*The Occurrence
and Distribution of Erionite
at Yucca Mountain, Nevada*

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THE OCCURRENCE AND DISTRIBUTION OF ERIONITE AT YUCCA MOUNTAIN, NEVADA

by

Steve J. Chipera and David L. Bish

ABSTRACT

We have conducted an investigation to determine the occurrence and distribution of erionite, a potential carcinogen, at Yucca Mountain, Nevada. Using x-ray powder diffraction techniques yielding detection limits to below 0.05 wt%, we positively identified erionite in only 3 out of 76 bulk and 12 fracture samples investigated. The three erionite-bearing samples (J12-620/630, UE-25a#1-1296.2, and USW G4-1314) all occur above the static water level in clay/zeolite-rich horizons near the top of vitrophyres. Erionite occurs as trace amounts of less than 1 wt% in the whole rock, although it may occur locally in significant amounts as fracture fillings (e.g., UE-25a#1-1296.2 where it comprises approximately 45 wt% of the fracture-filling material). All three occurrences appear to be extremely isolated cases since erionite was not detected in neighboring samples. Erionite at Yucca Mountain apparently formed only in localized microenvironments, possibly restricted to fractures. Since erionite occurs in trace amounts only in extremely isolated instances, it should pose little or no health hazard to workers in the potential repository at Yucca Mountain or to the public. The amounts of erionite liberated to the biosphere should be negligible, particularly when compared with the amounts of erionite occurring naturally at the surface in Nevada and surrounding states.

I. INTRODUCTION

Before 1959, the fibrous zeolite erionite was considered extremely rare and was known to occur only in a deposit at Durkee, Oregon (Gottardi and Galli 1985). It was not until Deffeyes (1959) reported erionite from several sedimentary occurrences in the western U.S. that erionite was recognized to be a relatively common zeolite. Since then, it has been found in numerous

sedimentary zeolite deposits throughout the world (Surdam and Sheppard 1978). In the past 10 years, additional attention has been focused on erionite due to its postulated association with malignant mesothelioma in Turkey, although mineralogic studies demonstrate that this connection is not clear (Mumpton 1979). Mumpton (1979) showed that, although erionite does occur in the villages where malignant mesothelioma occurs, erionite also occurs in Turkish villages with no reported cases of mesothelioma, suggesting that some other agent may be responsible for the high incidence of mesothelioma. More recently, Rohl et al. (1982) re-examined lung tissue and rock samples from south-central Turkey. They found significant occurrences of tremolite and chrysotile (asbestos minerals) in addition to erionite in both environmental and lung tissue samples. Suzuki and Kohyama (1988) studied the carcinogenic and fibrogenic effects of the mineral zeolites erionite and mordenite and synthetic zeolite 4A. Their results show that erionite produced malignant tumors at a high rate after considerable latency and suggest that the long-term persistence of the fibrous erionites in the mesothelium tissue seemed to be important in the development of mesothelioma.

Because of the potential link between erionite and malignant mesothelioma, and to address possible concerns about exposure of repository workers or the public to hazardous minerals, we have analyzed a wide assortment of samples to assess the distribution and abundance of erionite at Yucca Mountain. Yucca Mountain, a potential site for a high-level radioactive waste repository, is being studied by the Yucca Mountain Project (YMP), under direction of the Yucca Mountain Project Office of the U.S. Department of Energy, Nevada Operations Office. Quality Assurance information for this report is contained in Appendix I.

II. METHODOLOGY

A total of 76 bulk rock and 12 fracture samples were chosen from 13 drill holes (Fig. 1) at varying depths to ensure thorough coverage around Yucca Mountain. Samples were also chosen to provide a wide assortment of rock types, ranging from zeolite rich to zeolite poor with varying amounts of glass and smectite.

All samples were analyzed on an automated Siemens D500 x-ray powder diffractometer using pulse height analysis, Cu K α radiation, 1.0° receiving and divergence slits, 0.05° scatter slit, incident- and diffracted-beam Soller slits, and a graphite monochromator. X-ray runs were conducted twice on each sample. Samples were first examined from 2° to 36° 2 θ , with a step size of 0.02° and count times of at least 2 s per step to characterize the total mineralogy. They were then run from at least 6° to 9° 2 θ , with a step size of 0.02° and count times of between 120 and 360 s per step to improve the peak-to-background ratio in the region of the major erionite x-ray reflection (100) at about 7.67° 2 θ .

Fig. 1. Location map of Yucca Mountain, Nevada, showing the outline of the exploration block for the Yucca Mountain Project and the location of most drill holes mentioned in the text. Drill hole J-12 is located outside of this figure to the southeast and is shown on the location map published in Bish et al. (1984).

Samples were prepared either as powders pressed into a cavity in a glass plate or as water-smears on an off-axis-cut (zero background) quartz plate. Water-smear mounts were glycolated to shift any smectite peaks to lower 2θ values, thus reducing the smectite overlap on the erionite 100 reflection. The glycolated mounts were x-rayed in an ethylene-glycol-saturated atmosphere using an enclosed sample cell fitted with x-ray-transparent windows.

The erionite 100 reflection at approximately $7.67^\circ 2\theta$ is commonly used to indicate the presence of erionite because this is its most intense reflection. Identification of trace amounts of erionite in clinoptilolite-bearing samples, however, is complicated by the presence of the relatively weak 110 clinoptilolite reflection at approximately $7.5^\circ 2\theta$ [note the calculated clinoptilolite pattern in von Ballmoos (1984)]. The 110 clinoptilolite peak can result in the misidentification of erionite in clinoptilolite-bearing samples, an easy mistake since none of the observed x-ray diffraction patterns for clinoptilolite from the Joint Committee on Powder Diffraction Standards (JCPDS 1986) indicate the existence of this reflection. Great care must be used therefore when postulating the presence of erionite in samples that contain clinoptilolite.

Bish and Chipera (1987; in prep.) show that erionite coexisting with clinoptilolite can be detected in amounts below 0.05 wt%. They prepared numerous mixtures of erionite in clinoptilolite ranging from 0.05 to 20.0 wt% erionite. Mixtures containing less than 0.05 wt% (500 ppm) erionite were not prepared due to the uncertainties involved in weighing and homogenizing very small amounts of erionite with large amounts of clinoptilolite. They found that erionite in relatively pure clinoptilolite can be readily detected down to 0.25 wt% using average run conditions, and amounts down to 0.05 wt% can be detected using long count-time runs. Because of diffraction from smectite, the detection limits of erionite in clinoptilolite are significantly worse when smectite is present, but glycolation of the sample allows increased resolution of the clinoptilolite/erionite reflections by shifting the smectite peaks to lower 2θ values. In samples that do not have clinoptilolite or smectite, the limit of detection for erionite is below 0.05%.

Scanning electron microscope (SEM) images were obtained using both secondary- and backscattered-electron modes on an ISI model DS-130 scanning electron microscope operating between 19 and 20 kV. Samples were prepared by mounting small chips on aluminum stubs and applying a gold coat.

III. RESULTS AND DISCUSSION

Erionite was not found to be a common mineral in detectable abundances (>0.05 wt%) at Yucca Mountain. Out of 88 samples analyzed, erionite was positively identified in only 3 (J12-620/630, UE-25a#1-1296.2, and USW G4-1314). In two of the three cases, erionite was

detected in amounts of less than 1 wt% in the whole rock, and in the third case (UE-25a#1-1296.2), the erionite was restricted to a fracture. All three occurrences are above the water table in clay/zeolite-rich horizons at the top of vitrophyres. Mineral abundances for the samples analyzed are listed in Table I. All data except for the fracture samples J13-1345 and UE-25a#1-1296.2 were taken from Bish and Chipera (1989). The fracture samples were analyzed for this report using methods described by Bish and Chipera (1989).

Erionite from sample UE-25a#1-1296.2 occurs in a fracture at the top of the Topopah Spring Member vitrophyre. Whole-rock XRD analyses of samples 20 ft above and 28 ft below the fracture did not show detectable amounts of erionite. Nine neighboring fracture samples ranging from 54 ft above to 66 ft below and as close as 6 ft to the erionite-containing fracture (samples provided by B. Carlos) also do not show any evidence of erionite. Qualitative mineralogic analyses for these samples (Table II) were obtained using the methods described in Bish and Chipera (1989). A fracture sample at 1282.6 ft (13.6 ft above the erionite-bearing sample) contains only clinoptilolite. Likewise, a sample at 1301.5-1302.2 ft (~6 ft below the erionite-bearing sample) has no detectable erionite. This sample, however, contains not only clinoptilolite but also phillipsite. The fracture sample at 1322.9-1323.2 ft (an additional 21 ft lower) contains neither erionite nor phillipsite, but it does contain clinoptilolite and mordenite.

Figure 2 is a diffraction pattern of the fracture-filling material hand-scraped from sample UE-25a#1-1296.2 by D. E. Broxton. Erionite peaks are labeled Er, clinoptilolite peaks Cl, smectite peaks Sm, and the mica peak Mi. This sample was x-rayed from 2° to 36° 2 θ , using 0.02° steps with a count time of 180 s/step in a helium atmosphere to reduce air scattering and the low-angle background. The sample contains approximately 45 wt% erionite, 45 wt% clinoptilolite, 10 wt% smectite, and a trace of mica.

Figure 3 shows SEM photographs of the UE-25a#1-1296.2 fracture-coating minerals. The erionite in this fracture (Fig. 3a) is extremely fine grained having a length of approximately 5 to 20 μm and a width of less than 0.1 μm with a hairlike morphology. Figure 3b shows the smectite that is also lining the fracture. The fracture surface is readily apparent by its striated nature. Smectite apparently formed later than erionite since it overlays erionite in places, and both smectite and erionite appear to postdate the tectonic activity that produced this fracture.

Figures 4 and 5 show electron micrographs of various naturally occurring erionites to demonstrate the range of fibrous to acicular habits of this zeolite. The erionite sample from Shoshone, California, shows two separate generations and types of erionite. One is composed of larger, radiating-acicular crystals with well-developed hexagonal morphology; the other is composed of bundles of tiny needles forming the small barrel-shaped objects in the electron micrographs (Figs. 4a, 4b). The sample from Durkee, Oregon, the holotype location, shows the fibrous woolly morphology that erionite can assume (Figs. 5a, 5b).

TABLE I
X-RAY DIFFRACTION ANALYSES OF TUFF

Sample ^a	Method ^b	Smectite	Mica	Erion- ite	Clino- ptilolite	Morden- ite	Quartz	Cristo- balite	Opal-CT	Alkali Feldspar	Glass	Other
J12-620/630	E	9±4	3±2	<1	-	-	-	6±3	-	53±10	30±20	-
J12-650/660	E	1±1	2±1	-	2±1	-	2±1	10±3	-	70±10	-	1±1 ^c , 13±4 ^d
J12-770/780	E	1±1	-	-	-	-	14±2	4±2	-	81±10	-	1±1 ^c
J12-1093/1097	E	38±7	-	-	51±10	-	1±1	11±3	-	-	-	-
J12-1107/1110	E	-	-	-	4±2	-	1±1	6±3	-	9±4	80±20	-
J12-1121/1126	E	-	-	-	-	-	2±1	4±2	-	14±5	80±20	-
J12-1136/1139	E	33±7	-	-	54±10	-	2±1	10±3	-	-	-	-
J13-591	I	5±1	-	-	-	-	1±1	-	-	-	94±1	-
J13-607	E	73±18	-	-	-	-	Tr.	7±1	-	-	20±18	-
J13-689	E	26±5	-	-	1±1	-	5±1	13±1	-	54±6	-	Tr. ^c
J13-1102	I	Tr.	Tr.	-	-	-	20±1	-	-	78±10	-	Tr. ^c , 2±1 ^d
J13-1293	I	-	Tr.	-	-	-	33±1	-	-	63±7	-	Tr. ^c
J13-1345	I	-	-	-	-	-	Tr.	-	11±2	8±1	81±3	-
J13-1345 Fracture	E	-	-	-	60±10	-	Tr.	-	25±10	-	-	15±5 ^e
J13-1457	I	2±1	-	-	80±8	-	2±1	-	8±2	7±1	-	Tr. ^f
J13-1515	I	4±1	-	-	64±6	-	1±1	-	12±2	14±3	-	-
J13-2533	I	2±1	2±1	-	-	-	32±1	-	-	62±7	-	Tr. ^c
J13-2680	I	3±1	3±1	-	-	-	30±1	-	-	61±7	-	Tr. ^c , Tr. ^f
UE-25a#1-226	I	42±8	2±1	-	-	-	-	Tr.	-	19±2	36±9	-
UE-25a#1-251	I	24±5	2±1	-	-	-	Tr.	Tr.	-	14±2	59±5	-
UE-25a#1-277	I	-	1±1	-	-	-	-	Tr.	-	16±2	80±2	2±1 ^c
UE-25a#1-836	I	1±1	Tr.	-	Tr.	-	31±1	Tr.	-	66±8	-	Tr. ^c
UE-25a#1-1264	I	1±1	Tr.	-	5±1	-	24±1	8±3	-	61±8	-	-
UE-25a#1-1279	I	6±1	Tr.	-	-	-	2±1	-	-	6±1	85±2	-
UE-25a#1-1296.2 Frac.	E	10±5	Tr.	45±10	45±10	-	-	-	-	-	-	-
UE-25a#1-1324	I	-	-	-	80±12	6±2	2±1	-	6±1	4±1	-	-
UE-25a#1-1358	I	-	-	-	69±17	10±2	Tr.	-	17±3	2±1	-	-
UE-25a#1-1478	I	2±1	-	-	63±7	-	4±1	-	23±5	9±2	-	-
UE-25a#1-1680	I	-	-	-	66±14	11±3	3±1	-	17±3	5±1	-	-
UE-25a#1-2220	I	1±1	-	-	50±14	18±5	Tr.	-	15±3	14±4	-	-
UE-25p#1-1260/1270	E	1±1	-	-	62±10	-	Tr.	-	23±8	14±4	-	-
UE-25p#1-1340/1350	I	Tr.	-	-	56±4	-	2±1	-	20±6	21±4	-	-
UE-25p#1-1420	I	12±4	1±1	-	-	-	24±2	-	-	40±5	22±7	1±1 ^c
UE-25p#1-1730/1740	I	3±1	-	-	60±4	-	4±1	-	14±4	17±3	-	-
UE-25p#1-1790/1800	I	1±1	-	-	45±8	23±7	12±1	-	-	18±5	-	-

TABLE I Continued

Sample	Method	Smectite	Mica	Erion- ite	Clino- ptilolite	Morden- ite	Quartz	Cristo- balite	Opal-CT	Alkali Feldspar	Glass	Other
USW G1-1286	I	33±7	-	-	10±1	-	3±1	16±1	-	38±5	-	-
USW G1-1400	I	Tr.	-	-	83±10	-	2±1	-	12±2	2±1	-	-
USW G1-1539	I	1±1	Tr.	-	46±7	Tr.	11±1	-	19±4	17±3	-	-
USW G1-1799	I	3±1	-	-	51±12	-	1±1	-	35±7	12±2	-	-
USW G1-2198	I	1±1	Tr.	-	48±9	2±1	4±1	-	20±4	20±4	-	-
USW G1-2600	I	-	-	-	48±22	39±9	Tr.	-	2±1	12±4	-	-
USW G2-762	E	3±2	-	-	75±8	-	-	10±5	-	3±2	-	15±5 ^d
USW G2-1634	E	40±10	2±1	-	40±10	-	-	23±7	-	-	-	-
USW G2-1798	E	2±1	-	-	50±10	23±7	10±5	15±5	-	23±7	-	-
USW G2-3192	E	7±3	-	-	30±10	10±5	30±10	3±2	-	30±10	-	Tr. ^g
USW GU3-1874.0	E	-	-	-	50±5	-	7±3	5±3	-	40±5	-	-
USW GU3-2577.4	E	3±1	6±2	-	50±5	-	2±1	5±3	-	35±5	-	1±1 ^h
USW GU3-3854.8	E	7±3	2±1	-	35±5	-	25±5	-	-	30±5	-	-
USW G4-123	E	25±10	-	-	-	-	-	15±5	-	40±10	20±10	-
USW G4-148	E	35±15	-	-	-	-	-	15±10	-	-	50±20	-
USW G4-236	E	-	-	-	-	-	10±5	10±5	-	20±10	60±20	-
USW G4-1310	E	1±1	1±1	-	3±2	-	5±2	24±5	-	65±10	-	-
USW G4-1314	E	45±10	-	<1	28±5	-	2±1	14±4	-	11±5	-	-
USW G4-1330	E	-	-	-	-	-	10±5	-	-	20±10	70±20	-
USW G4-1392	E	2±1	-	-	70±15	-	2±1	4±2	-	21±10	-	-
USW G4-1470	E	3±2	-	-	77±10	-	6±2	14±4	-	-	-	-
USW G4-1685	E	1±1	-	-	50±10	15±10	4±2	7±3	-	19±10	-	-
USW G4-1779	E	2±1	-	-	45±10	-	-	10±4	-	44±10	-	-
USW G4-1989	E	-	1±1	-	44±10	-	7±3	15±4	-	33±10	-	-
USW G4-2238	E	1±1	-	-	50±10	25±10	6±2	-	-	18±10	-	-
USW G4-2792	E	-	2±1	-	2±1	71±14	5±1	-	-	19±9	-	-
USW H4-1350/1360	E	-	-	-	78±10	-	3±2	9±4	-	10±5	-	-
USW H4-1410/1420	E	-	-	-	52±10	5±3	7±2	9±4	-	31±10	-	-
USW H4-1540/1550	E	3±2	-	-	29±10	16±5	11±3	16±4	-	31±10	-	-
USW H4-1600/1610	E	-	9±3	-	31±10	-	17±4	9±4	-	35±10	-	-
USW H4-1980/1990	E	-	3±2	-	11±5	23±6	2±1	6±3	-	55±10	-	2±2 ^h
USW H5-1590/1600	E	35±10	-	-	10±5	-	-	17±5	-	40±10	-	-
USW H6-1511.7	E	10±5	2±1	-	36±5	-	7±5	-	-	49±10	10±5	-
USW H6-3003.2	E	-	15±5	-	26±5	-	-	5±3	-	51±10	-	3±2 ^h

TABLE I Continued

Sample	Method	Smectite	Mica	Erion- ite	Clino- ptilolite	Morden- ite	Quartz	Cristo- balite	Opal-CT	Alkali Feldspar	Glass	Other
USW WT1-1320/1330	E	2±1	1±1	-	14±4	-	20±2	13±4	-	50±10	-	-
USW WT1-1380/1390	E	-	1±1	-	40±10	12±4	8±2	7±3	-	31±6	-	-
USW WT1-1410/1420	E	-	Tr.	-	40±10	8±3	3±2	8±3	-	40±8	-	-
USW WT1-1510/1520	E	-	1±1	-	43±10	10±4	8±3	5±2	-	33±7	-	-
USW WT1-1550/1560	E	-	1±1	-	40±10	12±4	14±3	7±3	-	26±5	-	-
USW WT2-1520/1530	E	3±2	1±1	-	24±5	-	11±3	12±4		48±10	-	-
USW WT2-1820/1830	E	4±2	-	-	19±4	-	5±2	14±3		59±10	-	-
USW WT2-1910/1920	E	-	1±1	-	42±10	-	5±2	6±3		47±10	-	-
USW WT2-2000/2010	E	-	-	-	30±8	10±4	3±2	3±2		55±10	-	-

All mineral abundances were obtained from the Revised Mineralogic Summary of Yucca Mountain (Bish and Chipera 1989) except for fracture samples J13-1345 and UE-25a#1-1296.2, which were analyzed for this report. For details of analyses, refer to Bish and Chipera (1989).

^aSample number is the depth in feet. A single number represents drill core; a double number represents the depth interval for drill cuttings.

^bMethod -- J: Internal standard method. E: External standard method. (For details, see Bish and Chipera 1989)

^cHematite.

^dTridymite.

^eChabazite.

^fCalcite.

^gAnalcime.

^hHornblende.

TABLE II
PROMINENT FRACTURE ALTERATION MINERALOGY
FROM DRILL HOLE UE-25a#1

<u>DEPTH (ft)</u>	<u>Sm</u>	<u>Cl</u>	<u>Mo</u>	<u>Er</u>	<u>Ph</u>
1242.7-1243.1		X	X		
1252.3		X	X		
1274.5	X	X			
1276.0-1276.2	X	X			
1282.6	X	X			
1296.2	X	X		X	
1301.5-1302.2	X	X			X
1322.9-1323.2	X	X	X		
1339.5-1339.7		X	X		
1361.8-1362.0	X	X	X		

Sm = smectite
Cl = clinoptilolite
Mo = mordenite
Er = erionite
Ph = phillipsite

Fig. 2. X-ray diffraction pattern of the fracture-filling material hand-scraped from sample UE-25a#1-1296.2 by D. E. Broxton. Er = erionite, Cl = clinoptilolite, Sm = smectite, and Mi = mica.

Fig. 3a. SEM photomicrograph of the fracture-filling erionite from sample UE-25a#1-1296.2. Note the hairlike morphology.

Fig. 3b. SEM photomicrograph of fracture-filling smectite from sample UE-25a#1-1296.2. The fracture surface is readily apparent by its striated nature.

Fig. 4a. SEM photomicrograph of erlonite from Shoshone, California. Note the acicular, needle-like morphology of this zeolite in both the radiating-acicular crystals and in the bundles of tiny needles.

Fig. 4b. SEM photomicrograph of erlonite from Shoshone, California. End-on view of a radiating cluster of needles. Note the hexagonal morphology.

Fig. 5. SEM photomicrographs of erionite from Durkee, Oregon, the holotype location. Note the fibrous woolly morphology.

The nature of the erionite occurrence in sample J12-620/630 (drill cuttings) is not readily apparent. Although several pieces of this sample were examined under a binocular microscope, no fractures were noted in which erionite might occur. If the erionite in this sample is restricted to fractures, it may have been in a fracture filling in one of the pieces of drill cuttings that was ground for the x-ray mount. It is possible that the erionite in this sample may be disseminated in the whole rock, possibly existing as an alteration product along the edges of partially devitrified glass fragments. A sample examined from ~30 ft lower in the hole (J12-650/660) did not show any evidence for the presence of erionite.

The exact mode of occurrence of the erionite in sample G4-1314 also is not readily apparent. The sample is friable and crumbly, so it is difficult to discern if the erionite is isolated in fractures or if it is part of the rock matrix. Whole-rock XRD analyses from samples 4 ft above and 16 ft below this sample did not show any detectable erionite. A fracture sample provided by B. Carlos from the interval 1316.8-1317.1 ft (~3 ft below the erionite-bearing sample) also did not show any detectable erionite.

To determine the approximate grain size of the erionite in the G4-1314 sample, a size fractionation was conducted using Stokes-Law settling in water. The size fractions obtained were >10 μm , 10-3 μm , 3-1 μm , 1-0.35 μm , 0.35-0.10 μm , and <0.10 μm . Most of the erionite was found in the 10-0.35- μm fractions; no erionite was found in the <0.35- μm fractions; and only a trace amount was found in the >10- μm fraction (Fig. 6). This size distribution is consistent with SEM observations on other erionite-containing samples.

Heiken and Bevier (1979) and Sykes et al. (1979) reported erionite in several samples from drill holes UE-25a#1 and J-13 based primarily on electron microprobe and scanning electron microscope data. These samples, JA-15 (J13-1292), JA-32 (J13-2532), JA-33 (J13-2680), and YM-34 (UE-25a#1-1358), were examined by Bish and Vaniman (1985) and again in the present study using x-ray diffraction, but no evidence for the presence of erionite in these samples was found. There are several explanations for the previous erionite identifications. All of the JA erionite identifications were based upon electron microprobe data. Bish and Vaniman (1985) pointed out that it is difficult to obtain reliable chemical data for hydrous, finely intergrown materials, and distinctions between zeolites based upon microprobe chemical analyses alone are suspect. Furthermore, it is possible for several different zeolites to yield similar chemical analyses, particularly erionite and mordenite. The tentative identification of erionite in sample YM-34 was based on the morphology observed with the SEM. However, Caporuscio et al. (1982) observed identical morphologies in mordenite-rich tuffs containing no erionite.

Zeolite Genesis

Previous to about 1958, erionite was considered a rare mineral, found as woolly masses in only one locality near Durkee, Oregon (Mumpton and Ormsby 1976). Since then, it has been

Fig. 6. X-ray diffraction patterns of the size fractions obtained for sample USW G4-1314. Cl = clinoptilolite, Er = erionite, and Mi = mica.

found in numerous saline-lake zeolite deposits (Surdam and Sheppard 1978) associated with the common sedimentary zeolites, clinoptilolite, mordenite, analcime, chabazite, and phillipsite.

Most zeolite occurrences can be assigned to one of several types of geologic environments or hydrologic systems (Hay 1978). They are (1) saline, alkaline lakes; (2) saline, alkaline soils and land surfaces; (3) marine sediments; (4) percolating water in an open hydrologic system; (5) hydrothermal alteration; and (6) burial diagenesis or metamorphism. Erionite is not known to form as a weathering mineral or in soils, nor has it been found in deep sea sediments; its rare presence in deep sea samples is due to hydrothermal deposition in basalts (Gottardi and Galli 1985). It is also more common in sedimentary rocks than in hydrothermal deposits (Gottardi and Galli 1985).

Surdam and Eugster (1976) studied an active saline-alkaline lake zeolite deposit at Lake Magadi, Kenya. They found that erionite was the most common zeolite present although minor amounts of chabazite, clinoptilolite, mordenite, and phillipsite were also recognized. They postulated that the erionite formed directly from trachytic glass solely through the addition of H_2O .

To answer the question of why erionite is the dominant zeolite phase found at Lake Magadi, Surdam and Eugster offered the following observations.

1. The trachytic glass starting material is rich in alkalis and poor in alkaline earth elements.
2. There is an abundance of silica and silicate phases indicating high silica activities.
3. The inflow waters into the Magadi basin and the brines in the basin are rich in sodium and silica and poor in alkaline earths, especially calcium.

They used these observations to infer that erionite will form as the initial zeolite phase in an environment characterized by high silica, high sodium, and extremely low calcium activities. They stated that erionite can form directly from trachytic glass solely by the addition of water. However, this water is unlikely to be dilute surface or groundwater because such water would probably contain calcium obtained from either the weathering of plagioclase or the dissolution of carbonates.

According to Surdam and Sheppard (1978), zeolite assemblages are determined by several variables that include but are not limited to the composition of the host rock and pore water (Si/Al ratios, cation ratios, activity of H_2O , salinity and alkalinity of the H_2O), pH of the system, temperature, pressure, and time.

A phase equilibrium study would help determine what zeolites form under which environmental conditions. However, thermodynamic data do not exist for many of the zeolite phases. Chermak and Rimstidt (to be published in *American Mineralogist*) proposed a method

of estimating the thermodynamic properties of silicate minerals based on summing the thermodynamic properties of the individual polyhedral units composing the mineral. Figure 7 is an activity-activity diagram of phillipsite, erionite, and clinoptilolite from Chermak and Rimstidt, which they calculated using thermodynamic data obtained from their estimation method. This diagram shows that erionite is stable only under a restricted range of silica activity, and clinoptilolite is the stable phase at higher silica activities. The stability fields shown in Fig. 7 do not support in detail the conclusions of Surdam and Eugster regarding the conditions conducive to erionite formation, although such a restricted stability range would be difficult to predict based on the Lake Magadi occurrence.

The more exotic zeolites not common at Yucca Mountain (i.e., erionite and phillipsite in drill hole UE-25a#1 and chabazite in drill hole J13) were all found in vitrophyre samples. This suggests that chemical microenvironments exist in the vitrophyre fractures that are unique with respect to the bulk of Yucca Mountain, which is dominated by more siliceous zeolites such as clinoptilolite.

Fig. 7. Activity-activity diagram of phillipsite, erionite, and clinoptilolite from Chermak and Rimstidt (to be published in *American Mineralogist*). They used their estimation method to obtain the thermodynamic data to calculate this diagram.

IV. CONCLUSIONS

Erionite at Yucca Mountain, although occurring over a wide area, does not appear to be a common mineral in detectable abundances (>0.05 wt%). It occurs mainly as a trace phase of less than 1 wt% in bulk-rock samples, although it may occur locally in significant amounts in fracture fillings, as is the case for sample UE-25a#1-1296.2. In the samples where erionite was found, neighboring samples have no evidence for the presence of erionite, suggesting that erionite at Yucca Mountain formed only in localized microenvironments, possibly restricted to fractures.

In all three cases, erionite was found above the water table, in clay/zeolite-rich horizons near the top of vitrophyres at depths ranging from 620 to 1314 feet below the ground surface. Since it occurs in trace amounts in extremely isolated occurrences, it should pose little or no health hazard to the workers in the potential repository at Yucca Mountain, which would be built in devitrified tuff significantly above the Topopah Spring Member vitrophyre (Rautman et al. 1987). In addition, the amounts of erionite liberated to the biosphere should be negligible, and hazard to the public should not increase, particularly when compared with the significant amounts of erionite occurring naturally at the surface in Nevada and surrounding states (Papke 1972; Sheppard and Gude 1980).

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