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GEOLOGICAL SURVEY

Evaluation of ash-flow tuffs as hosts for radioactive waste: criteria based on selective leaching of manganese oxides

By

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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Introduction

As investigations of possible waste disposal sites in igneous rocks become more focused, detailed geochemical and isotopic studies will provide additional criteria for screening candidate sites. For example, isotopic disequilibria in rocks and minerals may indicate open-system behavior related to low-temperature alteration or to thermo-tectonic events (Smedes, 1980; Zielinski and others, 1981).

This study presents a new geochemical test for site selection in moderately to densely welded ash-flow tuffs. A selective dissolution procedure is used to determine the amount of secondary oxides of manganese that are present as incipient alteration products and that may act as sorbants for dissolved uranium, and possibly other actinides of the waste package (Means and others, 1978). The association of uranium with secondary manganese oxides is herein documented by the covariance of uranium and manganese in leachates and by fission track radiography of polished thin sections. The results allow relative ranking of welded tuff intervals that appear comparable on the basis of other criteria such as petrographic freshness, water content, degree of welding, or ratio of radium equivalent uranium (RaeU) to actual uranium (U).

Sample Location and Description

In this preliminary investigation, 41 core samples of Tertiary rhyolitic ash-flow tuff exhibiting varying degrees of welding, fracturing and alteration were obtained from drill hole USW-G1 at Yucca Mountain, a volcanic highland along the western boundary of the Nevada Test Site (fig. 1). The hole is one of several drilled by the Department of Energy for the purpose of detailed geologic evaluation of a possible waste disposal site. The stratigraphic section consists of thick intervals of ash-flow tuff and volcanic breccia, with lesser amounts of interbedded volcaniclastic rocks (Spengler and others, 1981). In order of increasing depth the units sampled include: (1) Topopah Spring Member of the Paintbrush Tuff (755-1435 ft), (2) tuffaceous beds of Calico Hills (1425-1801 ft), (3) Bullfrog Member, and (4) Tram unit of the Crater Flat Tuff (2173-3558 ft), (5) tuff of Lithic Ridge (3946-4940 ft), and (6) older undivided tuffs (4940-6000 ft). With the exception of units (2) and (5), all sampled units contain intervals of moderately to densely welded, devitrified, relatively unaltered ash-flow tuff that, on the basis of physical-mechanical properties, is considered a potential host for disposal of high-level radioactive waste. The majority of samples (21) are of material of this type (table 1) with the remainder chosen to be spatially close to welded devitrified samples but to exhibit increased zeolitization, or decreased welding (table 1). Three samples of variably fractured vitro-

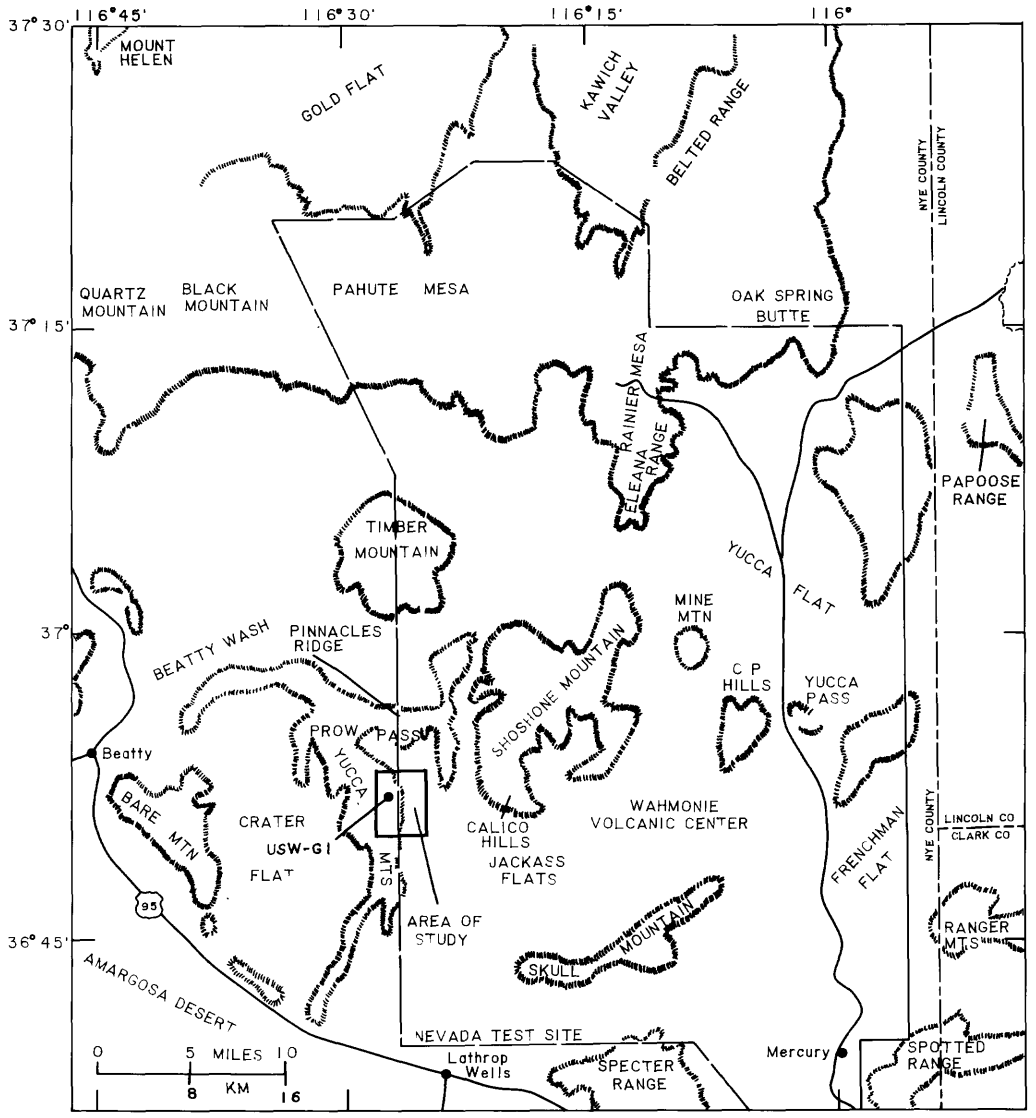


Figure 1.--Index map of the Nevada Test Site and vicinity showing location of the study area. From Spengler and others, 1981. The approximate location of drill hole USW-G1 is indicated by a dot within the study area.

phyre from the Topopah Spring Member were included to contrast with devitrified equivalents. An additional sample of fractured, faulted rhyodacite breccia (#31, 3640 ft) was also included for comparison with similarly fractured rhyolites. Detailed lithologic descriptions of the sampled units are given in Spengler and others, 1981.

Analytical Methods

Major-element analyses of whole-rock powders were performed by X-ray fluorescence (Taggart and others, 1981) which is precise to within ±5 percent (1 sigma) for most reported oxides. Volatile content was determined by weight loss after ignition at 900°C and is precise to approximately ±10 percent (1 sigma). A delayed neutron method (Millard and Keaten, 1982) was used to measure uranium in whole-rocks, whereas thorium and radium-equivalent uranium (RaeU) were determined by gamma spectrometry (Bunker and Bush, 1966). The precision of U, Th, and RaeU analyses is equal to or better than ±5 percent (1 sigma). The uranium distribution in polished thin sections was determined by fission-track radiography, using muscovite mica detector material (Zielinski and Rosholt, 1978).

The amount of secondary manganese oxides and calcite in the studied samples was estimated by a selective leach procedure. The leach solution (1 M hydroxylamine hydrochloride + 25% (v/v) acetic acid, pH ~2) has been used to dissolve manganese oxides and associated metals from sediments and ferromanganese nodules (Chester and Hughes, 1967), but it is also capable of dissolving calcite and amorphous iron oxides, and of removing weakly adsorbed metals from clays. Three grams of each sample were ground to -250 mesh, combined with 30 mL of leach solution in a polyethylene centrifuge tube, and mechanically shaken for 4 hours at room temperature. Liquids were separated by centrifugation (15,000 rpm for 30 minutes), followed by filtration through 0.2 micrometer opening filter paper. The leachates were analyzed for dissolved Mn, Ca, Fe, and Al by plasma-optical-emission spectrometry (Lichte and others, 1980), which is precise to ±3 percent (1 sigma). The uranium concentration in leachates was determined by a fission-track method (Zielinski, 1979), which has a precision of approximately ±10 to 20 percent (1 sigma), based upon counting statistics.

The assignment of leached elements to specific dissolved minerals is subject to some qualification. For example, dissolved manganese is here attributed to manganese oxides and dissolved calcium to calcite, but other possible sources of cations such as organic matter, clays, and zeolites may be partially leached as well. Such complications are minimized if the leached samples contain relatively small abundances of these phases and such is the case for the moderately to densely welded

tuffs of this study (table 1). In addition, a particular leach procedure many not produce 100 percent dissolution of the phase under attack.

In view of the above limitations, selective leaching results are most correctly interpreted as indicating the relative abundance of operationally defined sites (i.e., acid-reducible) in a group of similar samples. In accord with this interpretation, the emphasis of this study is on relative differences between units.

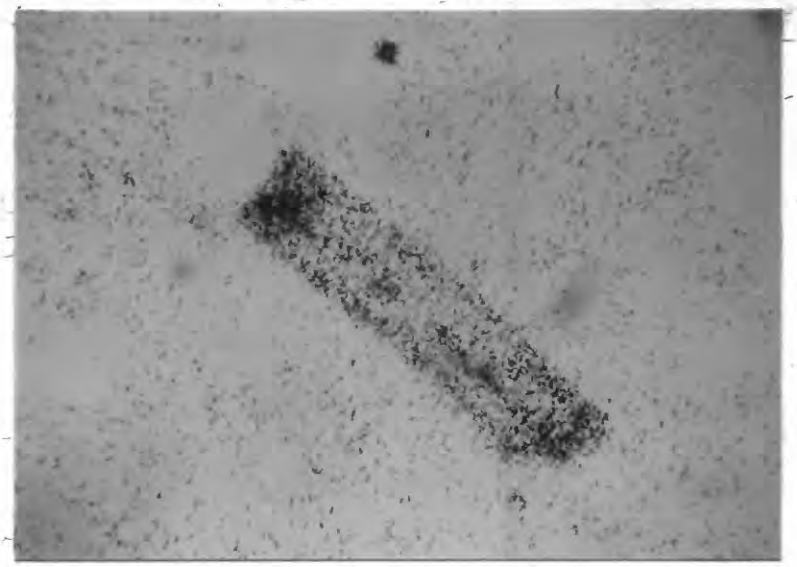
Results and Discussion

Major-element analyses of whole-rock samples (table 2) confirm their petrographic identification as rhyolite. Volatile-corrected analyses (table 3) indicate that most of the rhyolites are high-silica and alkali-rich. Non-zeolitized rhyolite of the Topopah Spring Member (samples 1-11) is particularly homogeneous, as noted in a previous study of surface samples (Lipman and others, 1966). Chemical homogeneity suggests a common origin and eruptive history, followed by minimal posteruptive alteration.

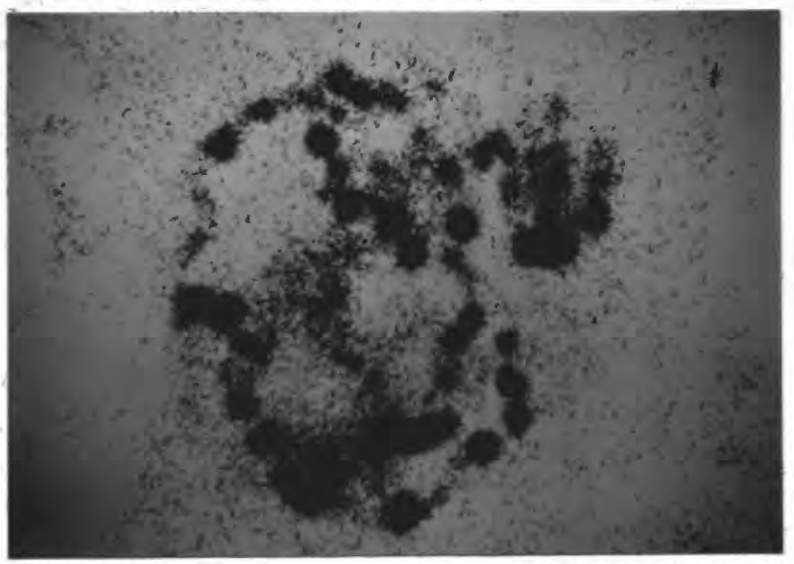
Trace-element data (table 2) provide additional indications of the degree of chemical homogeneity in the studied units. The narrow range of thorium values (24.2-24.9 ppm) within the rhyolitic portion of the Topopah Spring Member (samples 1-11) indicates exceptional homogeneity of that unit. Because of the relative insolubility of thorium compounds in normal surface and ground waters, homogeneity of thorium is interpreted to indicate a uniformity of magma composition and of physical processes acting during eruption (crystal-melt separation, contamination with lithic inclusions). Homogeneity of uranium while good (4.2-5.1 ppm), is not as great as that for thorium, suggesting minor posteruptive mobilization of uranium by oxidizing solutions. The other studied units are generally more variable in thorium and/or uranium, suggesting more complex magmatic and postmagmatic histories (table 2; Bunker and others, 1983).

Preliminary megascopic and X-ray observations of moderately to densely welded samples from the Topopah Spring Member and other sampled units showed little indication of alteration other than fracture coatings of silica, calcite, Fe-Mn oxides, and rare clay (Spengler and others, 1981). Thin-section observations of this study indicate the additional presence of secondary oxides of iron and manganese as dendritic stains, micro-fracture fillings, and coatings of ferromagnesian minerals that occur as phenocrysts or as components of lithic fragments.

Fission-track radiography of thin-sections indicates a common spatial association of uranium with the secondary oxides of iron and manganese (fig. 2). Secondary oxides of iron and

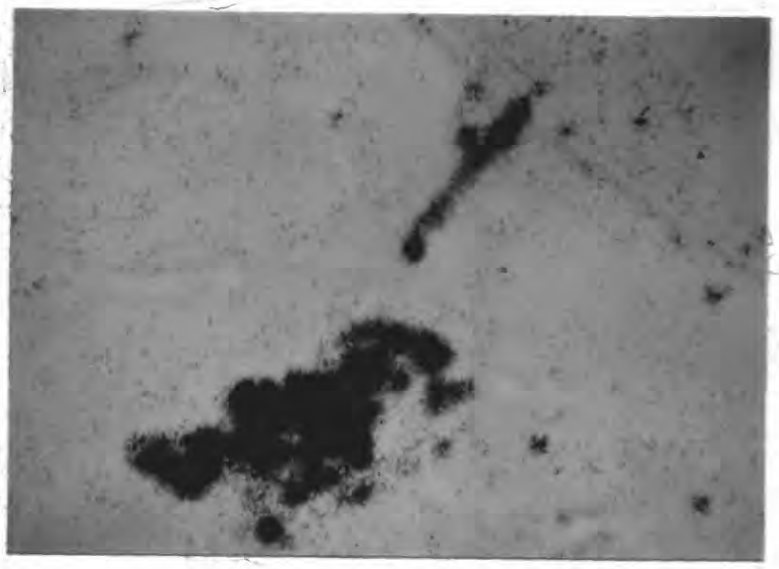


A) Oxidized biotite lath in nonwelded zeolitized tuff of Calico Hills (1,728.5-1,729.2 ft). Uranium is associated with secondary oxides that rim the grain and that follow cleavage traces.

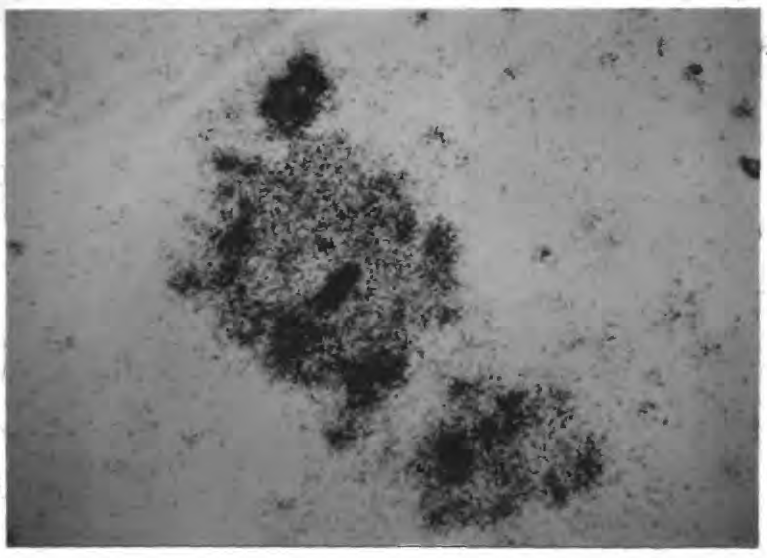


B) Oxidized magnetite grain in nonwelded devitrified tuff, Bullfrog Member, Crater Flat Tuff (2,245.3-2,245.9 ft). Uranium is concentrated in secondary iron oxides that rim the grain and that follow internal fractures.

Figure 2.--Fission-track images of uranium distribution in ash-flow tuffs, Yucca Mountain, Nevada. Dark areas correspond to highest uranium concentration. Scale of each view = 1.0 x 0.6 mm.



C) Uranium-rich manganese-oxide stain in densely welded devitrified tuff, Topopah Spring Member, Paintbruch Tuff (1,184.6-1,185.0 ft).



D) Oxidized ferromagnesian mineral in nonwelded zeolitized tuffaceous beds of Calico Hills (1,453.8-1,454.4 ft). Uranium is associated with secondary oxides that coat the grain and that fill a small microfracture that intersects the grain.

manganese, especially hydrous forms, are well-documented adsorbents of dissolved transition metals and uranium (Krauskopf, 1956; Jenne, 1968; Murray, 1975; Van der Weijden and others, 1976; Zielinski, 1978). Thus, the radiographic data indicate the presence of redistributed, soluble uranium during incipient alteration of welded tuffs. However, the agreement between chemical uranium concentrations and radiometric uranium (RaeU) concentrations of whole-rock samples (table 2, fig. 3) indicates that on a whole-rock scale, samples have not been open to analytically detectable movement of uranium or of its long-lived daughters within approximately the last 300,000 years. An important exception to this observation is the RaeU/U ratio of 1.24 for fractured rhyodacite breccia (#31) collected from a fault zone. This analytically significant ratio suggests recent daughter gain or uranium loss; a probable consequence of relatively high fracture permeability.

The manganese content of leachates (table 4, fig. 4) indicates dramatic between-sample and between-unit differences in the amount of manganese oxides. As expected, vitrophyre samples contain the smallest amounts of leachable manganese (2.5 to 17.5 percent of the amount of Mn present). Surprisingly, the zeolitized samples do not contain large amounts of leachable manganese, perhaps because of prior manganese removal during zeolitic alteration. Of greatest interest are the up to five-fold differences in the amount of leachable manganese between samples of moderate to dense welding. Leachable manganese is more variable and attains highest values in the moderately to densely welded samples of the Bullfrog and Tram units, compared to similarly welded samples of Topopah Spring and older tuffs.

Radiographic observations that indicate an association of uranium with manganese oxides are corroborated by the leachate data. The amount of leachable manganese in 21 welded tuffs (10 to 75 percent of the amount present) correlates positively (fig. 5) with the amount of leachable uranium (1.5 to 25 percent of the amount present). A correlation coefficient of 0.96 is reduced to 0.56 if a highly fractured sample (#26) is omitted, but the correlation remains significant at the 95 percent confidence level. In contrast, leachable manganese does not correlate with leachable calcium or with water content, the latter estimated by loss on ignition (LOI) at 900°C (table 2). For example, samples of similar LOI occur in similarly welded intervals of the Topopah Spring and Bullfrog Members, but leachable manganese differs by up to a factor of five (compare samples 1-5 with 21-23 of table 2, fig. 4). A possible cause of systematic differences in leachable manganese may be the location of the Topopah Spring Member above the water saturation level (1900 ft), which is an obvious control on the development of alteration. The amount of leachable manganese also appears to be highest in welded tuff units that contain high proportions of manganese oxides in megascopic

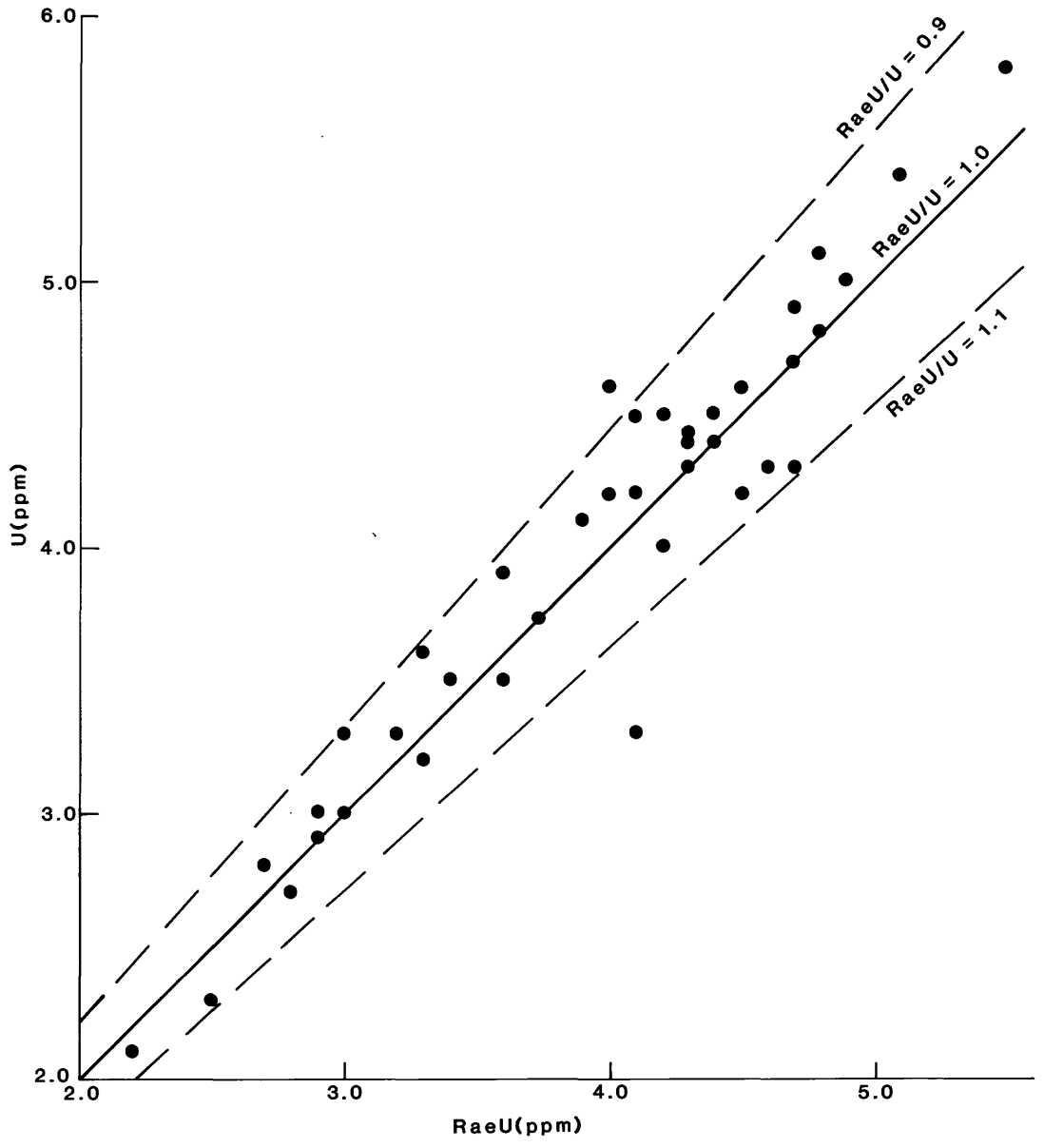


Figure 3.--RaeU/U ratios in 39 whole-rock samples from Yucca Mountain, Nevada. Ratios in excess of 1.0 ± 0.1 (2 sigma) are analytically significant indications of disequilibrium abundances of uranium and its long-lived daughters. The error envelope for the ratio is delimited by dashed lines and is calculated from the precision estimates for both RaeU and U determinations.

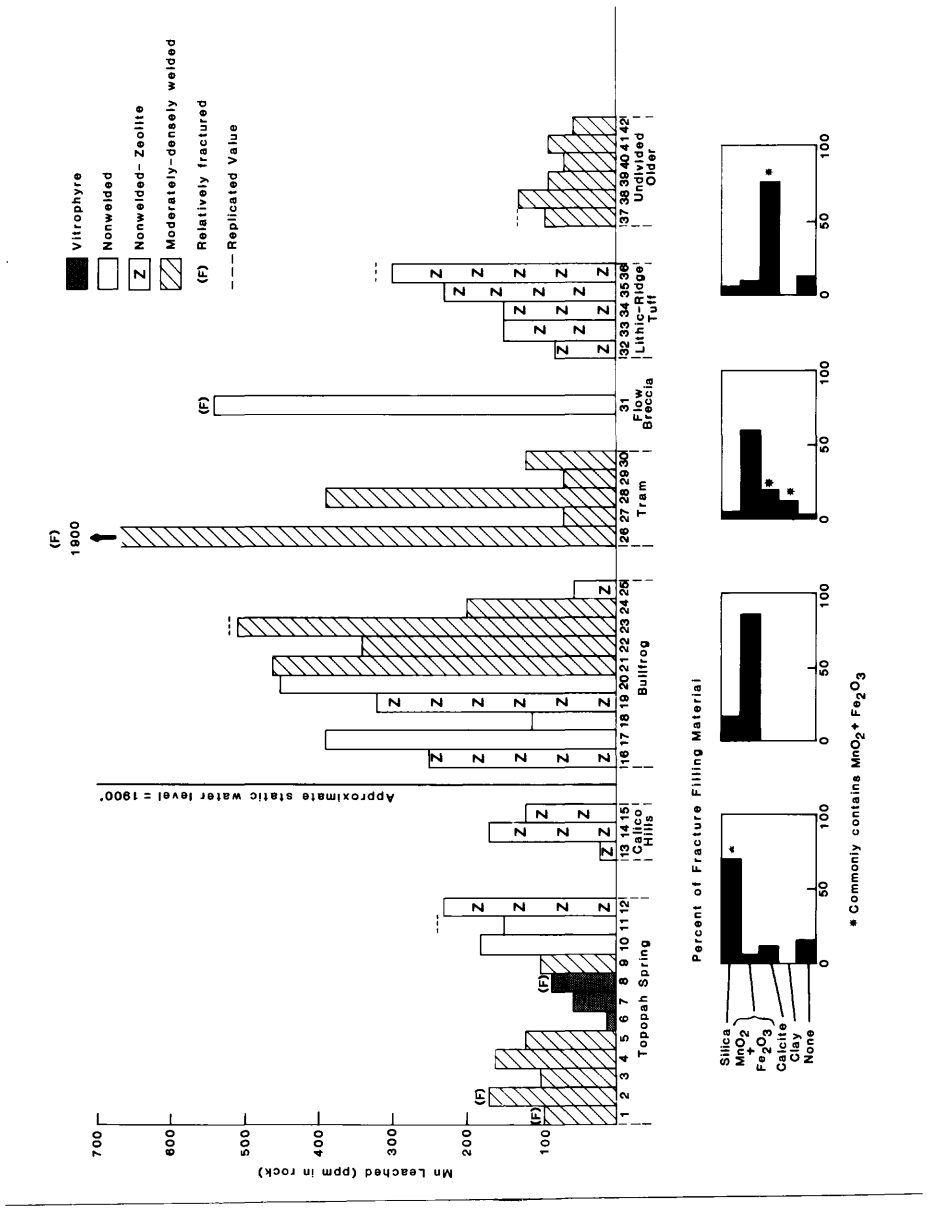


Figure 4.--The Manganese content of leachates (as ppm in rock) plotted versus sample number. The abundance of fracture filling materials in each of four welded ash flows is included for comparison.

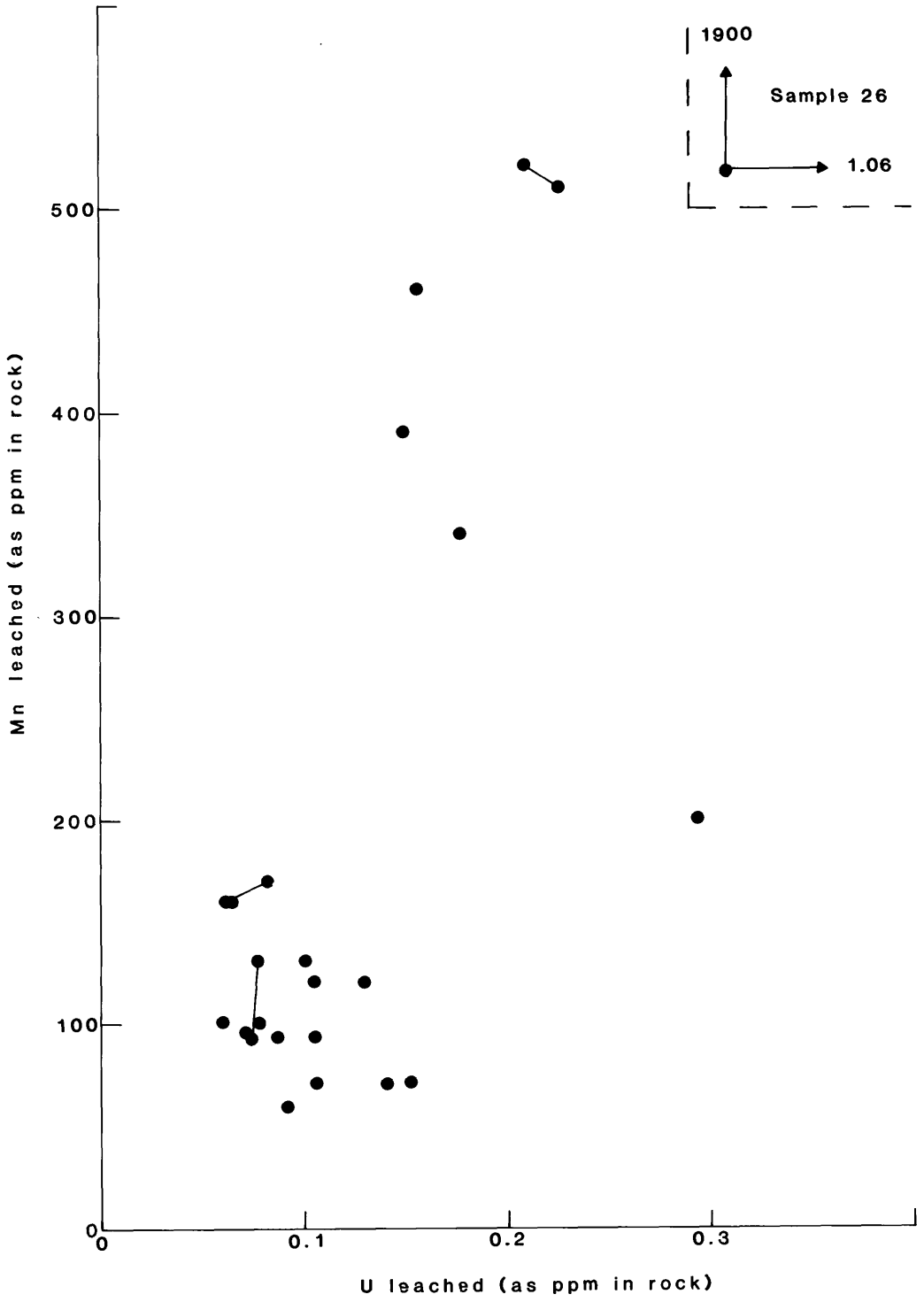


Figure 5.--The manganese content of leachates of moderately to densely welded tuffs plotted versus the uranium content of leachates. Tie lines connect leachate compositions of replicated samples. One highly fractured sample (#26) plots off the figure as shown.

fractures (fig. 4). Likewise, the amount of leachable calcium tends to be high in welded tuff units that contain high proportions of calcite in megascopic fractures (fig. 6). Thus, the observations suggest that the alteration mineralogy of competent, welded tuffs is similar to that observed in megascopically fractured intervals of the same unit.

The single sample of rhyodacite flow breccia is anomalous in its leaching characteristics; combining low leachable uranium (fig. 7) (1.5 percent of the amount present) with relatively high leachable manganese (75 percent of the amount present). This may indicate a fundamental difference in the distribution of uranium that is related to bulk composition, or it may indicate prior removal of uranium, as suggested by a high RaeU/U ratio (fig. 3). Net removal of uranium from whole-rocks that contain uranium adsorbents may occur if local pore-water compositions stabilize dissolved uranium or if a low Mn-oxide/solution ratio prevails (Balistrieri and Murray, 1982). The latter condition is likely in host rocks of high transmissivity, such as the sample of fractured and faulted flow breccia.

As mentioned, the amount of leachable calcium in moderately to densely welded tuffs is typically high in units that contain observable calcite in large fractures (fig. 6). The relatively large amounts of leachable calcium in nonwelded and zeolitized tuffs may indicate additional leaching of calcium from zeolite. The Topopah Spring Member is the only sampled unit in which welded tuffs have consistently low amounts of leachable calcium and manganese, even in relatively fractured intervals. This, combined with low to moderate LOI (table 2) suggest relatively small amounts of alteration products in welded tuffs of this unit.

Leachable aluminum was monitored as an index of the complicating effect of aluminosilicate dissolution, and ranged from 0.25 to 1.5 percent of the amount present, averaging 0.83 percent. Although a negative correlation of leachable aluminum with degree of welding is suggested by the data, the generally small percentages of dissolved aluminum compared to other elements supports the assumption of minimal aluminosilicate dissolution. For comparison, average leached percentages of Mn, Ca, Fe and U are 38.7, 22.9, 13.1, and 4.3, respectively (table 5). Leachable iron is more difficult to interpret because of relatively poor precision of dissolved iron obtained from similarly leached splits of the same powdered sample (table 4). An explanation for this is not readily apparent but a more restricted particle size range for leached powders and a more careful sample splitting procedure may help to reduce this variability. The reported values of dissolved iron do not correlate with dissolved manganese or dissolved uranium. This is counter to the apparent association of secondary iron oxides with

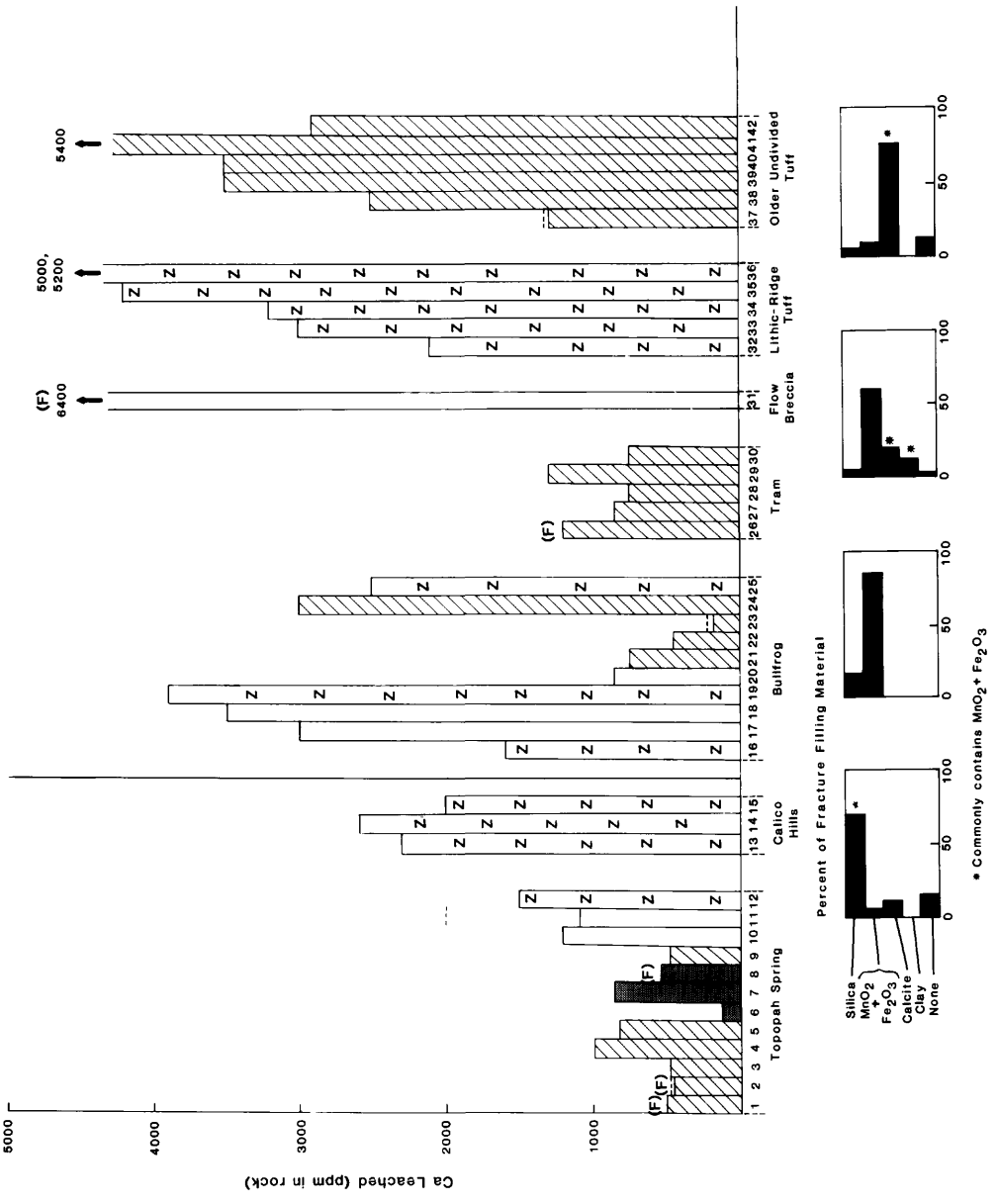


Figure 6.--The calcium content of leachates (as ppm in rock) plotted versus sample number. The abundance of fracture filling materials in each of four welded ash-flows are included for comparison. Symbols are those of figure 4.

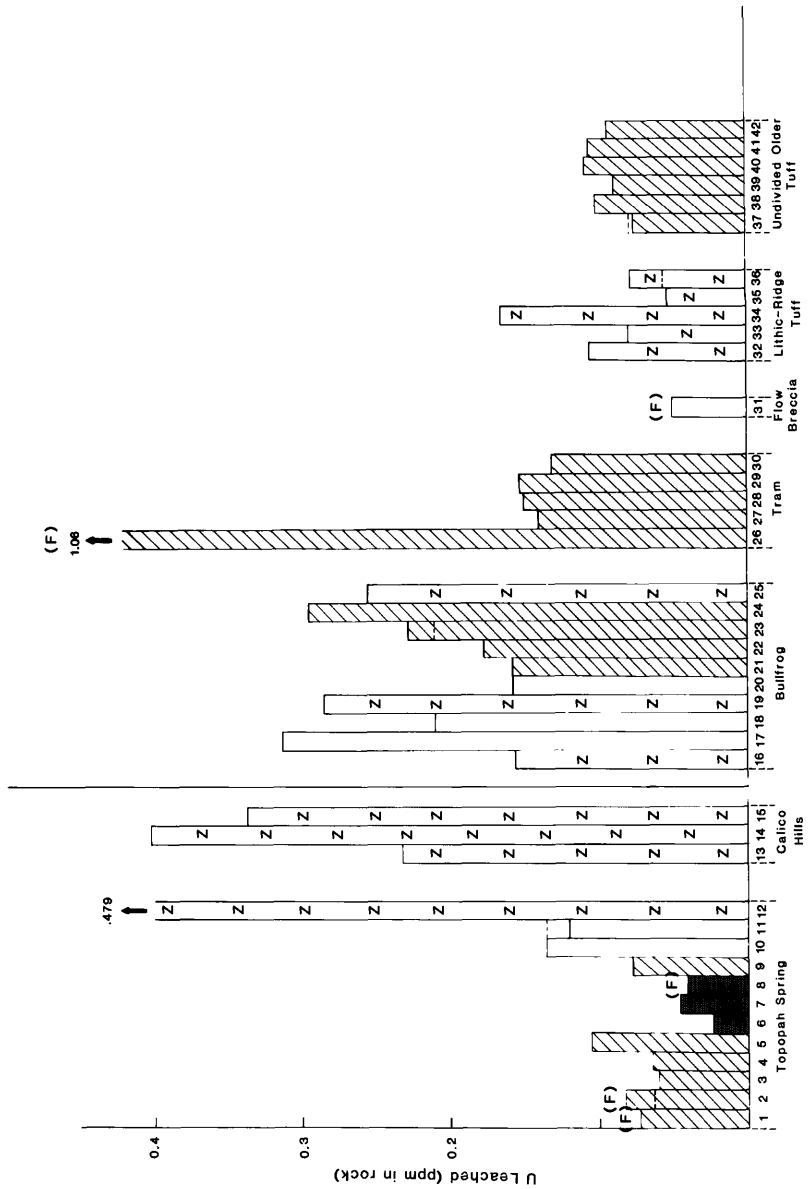


Figure 7.--The uranium content of leachates (as ppm in rock) plotted versus sample number. Symbols are those of figure 4.

manganese oxides and uranium as is observed in thin sections and radiographs. More precise data for dissolved iron are required in order to explain this discrepancy.

Conclusions

Selective leaching is presented as a sensitive method for evaluating moderately to densely welded ash-flow tuffs as host rocks for radioactive waste. The amount of manganese leached by a mildly reducing, acetic-acid-based solvent provides a quantitative estimate of the amount of manganese oxides that are present as incipient alteration products and that act as adsorbents for dissolved uranium. Leachable uranium correlates with leachable manganese, and the association of uranium with manganese oxides is confirmed by fission-track radiography. In addition, the amount of calcium leached from ash-flow tuffs provides an estimate of the relative abundance of calcite ± zeolite.

The results are used to rank welded tuff units that appear similar on the basis of other criteria such as petrographic freshness, bulk chemistry, RaeU/U, water content, or degree of welding. If a minimum degree of time-integrated rock/water interaction is desirable, favored units should contain relatively small amounts of incipient alteration products such as manganese oxides. Conversely, if the presence of adsorbents for radionuclides is deemed a more important criteria, abundant manganese oxides are preferred. Of the studied units, the Topopah Spring Member of the Paintbrush Tuff shows the least evidence for incipient alteration; a finding that is consistent with its location above the present static water level. More deeply buried units such as the Bullfrog Member and Tram Unit contain the greatest abundance of manganese oxides. In general, the relative abundance of manganese oxides and calcite in competent, densely welded tuffs mimics their observed relative abundance in macroscopically fractured intervals of the same tuff unit.

In spite of differences in the amount of incipient alteration and of adsorbed uranium, agreement of actual uranium concentrations with radiometric uranium concentrations (RaeU) of individual whole-rock samples indicates dominant closed-system behavior of uranium and its long-lived daughters and suggests that the amount of recent (<300,000 yr) uranium mobility is minor or dominantly intergranular. Thus, the present physical-chemical environment of the studied rocks appears to limit uranium mobility; a desirable attribute of rocks in the vicinity of uranium-bearing radioactive waste.

These studies should be extended to include more samples from preferred units and samples from additional holes that allow comparison of the same unit above and below the static water level. Extension of the technique to other rocks (basalt, granite) also merits investigation.

Acknowledgments

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Table 1. Core samples, hole USW-G1, Yucca Mountain, Nevada.

Sample Number	Depth (ft)	Description[1/]	Geologic Unit[1/]
1	755.2-755.6	Densely welded, devitrified, lithopysae, fractured	Topopah Spring Member, Paintbrush Tuff
2	765.6-766.2	" "	" "
3	928.0-928.8	" "	" "
4	1184.6-1185.0	" "	" "
5	1252.2-1252.6	" "	" "
6	1302.9-1303.3	Vitrophyre	" "
7	1321.4-1321.9	Vitrophyre, moderately fractured	" "
8	1335.2-1335.8	Vitrophyre, highly fractured	" "
9	1348.4-1348.8	Moderately welded, vitric	" "
10	1369.8-1370.3	Nonwelded, vitric	" "
11	1389.4-1390.1	Nonwelded, vitric	" "
12	1399.2-1399.8	Nonwelded, slightly zeolitized and silicified	" "
13	1453.8-1454.4	Nonwelded, zeolitized, slightly argillic	Tuffaceous beds of Calico Hills
14	1728.5-1729.2	" "	" "
15	1770.5-1771.0	Bedded, zeolitized, moderately silicified	" "
16	2225.0-2225.7	Nonwelded, zeolitized, slightly argillic	Bullfrog Member, Crater Flat Tuff
17	2242.6-2243.1	Nonwelded, vapor phase crystallization	" "
18	2245.3-2245.9	Nonwelded, devitrified, slightly silicified	" "
19	2261.5-2262.2	Nonwelded, devitrified, slightly zeolitized	" "
20	2443.3-2443.9	Nonwelded, vapor phase crystallization	" "
21	2456.1-2456.7	Moderately welded, devitrified	" "
22	2474.0-2474.5	Densely welded, devitrified	" "
23	2544.2-2544.7	" "	" "
24	2557.0-2557.5	Moderately welded, devitrified	" "
25	2616.4-2617.0	Bedded, zeolitized	" "
26	2736.2-2736.8	Moderately welded, devitrified, fractured	Tram Unit, Crater Flat Tuff
27	2745.6-2746.2	" "	" "
28	2800.8-2801.1	" "	" "
29	2895.9-2896.3	" "	" "
30	2991.1-2991.6	" "	" "
31	3620.9-3621.5	Brecciated, devitrified, fractured, faulted	Rhyodacite flow breccia
32	4199.6-4200.0	Nonwelded, zeolitic, slightly argillic	Tuff of Lithic Ridge
33	4305.6-4306.1	" "	" "
34	4506.0-4506.4	" "	" "
35	4633.7-4634.0	" "	" "
36	4810.9-4811.3	" "	" "
37	5215.0-5215.5	Moderately welded, devitrified, slightly zeolitic	Older tuff
38	5290.6-5291.0	" "	" "
39	5635.8-5636.2	" "	" "
40	5739.0-5739.4	" "	" "
41	5786.7-5787.1	" "	" "
42	5880.6-5881.1	" "	" "

[1/] Sample descriptions and lithologic units from Spengler and others, 1981 (Plate 2).

Table 2. Core sample compositions [1/], hole USW-G1, Yucca Mtn., Nevada.
(Except where noted all units in weight percent, uncorrected for volatile content. Leaders (---) denote no data.

Sample Number	Geologic Unit	SiO_2	Al_2O_3	Fe_2O_3 [2/]	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	LOI [3/]	Σ	ppm by weight U	RaeU	Th
1	Topopah Spring Member, Paintbrush Tuff	75.3	12.3	2.06	0.16	0.44	3.22	4.88	0.08	<0.05	0.07	0.46	99.0	4.2	4.0	24.7
2	" "	75.7	12.4	1.83	0.15	0.44	3.21	4.91	0.08	<0.05	0.06	0.35	99.1	4.5	4.1	24.9
3	" "	75.5	12.5	1.69	0.17	0.45	3.16	4.91	0.08	<0.05	0.06	0.53	99.0	4.4	4.3	24.8
4	" "	75.0	12.4	1.83	0.32	0.48	2.97	4.83	0.08	<0.05	0.07	1.36	99.3	4.5	4.2	24.4
5	" "	75.1	12.4	1.79	0.23	0.51	3.12	4.76	0.08	<0.05	0.06	1.04	99.1	4.6	4.0	24.3
6	" "	73.5	12.4	1.21	0.10	0.51	3.38	4.59	0.08	<0.05	0.06	3.34	99.2	5.0	4.9	24.5
7	" "	73.5	12.4	1.00	0.12	0.59	3.29	4.54	0.08	<0.05	0.06	3.66	99.2	5.1	4.8	24.5
8	" "	73.3	12.5	1.16	0.11	0.55	3.29	4.57	0.08	<0.05	0.06	3.40	99.0	4.8	4.8	24.2
9	" "	73.3	12.5	1.26	0.11	0.54	3.14	4.71	0.08	<0.05	0.06	3.30	99.0	4.7	4.7	24.5
10	" "	73.1	12.5	1.23	0.12	0.62	2.70	4.78	0.08	<0.05	0.07	4.15	99.3	4.3	4.6	24.2
11	" "	72.6	12.2	1.02	0.10	0.63	2.64	4.81	0.08	<0.05	0.07	4.88	99.0	4.5	4.4	24.5
12	" "	74.3	10.6	1.24	0.10	0.69	2.64	3.93	0.07	<0.05	0.05	5.61	99.2	5.8	5.5	20.3
13	Tuffaceous beds of Calico Hills	67.6	11.9	0.83	<0.10	0.69	2.68	4.57	0.06	<0.05	<0.02	9.65	98.2	4.0	4.2	23.9
14	" "	69.9	11.6	1.10	0.12	0.77	2.74	4.15	0.06	<0.05	0.04	7.95	98.4	4.6	4.5	22.5
15	" "	71.8	11.8	1.40	0.24	1.20	2.79	3.76	0.10	<0.05	0.04	5.64	98.8	3.3	3.0	18.8
16	Bullfrog Member, Crater Flat Tuff	69.3	12.8	1.44	0.19	0.81	2.52	5.35	0.11	<0.05	0.06	5.86	98.4	2.9	2.9	21.3
17	" "	71.0	11.2	1.36	0.18	1.36	2.79	3.01	0.09	<0.05	0.07	7.73	98.8	3.5	3.6	18.5
18	" "	72.4	10.5	1.41	0.12	1.52	2.83	2.18	0.09	<0.05	0.02	8.14	99.2	5.4	5.1	22.4
19	" "	69.0	12.3	1.39	0.20	1.59	2.85	3.55	0.11	<0.05	0.07	7.99	99.1	4.2	4.1	17.4
20	" "	74.4	13.1	1.33	0.16	0.61	3.31	4.79	0.11	<0.05	0.10	1.05	99.0	4.3	4.3	20.1
21	" "	74.9	13.1	1.37	0.16	0.60	3.43	4.75	0.10	<0.05	0.09	0.95	99.5	4.9	4.7	22.4
22	" "	74.0	13.1	1.49	0.15	0.60	3.54	4.83	0.10	<0.05	0.09	0.71	98.6	4.4	4.4	22.8
23	" "	75.2	12.0	2.29	0.12	0.41	2.50	5.90	0.10	<0.05	0.11	0.54	99.2	4.2	4.5	21.0
24	" "	69.0	12.4	1.51	0.22	1.33	3.60	3.05	0.11	<0.05	0.05	7.88	99.2	3.9	3.6	21.0
25	" "	69.1	12.5	1.77	0.28	1.20	3.63	3.22	0.14	<0.05	0.04	7.53	99.4	3.5	3.4	21.2
26	Tram Unit Crater Flat Tuff	71.4	12.5	1.27	0.24	1.25	2.92	4.21	0.11	<0.05	0.32	4.93	99.2	4.3	4.7	21.4
27	" "	74.0	12.2	1.43	0.21	0.98	2.44	5.25	0.12	<0.05	0.03	2.37	99.0	3.7	3.7	21.5
28	" "	74.0	12.7	1.77	0.27	0.82	2.75	5.36	0.21	<0.05	0.08	0.87	98.8	---	4.7	21.3
29	" "	75.0	12.5	1.72	0.22	0.77	2.97	5.07	0.18	<0.05	0.04	0.59	99.1	---	4.4	22.0
30	" "	73.6	13.0	1.76	0.25	0.74	2.85	5.73	0.19	<0.05	0.11	0.55	98.9	---	4.6	22.5
31	Flow Breccia	62.0	16.3	4.93	1.14	4.36	3.17	3.11	0.85	0.29	0.09	2.76	99.0	3.3	4.1	17.8
32	Tuff of Lithic Ridge	70.7	13.6	2.55	0.55	1.10	3.35	4.17	0.29	0.07	0.04	2.98	99.4	3.0	2.9	18.2
33	" "	70.8	13.1	2.58	0.51	1.36	3.08	4.40	0.25	0.06	0.07	2.94	99.2	3.2	3.3	18.4
34	" "	69.9	13.8	2.82	0.69	1.19	3.01	4.47	0.32	0.08	0.03	2.93	99.2	2.1	2.2	18.3
35	" "	69.3	13.8	2.99	0.73	1.62	2.87	4.07	0.35	0.09	0.08	3.33	99.2	2.3	2.5	18.1
36	" "	71.0	13.4	2.36	0.61	1.36	2.87	4.47	0.27	0.07	0.06	2.95	99.4	2.7	2.8	18.5
37	Older tuff	72.8	13.0	1.96	0.30	0.73	3.25	4.98	0.20	<0.05	0.05	1.80	99.1	4.4	4.3	20.8
38	" "	72.5	13.2	1.69	0.35	0.92	2.90	5.43	0.19	<0.05	0.05	1.75	99.0	4.1	3.9	19.5
39	" "	67.6	14.6	3.11	0.76	2.33	4.17	3.27	0.38	0.12	0.07	2.90	99.3	3.3	3.2	16.7
40	" "	66.1	15.9	3.56	0.90	2.85	4.01	3.05	0.46	0.14	0.08	2.45	99.5	2.8	2.7	16.5
41	" "	65.2	16.4	3.66	0.98	2.88	3.79	3.32	0.49	0.15	0.07	2.01	99.0	3.6	3.3	17.5
42	" "	66.5	15.8	3.60	0.96	2.15	4.16	3.37	0.48	0.15	0.06	1.85	99.1	3.0	3.0	17.2

1/ Major element analyses by X-ray fluorescence, U by a delayed-neutron technique, RaeU and Th by gamma spectrometry. Most data have a precision equal to or better than ±10 percent (1 sigma).
2/ All iron calculated as Fe_2O_3.
3/ Loss on ignition to 900°C.

Table 3. Volatile-corrected compositions, hole USW-G1, Yucca Mountain, Nevada.

No.	Depth (ft)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	
1	755.2-755.6	76.4	12.5	2.09	0.16	0.45	3.26	4.94	0.08	<0.05	0.07	
2	765.6-766.2	76.7	12.5	1.85	0.15	0.45	3.25	4.97	0.08	<0.05	0.06	
3	928.0-928.8	76.7	12.7	1.72	0.17	0.46	3.21	4.99	0.08	<0.05	0.06	
4	1184.6-1185.0	76.6	12.6	1.87	0.33	0.49	3.03	4.93	0.08	<0.05	0.06	
5	1252.2-1252.6	76.6	12.6	1.83	0.23	0.52	3.17	4.84	0.08	<0.05	0.06	
6	1302.9-1303.3	76.7	12.9	1.26	0.10	0.53	3.53	4.79	0.08	<0.05	0.06	**Topopah Spring**
7	1321.4-1321.9	76.9	13.0	1.05	0.13	0.62	3.44	4.74	0.08	<0.05	0.06	
8	1335.2-1335.8	76.7	13.1	1.21	0.10	0.58	3.44	4.78	0.08	<0.05	0.06	
9	1348.4-1348.8	76.6	13.0	1.32	0.11	0.56	3.27	4.91	0.08	<0.05	0.06	
10	1369.8-1370.3	76.8	13.2	1.29	0.13	0.65	2.84	5.02	0.08	<0.05	0.07	
11	1389.4-1390.1	77.1	13.0	1.08	0.11	0.67	2.81	5.11	0.08	<0.05	0.07	
12	1399.2-1399.8	79.4	11.3	1.32	0.11	0.74	2.81	4.19	0.06	<0.05	0.05	
13	1453.8-1454.4	76.3	13.4	0.94	0.11	0.78	3.02	5.16	0.07	<0.05	<0.02	
14	1728.5-1729.2	77.3	12.8	1.22	0.13	0.85	3.02	4.57	0.07	<0.05	0.04	**Calico**
15	1770.5-1771.0	77.1	12.7	1.50	0.26	1.28	2.97	4.01	0.11	<0.05	0.04	
16	2225.0-2225.7	74.9	13.8	1.56	0.20	0.87	2.71	5.74	0.12	<0.05	0.06	
17	2242.6-2243.1	78.0	12.3	1.49	0.20	1.49	3.05	3.29	0.10	<0.05	0.08	
18	2245.3-2245.9	79.5	11.5	1.55	0.13	1.67	3.11	2.38	0.10	<0.05	0.02	
19	2261.5-2262.2	75.7	13.5	1.53	0.22	1.75	3.13	3.90	0.12	<0.05	0.08	
20	2443.3-2443.9	76.0	13.4	1.37	0.16	0.62	3.37	4.88	0.11	<0.05	0.10	**Bullfrog**
21	2456.1-2456.7	76.0	13.3	1.39	0.16	0.61	3.48	4.82	0.10	<0.05	0.09	
22	2474.0-2474.5	75.6	13.4	1.52	0.15	0.61	3.61	4.92	0.10	<0.05	0.09	
23	2444.2-2544.7	76.2	12.2	2.32	0.12	0.41	2.52	5.94	0.10	<0.05	0.11	
24	2557.0-2557.5	75.6	13.5	1.65	0.24	1.46	3.94	3.34	0.11	<0.05	0.05	
25	2616.4-2617.0	75.2	13.6	1.93	0.30	1.31	3.95	3.50	0.15	<0.05	0.04	
26	2736.2-2736.8	75.7	13.2	1.35	0.25	1.33	3.09	4.46	0.12	<0.05	0.34	
27	2745.6-2746.2	76.6	12.6	1.48	0.22	1.01	2.52	5.42	0.12	<0.05	0.03	
28	2800.8-2801.1	75.6	13.0	1.81	0.28	0.84	2.81	5.47	0.21	<0.05	0.08	**Tram**
29	2895.9-2896.3	76.1	12.7	1.75	0.22	0.78	3.02	5.15	0.18	<0.05	0.04	
30	2991.1-2991.6	74.8	13.2	1.79	0.25	0.75	2.90	5.83	0.19	<0.05	0.11	
31	3620.9-3621.5	64.4	16.9	5.12	1.18	4.53	3.29	3.23	0.88	0.30	0.09	**Rhyodacite Breccia**
32	4199.6-4200.0	73.3	14.1	2.64	0.57	1.14	3.47	4.31	0.30	0.07	0.04	
33	4305.6-4306.1	73.6	13.6	2.68	0.53	1.40	3.18	4.53	0.26	0.06	0.07	
34	4506.0-4506.4	72.6	14.3	2.93	0.72	1.24	3.13	4.64	0.33	0.08	0.03	**Lithic-Ridge**
35	4633.7-4634.0	72.3	14.4	3.12	0.76	1.69	2.99	4.25	0.37	0.09	0.08	
36	4810.9-4811.3	73.6	13.9	2.44	0.63	1.40	2.96	4.61	0.28	0.07	0.06	
37	5215.0-5215.5	74.8	13.4	2.01	0.31	0.75	3.33	5.10	0.21	<0.05	0.05	
38	5290.6-5291.0	74.6	13.6	1.74	0.36	0.95	2.98	5.58	0.20	<0.05	0.05	
39	5635.8-5636.2	70.1	15.1	3.23	0.79	2.41	4.31	3.38	0.39	0.12	0.07	**Older tuffs**
40	5739.0-5739.4	68.1	16.4	3.67	0.93	2.93	4.12	3.14	0.47	0.14	0.08	
41	5786.7-5787.1	67.2	16.9	3.77	1.01	2.97	3.91	3.43	0.51	0.15	0.07	
42	5880.5-5881.1	68.4	16.2	3.70	0.99	2.21	4.28	3.47	0.49	0.15	0.06	

Table 4. Leachate compositions (as ppm in rock).
Replicated analyses are shown in parentheses.

Sample Number	Geologic Unit	Ca	Mn	U	Fe	Al
1	Topopah Springs Member, Paintbrush Tuff	490	94	.072	1600	340
2	" "	460(440)	160(170)	.062(.083)	7400(8600)	290(310)
3	" "	470	100	.060	1900	290
4	" "	990	160	.065	3500	440
5	" "	820	120	.105	1400	440
6	" "	110	11	.023	280	170
7	" "	850	56	.044	1400	370
8	" "	530	85	.041	1200	300
9	" "	480	100	.078	690	390
10	" "	1200	180	.134	2500	770
11	" "	2000(1100)	240(150)	.134(.110)	1000(290)	950(860)
12	" "	1500	230	.479	2500	620
13	Tuffaceous beds of Calico Hills	2300	19	.232	450	910
14	" "	2600	170	.402	1800	830
15	" "	2000	120	.337	990	890
16	Bullfrog Member, Crater Flat Tuff	1600	250	.155	1200	640
17	" "	3000	390	.313	390	760
18	" "	3500	110	.209	2500	380
19	" "	3900	320	.286	420	670
20	" "	860	450	.158	440	320
21	" "	760	460	.158	1500	230
22	" "	460	340	.178	930	390
23	" "	220(180)	520(510)	.211(.227)	6200(5700)	390(410)
24	" "	3000	200	.295	590	1100
25	" "	2500	56	.256	1100	760
26	Tram Unit Crater Flat Tuff	1200	1900	1.06	1000	610
27	" "	850	69	.141	560	490
28	" "	770	390	.149	1900	490
29	" "	1300	70	.152	2200	400
30	" "	770	120	.130	1700	440
31	Flow Breccia	6400	540	.050	5500	540
32	Tuff of Lithic Ridge	2100	80	.104	1800	720
33	" "	3000	150	.078	1400	780
34	" "	3200	150	.164	3200	630
35	" "	4200	230	.053	1200	800
36	" "	5000(5200)	320(300)	.054(.077)	3200(2200)	560(680)
37	Older Undivided Tuff	1300(1300)	130(93)	.077(.074)	4500(1500)	450(740)
38	" "	2500	130	.101	660	760
39	" "	3500	92	.087	990	1000
40	" "	3500	69	.107	990	950
41	" "	5400	92	.105	1400	750
42	" "	2900	57	.092	880	750
Blank = Leached spectrometric grade SiO_2		37	2	.004	9	16

Table 5. Average leached amounts, as percentages of whole-rock abundances.

	Ca	Mn	U	Fe	Al
All (42)	22.9 ± 10.2	38.7 ± 21.5	4.3 ± 4.1	13.1 ± 11.4	0.83 ± 0.31
Vitrophyre (3)	11.6 ± 8.2	11.0 ± 8.1	0.77 ± 0.23	12.2 ± 8.1	0.44 ± 0.16
Moderately-to-Densely Welded (21)	18.3 ± 7.4	33.5 ± 19.6	4.1 ± 4.9	14.2 ± 14.0	0.76 ± 0.29
Nonwelded and Zeolitic (18)	30.1 ± 8.5	49.8 ± 18.8	5.3 ± 2.8	12.1 ± 8.0	0.99 ± 0.24