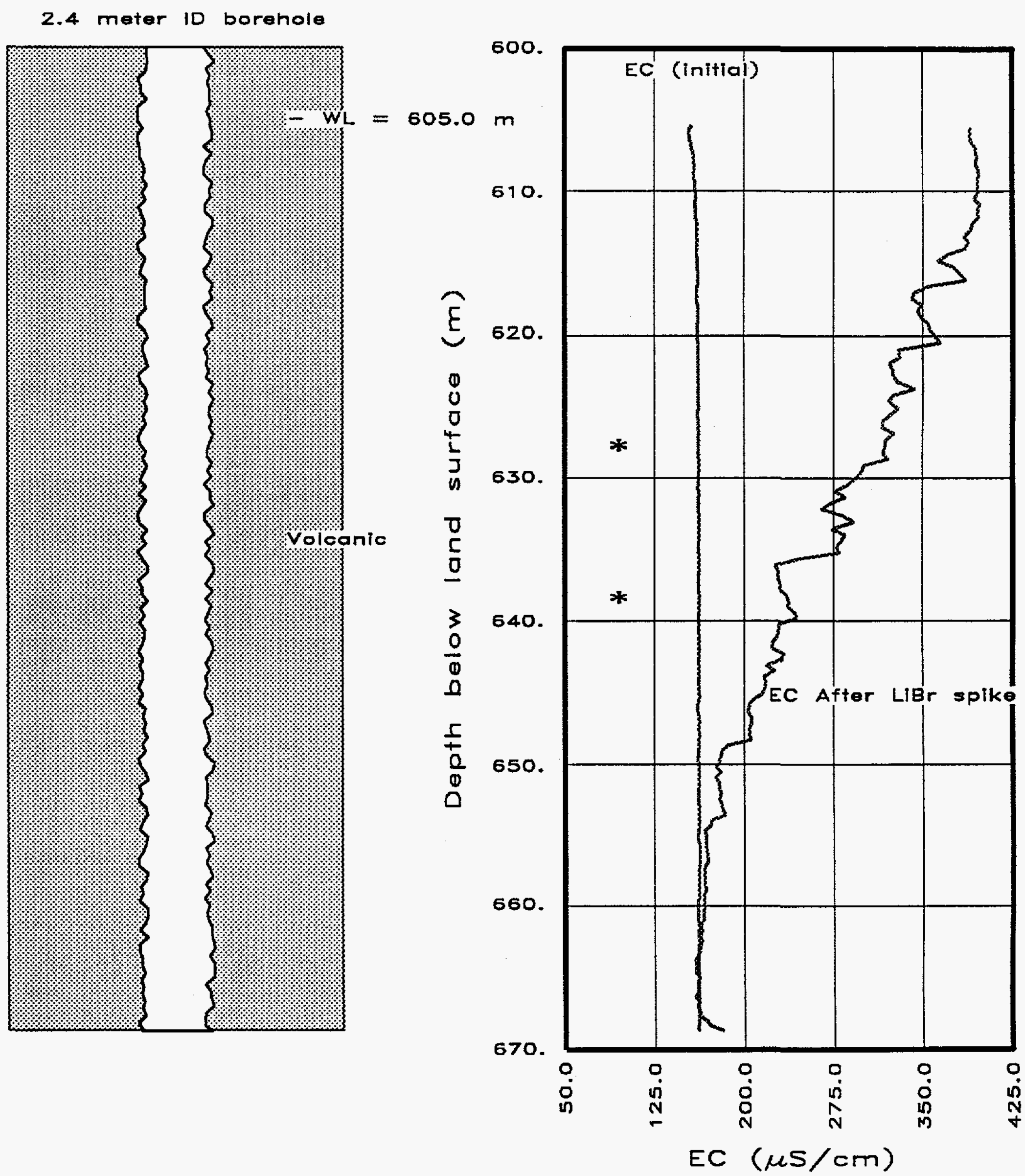

Figure 4. Electrical conductivity (EC) profiles of borehole U-19bk before and after addition of lithium bromide (LiBr) tracer. Asterisks denote water sample collection depths.

Initial water samples were collected from U-19bk to characterize the borehole water quality prior to adding the tracer. The major-ion analytical results of U-19bk along with historical water quality analyses of Water Well 20 and water well UE-19c are displayed on Figure 5. These plots of major dissolved ions show that all three waters are similar in character, and therefore the water in U-19bk may be either residual drilling fluids originating from Water Well 20 and UE-19c or naturally occurring Pahute Mesa groundwater.

Since distribution of the tracer within the borehole was not consistent throughout the water column at the time the tracer was added, a sampling depth that would have a sufficiently large Br-ion content was selected based on the EC profile. The analytical results of the initial sample collected after the tracer was added was 139 mg/L at 629.7 m bls. This concentration is well above the 0.02 mg/L measured natural concentration in the borehole and above the calculated average concentration of 77 mg/L if the tracer was evenly distributed throughout the water column. One month later, September 1, 1994, a decrease in Br-ion concentration (73 mg/L) was observed at the same sampling depth. No temperature and EC log of the borehole was conducted for this sample because of equipment problems and time limitations.

Because an EC log was not run for the September sample, the actual distribution of tracer within the borehole at that time is unknown. However, the combination of the initial EC logs and discrete samples allow the Br tracer content to be estimated for the water column. Background EC values logged before labeling the water were about 160 μS/cm (Figure 4). EC at the point of the analyzed sample collected immediately after addition of the tracer was 318 μS/cm; the measured Br concentration was 0.139 mg/cm^3. Given this information and assuming a linear relationship between Br concentration (C_{Br}) and EC, the equation

$$C_{Br}\left(\frac{mg}{cm^3}\right) = 1.14x10^{-3} \cdot \left[EC\left(\frac{\mu S}{cm}\right) - 160\right] \qquad (2)$$

can be derived. Using this relationship, the after-spike EC profile in Figure 4 gives the vertical distribution of Br throughout the borehole. Calculating the area between the two EC profiles in Figure 4, multiplying by the horizontal area of the water column (πr^2), and converting to moles should give the initial mass of the tracer. The result of such a calculation gives as mass 33% in excess of that introduced to the hole, indicating that a more correct formula is

$$C_{Br}\left(\frac{mg}{cm^3}\right) = 6.67x10^{-4} \cdot \left[EC\left(\frac{\mu S}{cm}\right) - 160\right] \qquad (3)$$

Using equation (3), an EC value for the September 1, 1994 sample can be estimated from the measured Br content (73 mg/L). The estimated value is 269 μS/cm, a value close to the average EC value (258 μS/cm) from the July 24, 1994 after-spike profile. Although the actual distribution of Br in the borehole on September 1, 1994 is unknown, this similarity in EC values suggest that the Br concentrations within the borehole should be homogeneous, and therefore no detectable loss of Br had occurred. Using equation (1), a minimum detectable horizontal velocity of groundwater through

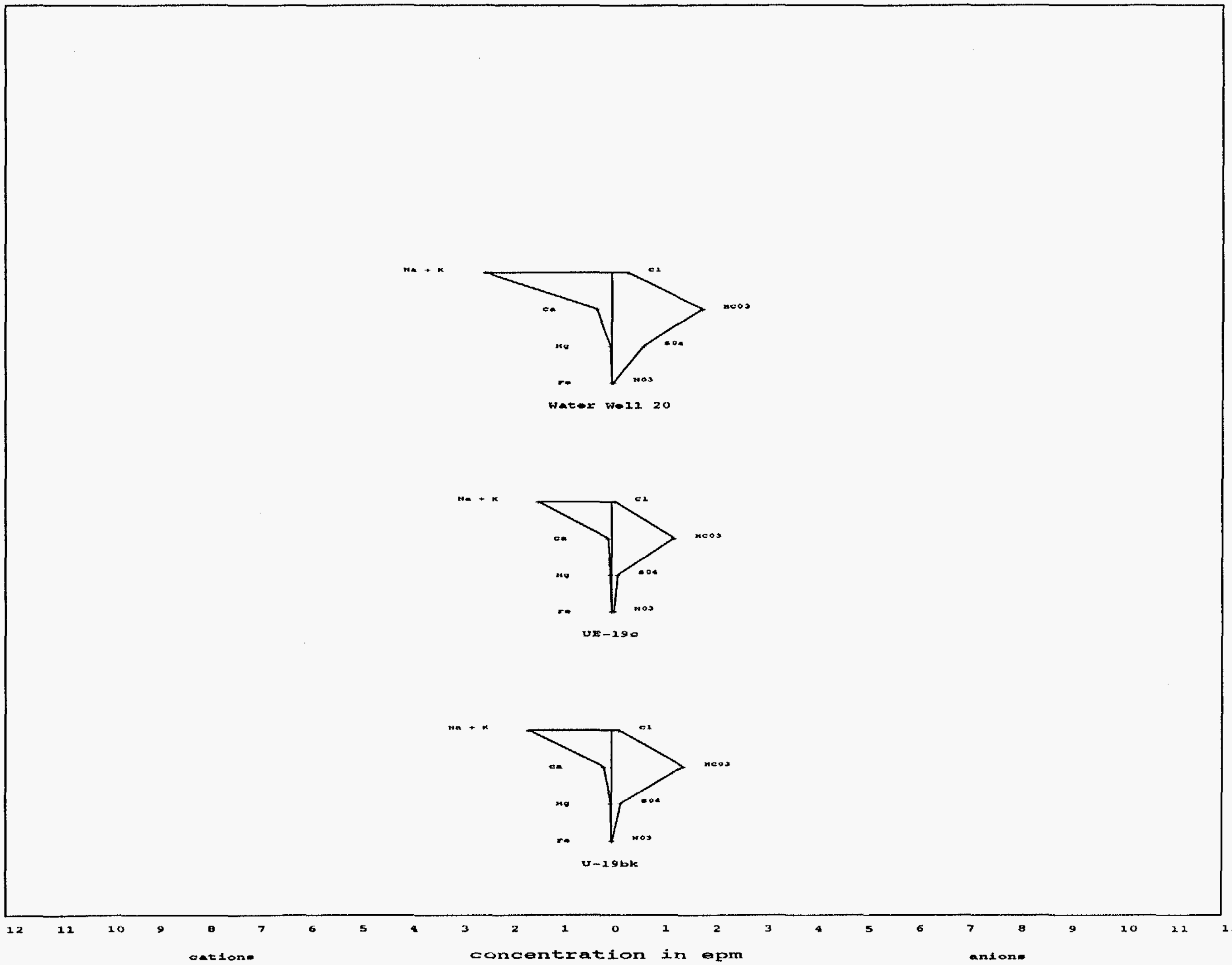

Figure 5. Major dissolved-ion plots of water from borehole U-19bk, Water Well 20, and water well UE-19c at Pahute Mesa.

the borehole can be calculated. In this case, the column height is 63.7 m, giving W=297.9 m^3, A=155.3 m^2, t=34 days, and other parameters as in the case of U-19bh. Over this short time period, the minimum detectable Darcy velocity (given limits in the precision of chemical analyses of Br) is 10.6 m/yr.

FUTURE WORK

Future monitoring of tracer concentrations at U-19bk is planned semiannually for the current fiscal year (i.e., two LiBr analyses and EC logs). If standing water in U-19bk is in contact with a regional aquifer, and modeled regional velocities of approximately one m/yr are correct (Waddell, 1982), Br concentrations should begin to show the effects of regional flow within a year of the initial labeling. Comparison of EC logs over time should reveal the level and approximate magnitude of any large inflow or outflow zones in the water column. Smaller variations in horizontal flows from/to the borehole will be masked by the rapid mixing of borehole water column as observed between July and September 1994. Additional monitoring on an annual basis would be advisable. U-19bh should be revisited once this fiscal year; a new measurement of borehole TD will also be made by the U.S. Geological Survey (G. Russell, personal communication, 1995). Subsequent samples should be collected no more than annually unless significant changes in Br contents are observed.

CONCLUSIONS

Although Pahute Mesa is widely considered to be a recharge area for the Oasis Valley and Alkalai Flat-Furnace Creek hydrologic subbasins (Waddell, 1982), the experiments described above have so far been unable to find evidence of significant groundwater fluxes in known perched water bodies. Perched aquifers with relatively large groundwater fluxes should be common at Pahute Mesa given this regional conceptual model. A number of above-water-table underground nuclear testing boreholes encountered such bodies, raising the specter of possible rapid transport of radionuclides to the regional water table by water from these perched aquifers. The results discussed here do not support such a model, and while preliminary, suggest that minimal horizontal and vertical movement of groundwater is taking place above the local water table where we have been able to investigate at Pahute Mesa. In effect, the shallow hydrologic system of Pahute Mesa appears to consist of isolated, relatively stagnant bodies of water (Brikowski, 1994); therefore, any contamination found in this shallow system may be immobile in most cases. Continued monitoring of tracer concentrations at the two sites discussed here can further constrain observed groundwater velocities, and will be important in confirming the surprising lack of mobility so far observed for perched water bodies at Pahute Mesa.

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