LA-UR- UR-98-4084

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CONF-9805180--

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Submitted to:
High-Level Radioactive Waste Management
La Grange Park, IL
May 11 - 14, 1998

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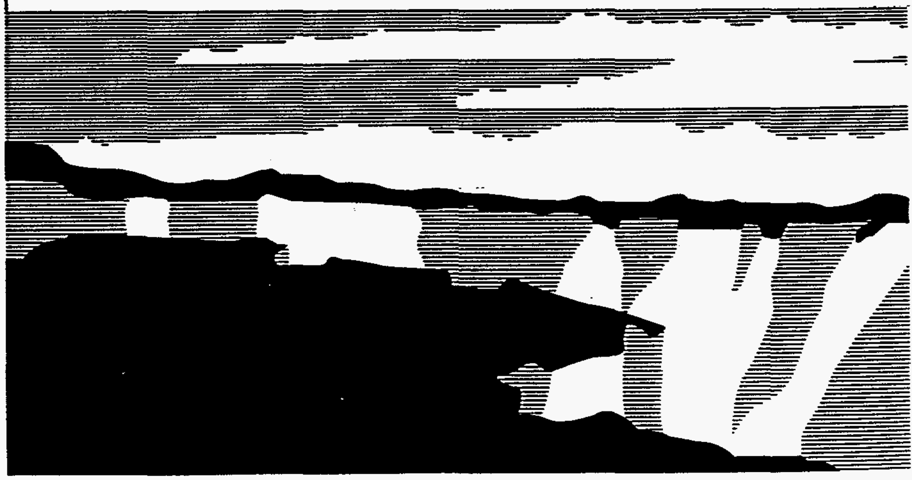

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LA-UR- 98-4084

USING CHLORIDE TO TRACE WATER MOVEMENT IN THE UNSATURATED ZONE AT YUCCA MOUNTAIN

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I. INTRODUCTION

The nonwelded Paintbrush Tuff (PTn) hydrogeologic unit is postulated as playing a critical role in the redistribution of moisture in the unsaturated zone at Yucca Mountain, Nevada. Fracture-dominated flow in the overlying low-permeability, highly fractured Tiva Canyon welded (TCw) unit is expected to transition to matrix-dominated flow in the high-permeability, comparatively unfractured PTn. The transition process from fracture to matrix flow in the PTn, as well as the transition from low to high matrix storage capacity, is expected to damp out most of the seasonal, decadal, and secular variability in surface infiltration. This process should also result in the homogenization of the variable geochemical and isotopic characteristics of pore water entering the top of the PTn. In contrast, fault zones that provide continuous fracture pathways through the PTn may damp climatic and geochemical variability only slightly and may provide fast paths from the surface to the sampled depths, whether within the PTn or in underlying welded tuffs. Chloride (Cl) content and other geochemical data obtained from PTn pore-water samples can be used to independently derive infiltration rates for comparision with surface infiltration estimates[1], to evaluate the role of structural features as fast paths, and to assess the prevalance and extent to which water may be laterally diverted in the PTn due to contrasting hydrologic properties of its subunits.

II. CHLORIDE MASS BALANCE METHOD

The Cl mass balance (CMB) method estimates the infiltration flux as a proportion of precipitation based upon the enrichment of Cl in pore water relative to its concentration in precipitation and has been used extensively to estimate infiltration in desert soils.[2-5] The underlying assumption for this approach is that pore-water concentrations provide a means to calculate the extent of water loss by evapotranspiration in the root zone through the assumption that the flux of Cl deposited at the surface ($P\ C_0$) equals the flux of Cl carried beneath the root zone by infiltrating water ($I\ C_p$). The infiltration rate I (mm yr^{-1}) is then estimated from

$$I = (P\ C_0)/C_p \qquad (1)$$

where P is average annual precipitation at Yucca Mountain (~170 mm yr^{-1})[6], C_0 is average Cl concentration in precipitation (0.62 mg L^{-1})[7], including the contribution from dry fallout, and C_p is the measured Cl concentration in pore water (mg L^{-1}). The CMB method assumes one-dimensional, downward piston flow, constant average annual precipitation rate, constant average annual Cl deposition rate, no run-on or run-off, no Cl source other than precipitation (e.g., Cl brought in by surface runoff and Cl released from weathering of surface rocks are assumed to be negligible), and no Cl sink (e.g., removal of Cl through the formation of halite is assumed negligible).

III. SAMPLE COLLECTION AND ANALYSIS

About 60 boreholes, each approximately 2 m in length and 0.15 m in diameter, were dry-drilled horizontally into rocks in the north ramp of the Exploratory Studies Facility (ESF) at Yucca Mountain along a 0.3-km section of this tunnel between Stations 727 and 1069, and in the southern half of the ESF along a 1.7-km section between Stations 5965 and 7633. (Stationing indicates the distance in meters from the North Portal entrance). The boreholes penetrated mainly the PTn, as well as units above and below it. Samples were sealed in Lexan Protecore in the field and stored under cool conditions until ready for analysis. Physical properties, unsaturated flow properties, and geochemical attributes were measured. Saturation and water-potential profiles confirm that the samples used for geochemical analyses in this study (between 1.4 and 1.8 m from the tunnel wall, Table 1) are beyond the drying front caused by ventilation in the tunnel. Pore water was extracted from the unsaturated drillcore using Beckman ultracentrifuges capable of operating at 10,000 to 16,000 rpm by running in a vacuum chamber. Typical yields were 0.2 to 2 mL for samples with masses of 35 to 160 g after an extraction period of about 24 hours. Solutions were analyzed for Cl, Br, and SO_4 using ion chromatography.

IV. RESULTS

Table 1 indicates the borehole, ESF station, hydrogeologic and lithostratigraphic unit, sample depth, local fracture density, and Cl, Br, and SO_4 concentrations for 37 pore-water samples. Cl/Br ratios confirm the absence of mine construction water (traced with LiBr to a Cl/Br ratio of 0.4) in all samples. The absence of significant Cl released from rock fluid inclusions is also indicated by Cl/Br ratios that fall generally well within the range expected for meteoric water (50 to 250). Exceptions occur for the welded samples from SR#5 and SR#18r, for which high Cl/Br ratios suggest a significant contribution of Cl released from the rock fluid inclusions, such that the measured Cl concentrations should be considered upper limits for infiltrating water at these locations.

Figure 1 plots apparent surface infiltration rates calculated by applying the CMB method to Cl concentrations in Table 1, compared against minimum and maximum surface infiltration rates within a circle of radius 100-m centered above the surface trace of the ESF, based on a site-scale infiltration model.[1] The following general observations are made from Table 1 and Figure 1.

(1) Infiltration rates calculated by the CMB method are generally consistent with bounding values of the site-scale infiltration model[1] insofar as only one sample falls outside the model's upper and lower infiltration limits (Figure 1). Cl concentrations range from 10 to 129 mg/L, with a geometric average of 30 mg/L that corresponds to an infiltration rate of 3.6 mm/yr using the CMB method. The average modeled infiltration rate for the site is only slightly higher at 4.5 mm/yr.[1]

(2) Cl porewater concentrations for the north ramp sample set (geometric average, 20 mg/L) are about half of the average value for the south ramp set (42 mg/L), corresponding to surface infiltration rates of 5.3 mm/yr in the north and 2.5 mm/yr in the south by the CMB method. This pattern is consistent with that estimated by the Flint et al. model for these areas.

(3) Most of the PTn Cl concentrations in Table 1 are considerably less than those reported elsewhere for PTn pore waters. The lowest Cl concentration in PTn pore waters in data published for Yucca Mountain is 32 mg/L, and the average value is 72 mg/L.[10-13] These earlier samples, which were extracted from drillcore from surface boreholes, may be spatially biased because they were sited in locations in channels and terraces, which tend to be zones of lower infiltration (and hence higher Cl concentrations) due to higher evapotranspiration losses.[1]

(4) The variability in Cl, Br, and SO_4 concentrations in PTn pore waters, even over fairly short distances, suggests that this unit may not be effective in homogenizing geochemical characteristics to the extent expected. Time-dependent isotopic signals (^3H, ^{14}C, and ^{36}Cl) from these same boreholes are now being measured in order to assess whether geochemical variability indicates that the expected damping of flux variability by the PTn may not be taking place.

(5) The infiltration model[1] is currently under revision to reflect enhanced infiltration in brecciated zones associated with faulting at the surface, at the base of sideslopes, and beneath large channels (such as Dune Wash in Figure 1). In addition, a more recent geologic map[14] is being used to define the spatial distribution of permeability, which exerts a dominant control on the modeled infiltration rates. These changes are expected to lead to closer agreement between the modeled rates and those calculated by the CMB method, particularly in the south part of the study area.

These geochemical data are being used to test alternative conceptual models of flow and transport in the unsaturated zone at Yucca Mountain and to establish bounding fluxes for the site-scale flow model, as illustrated by recent numerical model simulations of Cl transport.[15-16]

NOMENCLATURE

C_0	average Cl concentration in precipitation, including the contribution from dry fallout
C_p	measured Cl concentration in pore water
I	infiltration rate
P	average annual precipitation at Yucca Mountain

ACKNOWLEDGMENTS

We are greatly indebted to several of our colleagues in the U.S. Geological Survey for their invaluable contributions to the work reported in this paper. These include A.L. Flint, L.E. Flint, D.S. Sweetkind, A. Bridges, and D. Hudson. This work was supported and managed by the U.S. Department of Energy, Yucca Mountain Site Characterization Office. The Los Alamos Data Tracking Number for data presented in Table 1 is LAJF831222AQ98.001. The record package memorandum traceability information is LA-CST- TIP-97-018.

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Table 1. Chloride, bromide, and sulfate concentrations measured for ESF pore water samples

Borehole ID	ESF station[1]	Hydrogeologic unit[2]	Lithologic unit[2]	Frax density[3] (per 10m)	Sample depth from wall m	Concentration, mg/L			Cl/Br	SO_4/Cl
						Cl	Br	SO_4		
North Ramp holes										
NR#1a	727	TCw	Tpcplnc	32	1.8	29	0.38	37	75	1.3
NR#2	750	TCw	Tpcplnc/mw	16	1.5	20	0.23	32	88	1.6
NR#3	770	TCw	Tpcplnc/mw	18	1.7	35	0.26	47	134	1.3
NR#4	772	PTn	Tpcpv2	9	1.8	46	0.36	60	130	1.3
NR#5	783	PTn	Tpcpv2	17	1.7	27	0.20	31	133	1.1
NR#6	821	PTn	Tpcpv1	5	1.4	69	0.70	92	99	1.3
NR#7	867	PTn	Tpbt4	8	1.4	16	0.17	28	98	1.7
NR#8	870	PTn	Tpy	8	1.4	18	0.22	27	81	1.5
NR#10	880	PTn	Tpbt3	3	1.7	16	0.17	34	97	2.0
NR#13	1008	PTn	Tpbt2	13	1.7	10	0.14	21	74	2.1
LCPA #2	Alc #4	PTn	Tpbt2	6	1.8	18	0.25	36	71	2.0
LCPA #3	Alc #4	PTn	Tpbt2	6	1.7	17	0.24	41	72	2.4
NR#15	1054	PTn	Tptrv3/rv2	10	1.2	21	0.17	37	122	1.8
NR#16	1069	PTn	Tptrv2	19	1.5	13	0.12	22	106	1.8
South Ramp holes										
SR#5	6300	TSw	Tptpul	27	1.4	27	0.02	18	1129	0.6
SR#6	6388	TSw	Tptpul	18	1.7	87	0.35	106	250	1.2
SR#7	6480	TSw	Tptpul	4	1.8	63	0.27	64	231	1.0
SR#9	6641	TSw	Tptrn	2	1.7	86	0.43	100	198	1.2
SR#10	6648	TSw	Tptrv2	2	1.3	20	0.16	47	125	2.3
SR#11	6658	TSw	Tptrv3	0	1.6	26	0.16	42	165	1.6
SR#12	6668	PTn	Tpbt2	0	1.7	29	0.17	32	174	1.1
SR#13	6679	PTn	Tpbt2	0	1.7	37	0.21	26	178	0.7
SR#14	6696	PTn	Tpbt4	4	1.7	33	0.16	39	205	1.2
SR#15	6704	PTn	Tpcpv1	1	1.8	26	0.18	33	149	1.2
SR#16	6721	PTn	Tpcpv1	16	1.6	46	0.22	43	209	0.9
SR#18r	6748	TCw	Tpcplnc	12	1.5	45	0.12	50	382	1.1
SR#19	6826	TSw	Tptpul	4	1.8	17	0.11	13	158	0.8
SR#20	6936	TSw	Tptrn	6	1.7	129	1.16	74	111	0.6
SR#21	7054	PTn	Tpbt2	6	1.7	89	0.46	104	193	1.2
SR#22	7056	PTn	Tpbt2	6	1.6	108	0.57	127	190	1.2
SR#22r	7056	PTn	Tpbt2	6	1.7	100	0.57	132	175	1.3
SR#25	7435	TSw	Tptrn	10	1.8	34	0.17	27	209	0.8
SR#27	7444	PTn	Tptrv1	8	1.6	36	0.18	37	199	1.0
SR#28	7446	TSw	Tptrv2	8	1.6	42	0.21	51	200	1.2
SR#29	7453	TSw	Tptrv3	3	1.7	56	0.30	49	187	0.9
SR#30	7460	PTn	Tpbt2	3	1.5	101	0.51	101	200	1.0
SR#31	7465	PTn	Tpbt2	3	1.8	86	0.64	103	135	1.2

[1] Stationing indicates the distance in meters from the North Portal entrance of the ESF. Boreholes LCPA#2 and #3 were drilled in Alcove #4, which intersects the Main Drift at Station 1028.

[2] Lithostratigraphic units follow the nomenclature of Ref [8].

[3] Fracture densities are extracted from detailed line surveys conducted by the U.S. Bureau of Reclamation, and include fractures with mapped traces of 1-m or greater[9].

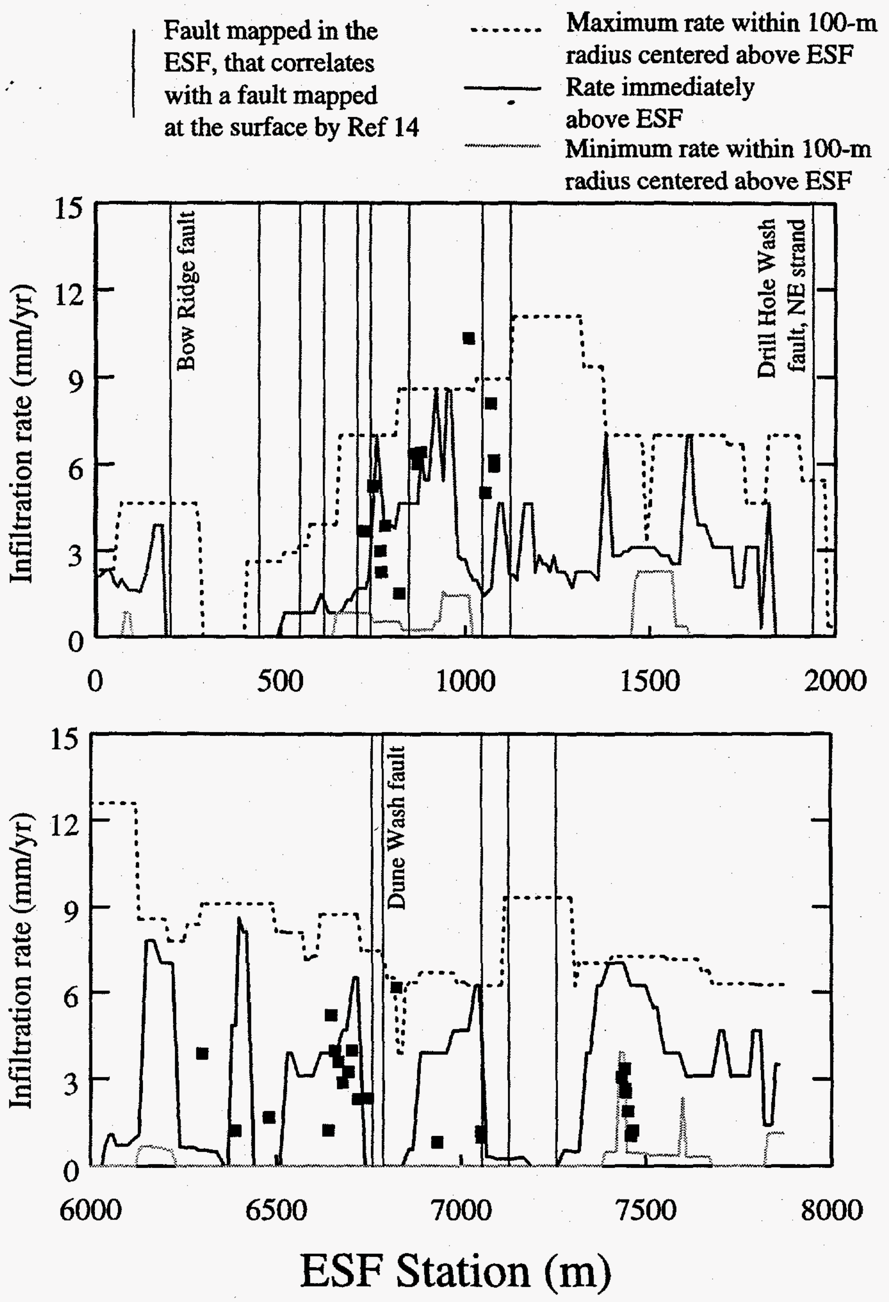

Fig. 1. Surface infiltration rates calculated from measured porewater Cl concentrations (black boxes), compared to infiltration rates estimated from the numerical model of Ref. [1] (lines). Cl data are from Table 1.