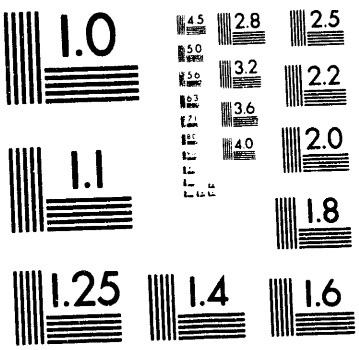
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TITLE: DISTRIBUTION AND CHEMISTRY OF FRACTURE-LINING ZEOLITES AT YUCCA MOUNTAIN, NEVADA

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DISTRIBUTION AND CHEMISTRY OF FRACTURE-LINING ZEOLITES AT YUCCA MOUNTAIN, NEVADA

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ABSTRACT

Yucca Mountain, a >1.5-km thick sequence of tuffs and subordinate lavas in southwest Nevada, is being investigated as a potential high-level nuclear waste repository site. Fracture-lining minerals are possible sources of information on past transport within the tuffs, and they may act as natural barriers to radionuclide migration along the fractures. Cores from several drill holes were examined to determine the distribution and chemistry of zeolite minerals in fractures. Fracture-lining minerals in the Paintbrush Tuff are highly variable in distribution, both vertically and laterally across the mountain, with mordenite, heulandite, and stellerite widespread in fractures even though the tuff matrix is generally devitrified and not zeolitic. Where heulandite occurs as both tabular and prismatic crystals in the same fracture, the two morphologies have different compositions, suggesting multiple episodes of zeolite formation within the fractures. In contrast to the Paintbrush Tuff, fractures in the Calico Hills Formation and the Crater Flat Tuff generally contain abundant clinoptilolite and mordenite only where the matrix is zeolitic, although mordenite does occur as fracture linings in some devitrified intervals of the Crater Flat Tuff as well. The fracture-lining zeolites correlate with the degree of alteration of the zeolitic tuffs, with clinoptilolite plus mordenite in tuffs containing clinoptilolite, and analcime in fractures limited to tuff intervals containing analcime. These data suggest that fracture-lining zeolite formation may have been coincident with the original alteration of the tuffs.

INTRODUCTION

Yucca Mountain in southwest Nevada (Fig. 1) is composed of a >1.5-km thick sequence of tuffs and subordinate lavas (Scott et al., 1983, Carr et al., 1986). The tuff units include partially-welded to densely-welded devitrified tuff, moderately-welded to densely-welded vitrophyre, and non-welded vitric tuff that in places has been extensively altered to zeolite minerals. Detailed descriptions of these ash flow tuffs are given in Lipman et al. (1966), Byers et al. (1976), and Carr et al. (1986). The stratigraphy of the drill cores examined in this study has been described by Spengler et al. (1979), Spengler et al. (1981), Lobmeyer et al. (1983), Maldonado and Koether

(1983), Scott and Castellanos (1984), and Spengler and Chornack (1984). From top to bottom, the units at Yucca Mountain are the Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring Members of the Paintbrush Tuff; the Calico Hills Formation; the Prow Pass, Bullfrog, and Tram Members of the Crater Flat Tuff; and older tuffs and lavas that are not included in this study (Fig. 2). The static water level (SWL) falls within the Crater Flat Tuff beneath most of Yucca Mountain. Mineralogy of the tuff units is described in Bish and Chipera (1989). Alteration of Yucca Mountain tuffs is discussed in Broxton et al. (1987), who described four zones of diagenetic alteration, increasing with depth. These zones can be identified by key minerals in the rock matrix of the partly to non-welded intervals. Zone I is above the SWL and is characterized by the presence of glass. Heulandite, but not mordenite, may be present in isolated intervals. Zone II extends from somewhat above the present SWL to some depth below the SWL. Zone II contains clinoptilolite and mordenite, which replace the glass. Zone III is characterized by the presence of analcime, although clinoptilolite and mordenite persist at least in the upper part of this zone. Quartz and authigenic potassium feldspar are also present. Zone IV contains albite, which replaces analcime. Quartz and potassium feldspar are also present. Broxton et al. (1987) noted that alteration is more intense toward the north and attributed the alteration to a thermal pulse related to the Timber Mountain-Oasis Valley caldera complex north of Yucca Mountain. Bish (1989) used interstratification of illite and smectite to determine the temperatures to which the different zones and drill cores had been subjected. The distribution of illite/smectite and the K/Ar age dates on illite of about 11 Ma support the hypothesis that alteration was the result of a regional increase in geothermal gradient related to Timber Mountain volcanism. There is no evidence of additional hydrothermal alteration since that time.

Yucca Mountain is being investigated as a potential site for a high-level nuclear-waste repository partly because the thick sequences of zeolitic tuffs provide a natural barrier to the migration of some radionuclides, notably the alkali and alkaline earth elements (Thomas, 1987). The potential repository horizon is in the lower portion of the Topopah Spring Member of the Paintbrush Tuff, >300 m below the surface of the mountain and 150 m above the SWL. Since fractures represent both past and potential future transport pathways, fracture-lining minerals are being studied as possible barriers to radionuclide migration and to provide information on past flow and transport within Yucca Mountain. The most abundant fracture-lining minerals at Yucca Mountain are silica polymorphs, zeolites, and Mn-oxides, with lesser amounts of smectite, sepiolite, palygorskite, calcite, and Fe-oxides (Carlos, 1985; 1987; Carlos et al., 1991, Carlos et al., 1993.)

The study of fracture-lining minerals has been limited to the Paintbrush Tuff, the Calico Hills Fm., and the Crater Flat Tuff, which are the units most likely to be encountered by future fluid flow between the potential repository and the accessible environment, and this paper focuses on the distribution, chemistry, and relationships of zeolite minerals in fractures at Yucca Mountain.

ANALYTICAL METHODS

Cores from several drill holes (USW G-1, G-2, GU-3, G-3, G-4, UE-25a#1, and UE-25b#1h), on and near Yucca Mountain (Fig. 1), were examined to determine the distribution of zeolite minerals in fractures. More than 500 samples from the Paintbrush Tuff, the Calico Hills Fm., and the Crater Flat Tuff were included in this study. Fracture coatings were examined using a binocular microscope to choose samples for grain mounts, thin sections, and scanning electron microscope (SEM) studies. Samples for chemical analysis were selected to represent each different fracture-lining zeolite mineral from the different intervals. Samples were limited to closed fractures for which thin sections could be made, and crystals with identifiable morphology which could be chipped off the fracture surface for grain mounts. Powders for X-ray diffraction (XRD) analysis were scraped from surfaces and then hand picked under the binocular microscope to remove rock-matrix contamination. XRD analyses were obtained with an automated Siemens D-500 powder diffractometer utilizing Cu Kα radiation, incident- and diffracted-beam Soller slits, and a Kevex Si (Li) solid-state detector. Samples were mounted either as powders pressed into a cavity machined into an aluminum or glass sample plate or by suspending the sample in deionized water or acetone and sedimenting it onto an off-axis cut (zero-background) quartz plate. Samples were typically run from 2-70° 2θ using 0.02° steps with count times of 16 s/step.

Open fracture surfaces were studied with a model DS-130 ISI scanning electron microscope (SEM), equipped with a series II Tracor Northern energy-dispersive X-ray (EDX) analytical system. Secondary-electron images (SEI) and backscattered-electron images (BEI) were acquired at magnifications up to 10,000x, using accelerating voltages between 19 and 29 kV. Thin sections across filled fractures and grain mounts of crystals scraped from fracture surfaces were examined using a Tracor Northern SEM, model ADEM, equipped with an integrated EDX analytical system. SEI and BEI were collected at magnifications up to 20,000x using accelerating voltages of 15 or 20 kV. EDX analyses assisted in the identification of minerals.

Quantitative chemical analyses of thin sections and grain mounts were acquired on Cameca MBX and Cameca SX-50 electron-probe microanalyzers using wavelength dispersive spectrometry. Both instruments were operated at an accelerating voltage of 15 kV and a beam current of 15 nA. A 10-20 μm rastered beam, combined with movement of the sample under the raster, was used to minimize Na migration during analysis. Compositions were calculated using Bence-Albee correction methods (Bence and Albee, 1968) for the MBX and using PAP correction methods (Pouchou and Pichoir, 1985) for the SX-50.

RESULTS

Fracture-lining zeolites at Yucca Mountain generally correlate with the diagenetic zone in which the fractures occur. The Zone I-II boundary is not actually co-incident with the base of the Paintbrush Tuff; however, as non-welded vitric tuff supports few fractures, samples from Zone I included in this study are limited to the welded portions of the Paintbrush Tuff.

Zone I, Paintbrush Tuff

The Paintbrush Tuff is a complex formation with four Members (Fig. 2). The Tiva Canyon and Topopah Spring Members are primarily densely-welded, devitrified tuffs with intervals of vapor-phase alteration and lithophysal cavities that formed during the early cooling and consolidation of the tuff. There are thin vitrophyres in the Tiva Canyon Member and near the top of the Topopah Spring Member, and a 15-20 m thick (basal) vitrophyre near the base of the Topopah Spring Member. The Pah Canyon and Yucca Mountain Members of the Paintbrush Tuff are generally non-welded and poorly represented in drill cores examined in this study. The extent and type of fractures in the Paintbrush Tuff are determined by the extent of welding and devitrification, and abundance of lithophysal cavities. The distribution of fracture-lining zeolites varies both laterally and vertically within the Paintbrush Tuff across Yucca Mountain. In addition, fracture-lining minerals within the devitrified intervals generally differ from those within the vitrophyres.

Devitrified Tuffs

In the densely-welded devitrified portions of the Paintbrush Tuff, mordenite, heulandite, and stellerite are widespread in fractures even though the tuff matrix is generally non-zeolitic. Cation compositions, Si:Al ratios, and heating tests on clinoptilolite/heulandite from fractures in USW G-4 indicate that the mineral coating fractures in the Paintbrush Tuff is heulandite and not clinoptilolite. In addition to zeolites, calcite, Ca-smectite, sepiolite, palygorskite, rancieite (Ca-, Mn-oxide), lithiophorite (Al-, Mn-oxide), and the silica polymorphs tridymite, cristobalite and quartz commonly occur in fractures above the basal vitrophyre of the Topopah Spring Member.

Heulandite and stellerite occur as small (10-50 μm) prismatic crystals on fractures throughout the devitrified intervals of the Topopah Spring Member in at least one drill core (USW G-1) and with more limited distribution in other drill cores. Although peak overlaps with heulandite, mordenite, and feldspar make XRD identification of stellerite difficult, heulandite and stellerite can be distinguished in SEM images by their terminations (Figs. 3 and 4) as well as by EDX analyses (Ca is the only exchangeable cation in stellerite; heulandite contains Mg and minor amounts of Na and K in addition to Ca). Heulandite and stellerite may occur together within a fracture or separately at different intervals within a drill core. Stellerite occurs in fractures throughout much of the Topopah Spring Member in USW G-1, but is much less abundant than heulandite in UE-25a#1. Heulandite and stellerite both have more limited distribution in USW G-2, the northernmost hole, where they occur alone or together in fractures and lithophysal cavities. Stellerite has not been identified at all in USW GU-3, the southernmost hole, nor in USW G-4. Large (50-300 μm) tabular heulandite crystals (Fig. 4) occur with prismatic heulandite (and sometimes with stellerite) from approximately 10-15 m above the basal vitrophyre to the top of the basal vitrophyre in most drill cores. In drill core USW GU-3, this interval immediately above the basal vitrophyre is only 1-m thick and is the only interval in the Topopah Spring Member in USW GU-3 that contains heulandite, although heulandite is also present in the lower part of the Tiva Canyon Member in this drill hole. Heulandite is not present in the Tiva Canyon Member in USW G-4 or UE-25a#1, and its presence in drill holes USW G-1 and G-2 is unknown as this interval was not cored. Chemical analyses of stellerite, heulandite, and coexisting tabular and prismatic heulandite from the same fractures are presented in Table 2. For coexisting heulandites in the same fracture, the exchangeable cation analyses for the prismatic heulandite cluster tightly and are significantly different from those of the tabular heulandite (e.g. sample UE-25a#1 1242 in Figs. 5a, and 5b). In addition, some tabular crystals optically appear to be zoned. Stellerite is not plotted on Figure 5a or 5b because there is little deviation from calcium end-member stellerite (Table 2): the structure of stellerite does not accommodate significant substitution of other extra-framework cations.

Mordenite occurs as discontinuous bluish-white crusts of very fine-grained (<1-μm long) crystals, particularly in the shallower intervals, and on smooth planar and curviplanar cooling fractures. It also occurs as mats of longer crystals (up to 100 μm) partially covering stellerite and/or heulandite, generally on rougher fractures and sometimes in lithophysal cavities. Although widely distributed in fractures across Yucca Mountain, mordenite is not equally abundant in all drill holes nor at all depths in the Paintbrush Tuff. Trace amounts of mordenite are identifiable in SEM images but not in XRD analyses. Mordenite has not been chemically analyzed because of small crystal size and the difficulty in obtaining separates.

Smectite occurs in the devitrified Topopah Spring Member as individual plates up to 10 μm in diameter or as clusters of plates (Fig. 6). It may occur alone, beneath, or as overgrowths on the zeolites discussed above.

Basal Vitrophyre

Fractures within the basal vitrophyre usually contain smectite and opal-CT, and may include one or two of several zeolites, most of which have been identified only by XRD as crystals with identifiable morphology have not been seen. Phillipsite crystals overlie smectite on fractures in the vitrophyre from two drill holes (USW GU-3 and UE-25a#1; Fig. 7). A representative microprobe analysis from sample USW GU-3 1200 is included in Table 2. As in many zeolites at Yucca Mountain, the Si:Al ratio obtained on this sample is higher than ideal phillipsite. Erionite occurs in trace amounts in limited intervals within the vitrophyre and in the altered tuff immediately above it in several drill holes (Bish and Chipera, 1991). It closely resembles mordenite and cannot be visually distinguished in hand-sample or in SEM images from the mordenite coating fractures immediately above or below those with erionite.

Chabazite has been identified by XRD in fracture-coatings within the basal vitrophyre of the Topopah Spring Member in water well J-13 (Carlos, 1989) in Jackass Flat (Fig. 1) and in drill hole USW VH-1 approximately 8 km southwest of Yucca Mountain in Crater Flat (Carlos et al., 1993). The vitrophyre in both these holes is below the SWL. As with many zeolites lining fractures in the basal vitrophyre at Yucca Mountain, visible crystals were not found.

Zones II and III

Zone II includes the zeolitic Calico Hills Fm., and, for most drill holes, the zeolitic portions of at least the upper Members of the Crater Flat Tuff. Unlike the matrix alteration, which is often dominated by clinoptilolite, mordenite is the principal fracture-lining zeolite, with subordinate clinoptilolite. Mordenite forms mats and crusts of fibers on fracture surfaces with individual mordenite crystals in the Calico Hills Fm. usually from 2 to 15-μm in length, occasionally reaching 30 μm in length. Opal-CT commonly occurs with mordenite, usually interstitial to the mordenite crystals, but it also can occur as spheres up to 10 μm in diameter underlying the mordenite. In the Crater Flat Tuff, mordenite forms thin discontinuous coatings or thick mats of crystals 10-30 μm, and rarely up to 100 μm in length (Fig. 8).

Clinoptilolite occurs with mordenite in Zone II, which extends to the base of the Crater Flat Tuff in the south (in USW G-3) but only includes the upper intervals of the Crater Flat Tuff in the more northern holes. Although clinoptilolite is present in most fractures in Zone II, clinoptilolite crystals large enough to be identified visually at 25x magnification are uncommon. Euhedral crystals of clinoptilolite, up to 200 μm in length, are either prismatic or tabular. Such crystals are restricted to the Calico Hills Fm. and to the Prow Pass and Bullfrog Members of the Crater Flat Tuff over most of Yucca Mountain, but they also occur in the Tram Member of the Crater Flat Tuff in the southernmost drill hole (USW G-3). Small euhedral clinoptilolite crystals (5-10 μm diameter) are covered by mordenite in some fractures. Clinoptilolite is often identified only by XRD analysis of fracture coatings, and it is presumed to be the small euhedral and anhedral plates 5 -10 μm in diameter seen in SEM images embedded in mats of mordenite. Analyses of some of the larger clinoptilolites from Zone II are presented in Table 3 and plotted in Figure 9. Large variation in exchangeable-cations was found to exist between samples. There are insufficient chemical data on fracture-lining clinoptilolites at Yucca Mountain to determine if they follow the same trends with increasing depth as do matrix clinoptilolites (Broxton et al., 1987); however, comparison of analyses in Table 3 with analyses of matrix clinoptilolites from similar intervals (Broxton et. al. 1986, Appendix F) shows that the fracture-lining clinoptilolites are similar in composition to those in the matrix in all cases. Within diagenetic Zones II and III, the cation compositions of matrix clinoptilolites vary from K-dominant to Na-dominant on the western side of Yucca Mountain, and toward Ca-dominant on the eastern side

Chabazite (Fig. 10) has been identified from one sample (UE-25b#1h 2165) in the Crater Flat Tuff at Yucca Mountain. It occurs in Zone II with clinoptilolite and alkali feldspar. Chemical analyses of the coexisting chabazite and clinoptilolite are included in Table 3 and on Figure 9.

Euhedral crystals of analcime (Fig. 11) occur in fractures (with mordenite) only at the northern end of Yucca Mountain where the Crater Flat Tuff is altered to diagenetic Zone III and where analcime also occurs in the matrix. Clinoptilolite/heulandite occurs in fractures below this depth and may coexist in the matrix with analcime (Bish and Chipera, 1989). A representative analysis of analcime from a fracture in sample USW G-2 3137 is given in Table 3. The fracture analcime has a Si-rich, Na end-member composition, similar to the analyses of matrix analcime reported by Broxton et al. (1987). Fractures are less common in the most altered intervals of the Tram Member of the Crater Flat Tuff and contain no zeolites, although analcime and clinoptilolite may be present in the matrix. Calcite is the most abundant fracture-filling mineral in the deepest portion of Zone III within the Tram Member.

The central portions of the three Crater Flat Members are moderately- to densely-welded devitrified tuff. Hematite, manganese oxide minerals, quartz, and calcite are the most abundant fracture coatings in the devitrified Crater Flat Tuff over most of the Yucca Mountain. Mordenite is generally the only zeolite found in fractures in devitrified Crater Flat Tuff, and its distribution and abundance varies across the mountain, with the greatest abundance in USW GU-3/G3. Smectite occurs with mordenite in some fractures in these intervals.

DISCUSSION

The distribution of zeolite minerals in fractures at Yucca Mountain appears to be dependent on several factors but generally correlates with the diagenetic alteration zones as defined by the matrix mineralogy (Broxton et al., 1987). Fracture-lining zeolites in diagenetic Zones II and III are closely related to the minerals in the tuff matrix. Correlation of fracture-lining zeolites with degree of zeolitization of the host tuff suggests that the fracture coatings may have formed at the same time as the alteration of the tuffs. An increase in degree of alteration in both fractures and matrix toward the north of Yucca Mountain indicates that this alteration may have been a result of hydrothermal activity related to the Timber Mountain volcanism.

The Zone I-Zone II boundary is neither co-incident with, nor parallel to the present SWL; it probably indicates the position of the SWL at the time of zeolitization, before the tectonic tilting of Yucca Mountain was completed, prior to deposition of the Rainier Mesa Member of the Timber Mountain Tuff 11.3 Ma ago (Broxton et al., 1987). Below this boundary, matrix and fracture-lining zeolites probably formed under saturated conditions with similar fluid chemistry.

Zone I contains a complex and diverse suite of zeolites in fractures although the matrix is predominantly not zeolitic. Stellerite has been identified only from the Paintbrush Tuff but is not present in all the cores and does not appear to be limited to one interval (e.g., vapor phase or densely welded lower non-lithophysal units). The prismatic zeolites stellerite and heulandite are most widely distributed in fractures in USW G-1 and UE-25a#1, which are located along Drill Hole Wash, suggesting there may be a relationship between proximity to the wash and abundance of heulandite and stellerite. In other drill cores, the prismatic zeolites occur in fractures over more restricted intervals. Although no fault or other regional structure controlling the location of the wash has been identified, a subsurface structure may have contributed to the development of these zeolites either by controlling flow or fluid chemistry at the time of formation. An additional hole being drilled along this wash (USW UZ-14) will provide additional information on whether proximity to the wash does relate to abundance of heulandite and stellerite. As future holes are drilled it will be possible to better define the lateral distribution of fracture-lining zeolites in Zone I and identify any correlations with structural features or areal distribution. Currently there is no evidence of an effect from the Timber Mountain volcanic center on fracture-linings in this shallow zone, but the possibility cannot be dismissed.

There is no direct evidence for the absolute age of fracture-lining zeolites in the Paintbrush Tuff. Fine-grained mordenite is slickensided on some fractures, indicating movement along the fractures after deposition of the mordenite. Other zeolites and coarser mordenite have not been affected by movement, suggesting that they may have been deposited after most of the tectonic activity at Yucca Mountain. Alternatively, most of the zeolites may have been deposited during the early history of the tuff, but movement was restricted to a few fractures or zones and either these did not contain coarser zeolites or they were destroyed during movement. In a few fractures in the Paintbrush Tuff, calcite overlies coarse zeolites and it may be possible to constrain the age of fracture-lining zeolite deposition by determining the age of the calcite.

The fact that zeolites occur in fractures where there are no zeolites in the matrix indicates that fracture-flow in the unsaturated zone has been important in the past. The presence of two different morphologies and at least two different compositions of heulandite in fractures in the Topopah Spring Member suggests at least two episodes of heulandite formation. Differing compositions for the large tabular crystals within a fracture suggest either that different crystals formed at different times over a period when the fluid composition was changing or that later fluids resulted in cation exchange within the crystals. Additional studies of individual crystals may determine whether the compositional variation in tabular crystals is a result of regular zoning, two or more compositions (generations) of tabular crystals and no zoning within a crystal, exchange along some preferred direction within the crystals, or some combination of the above.

Many fractures in Zone I that contain heulandite are not sealed and have open passages that are possible present or future flow paths. These zeolites may act as barriers to radionuclide migration away from the repository, or they may be affected by increased temperature after emplacement of waste, and react with water present in the rock to form other mineral assemblages. Mineral stability studies are being conducted by Bish and others (Bish, 1993) to address these questions.

Since fractures within zeolitic intervals in Zones II and III contain the same minerals as the matrix in those intervals, modeling of radionuclide retardation need only consider flow times rather than different mineralogy or chemistry for fractures in these intervals. However, thick mats of mordenite fibers that fill fractures will allow passage of water but may act as filters for any suspended colloids. Within the devitrified intervals in these zones, the only zeolite present is mordenite, and that is uncommon in most drill cores and therefore should not be considered when modeling radionuclide retardation.

SUMMARY AND CONCLUSIONS

Fracture-lining zeolites in the Paintbrush Tuff are highly variable in distribution both vertically and laterally across Yucca Mountain. Mordenite, heulandite, and stellerite are widespread in fractures although the Paintbrush Tuff is generally devitrified. Factors controlling formation of the fracture-lining zeolites in the Paintbrush Tuff are not yet understood, but the zeolites probably formed under different geochemical conditions, and possibly at different times than fracture-lining zeolites in the underlying tuffs. Fracture-lining zeolites in the Calico Hills Fm. and the Crater Flat Tuff include mordenite, clinoptilolite, analcime, and minor chabazite, and correlate with the zeolitic alteration of the tuffs containing them. Only mordenite occurs in the devitrified intervals of these units. The zeolites in fractures probably formed primarily during zeolitization of the non-welded portions those tuffs, most likely in response to a regional hydrothermal system related to the Timber Mountain Caldera to the north of Yucca Mountain.

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FIGURE CAPTIONS

1. Location map showing Yucca Mountain and the drill holes mentioned in this report.

2. Generalized stratigraphy of the tuff units studied at Yucca Mountain.

3. SEM image of stellerite crystals from USW G-2 1536. Scale bar is 50 µm.

4. SEM image of large tabular and small prismatic crystals of heulandite from UE-25a#1 1242. Scale bar is 50 µm.

5.a, b Ternary plots based on number of exchangeable cations showing chemical variability of heulandite in fractures in the Topopah Spring Member of the Paintbrush Tuff, and the difference between small prismatic crystals and co-existing tabular crystals in the same fracture in sample UE-25a#1 1242.

6. SEM image of smectite crystals over mordenite from USW G-1 1156. Scale bar is 5 µm.

7. SEM image of phillipsite crystals from USW GU-3 1200. (See Table 2 for chemical analysis.) Scale bar is 100 µm.

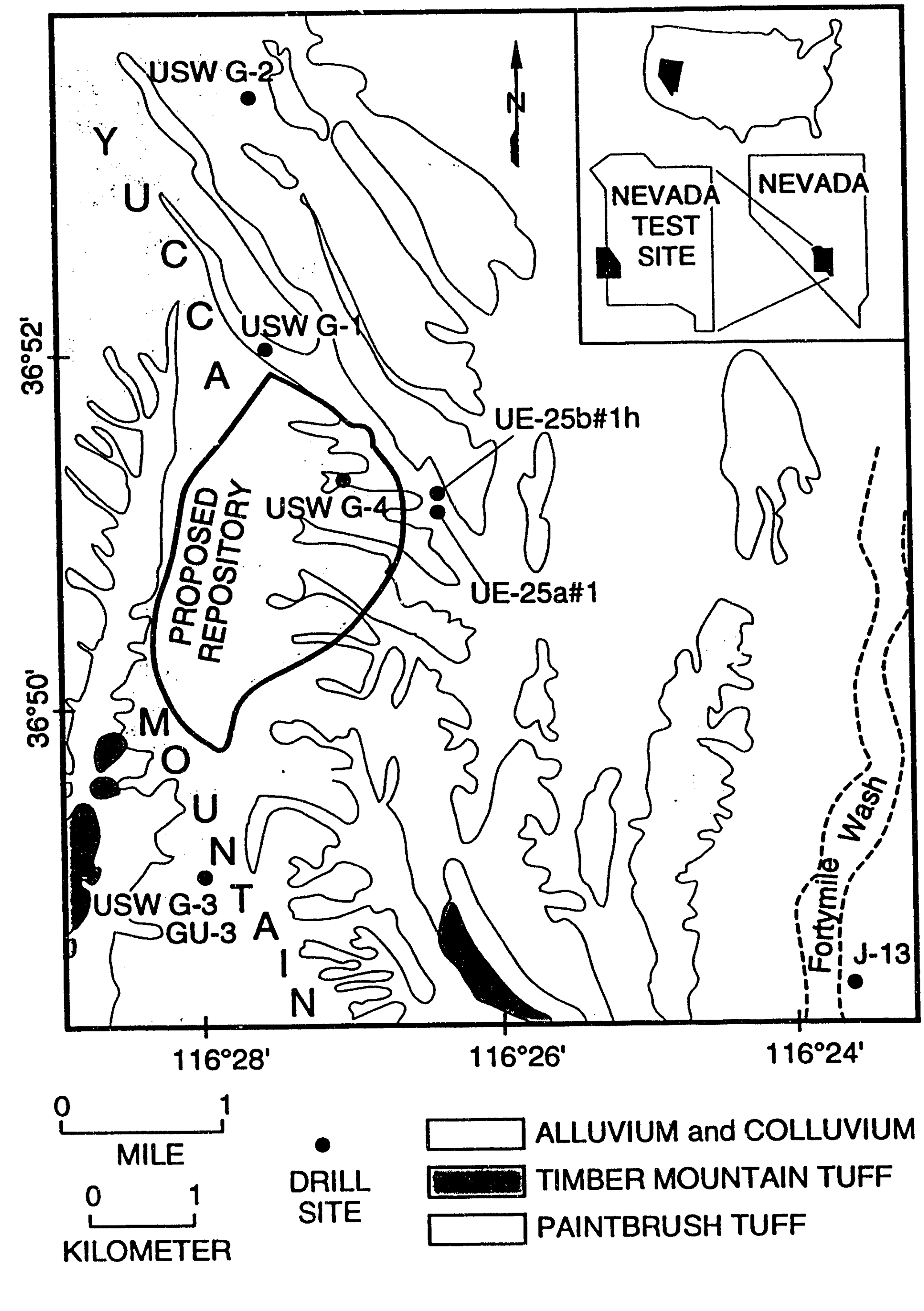
8. SEM image of mordenite from the Prow Pass Member of the Crater Flat Tuff in Zone II. Scale bar is 10 µm.

9. Ternary plot of clinoptilolite analyses from the Calico Hills Fm. and the Crater Flat Tuff, showing variation in composition between samples. Analyses of chabazite from UE-25b#1h 2165 are included for comparison with clinoptilolite from the same sample.

10. SEM image chabazite from UE-25b#1h 2165. Scale bar is 10 µm.

11. SEM image of analcime over quartz from USW G-2 3137. Mordenite is visible only as ropy feature in the upper left corner of photo. Scale bar is 100 µm.

Fig 1



USW G-2
Y
U
C
C
A
M
O
U
N
T
A
I
N
N
NEVADA TEST SITE
NEVADA
36°52'
36°50'
USW G-1
UE-25b#1h
USW G-4
UE-25a#1
PROPOSED REPOSITORY
USW G-3
GU-3
Fortymile Wash
J-13
116°28'
116°26'
116°24'
0 1
MILE
0 1
KILOMETER
DRILL SITE
ALLUVIUM and COLLUVIUM
TIMBER MOUNTAIN TUFF
PAINTBRUSH TUFF

2

GENERALIZED STRATIGRAPHY

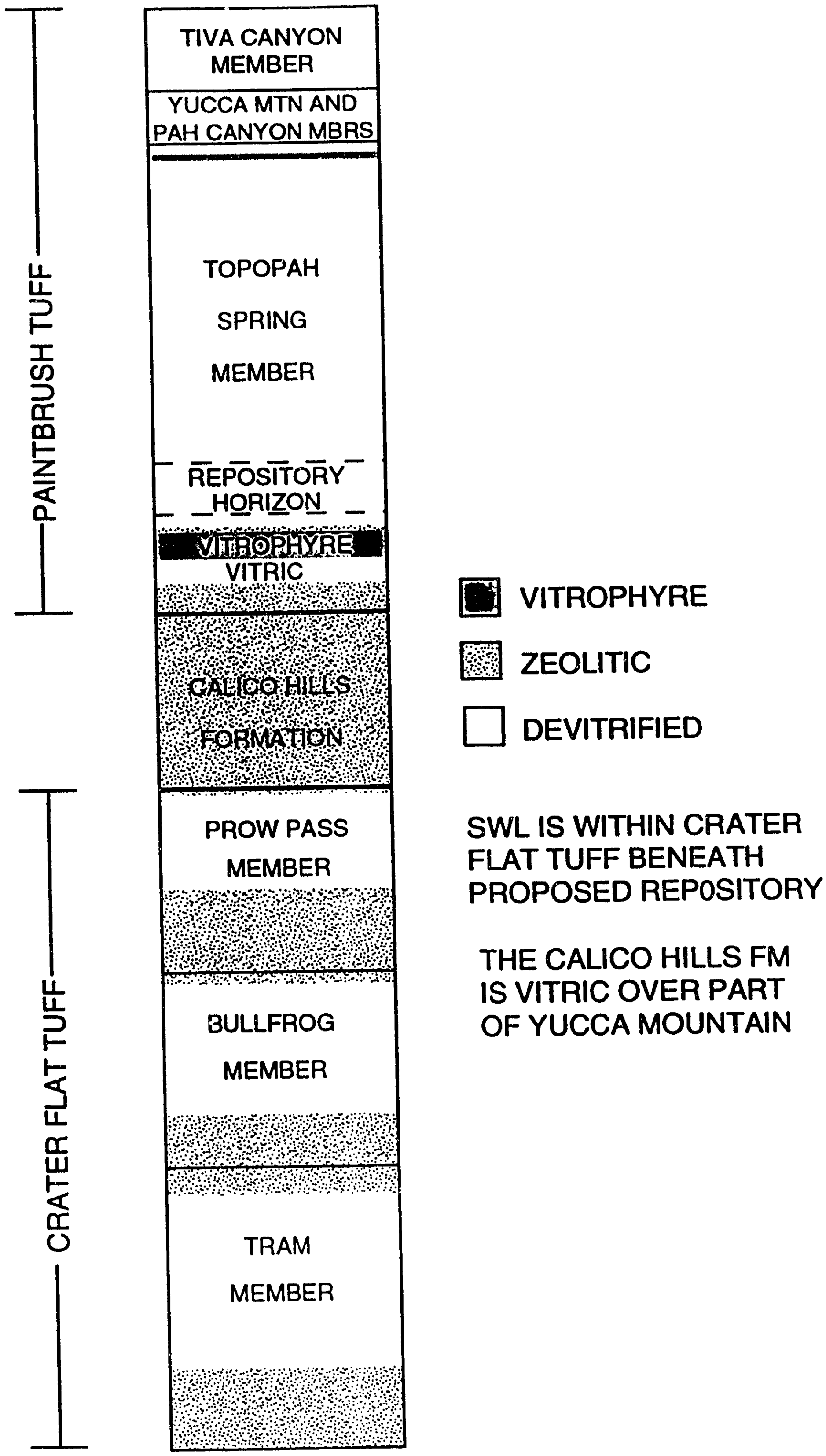
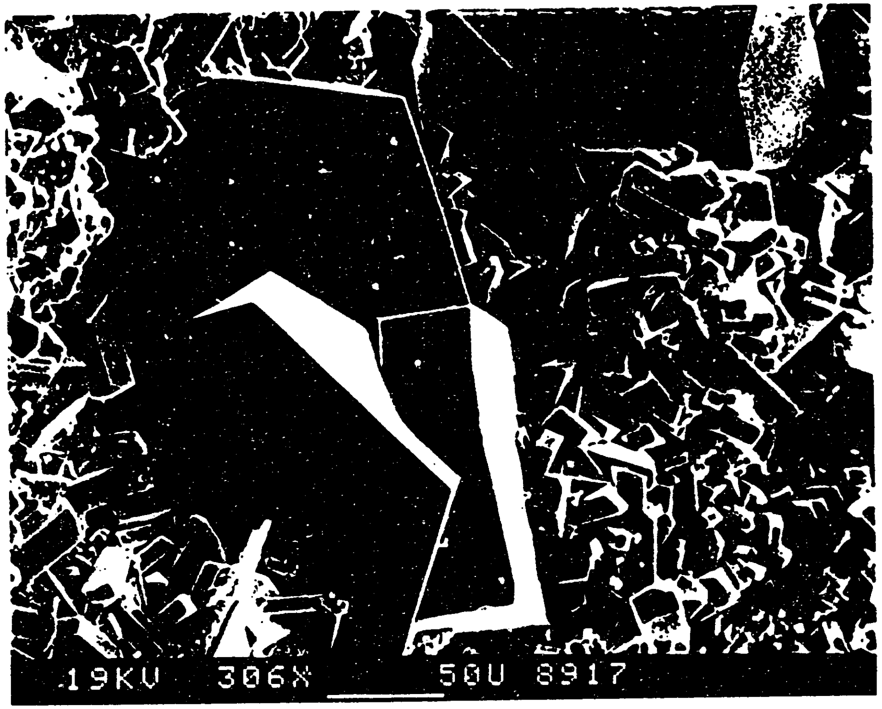
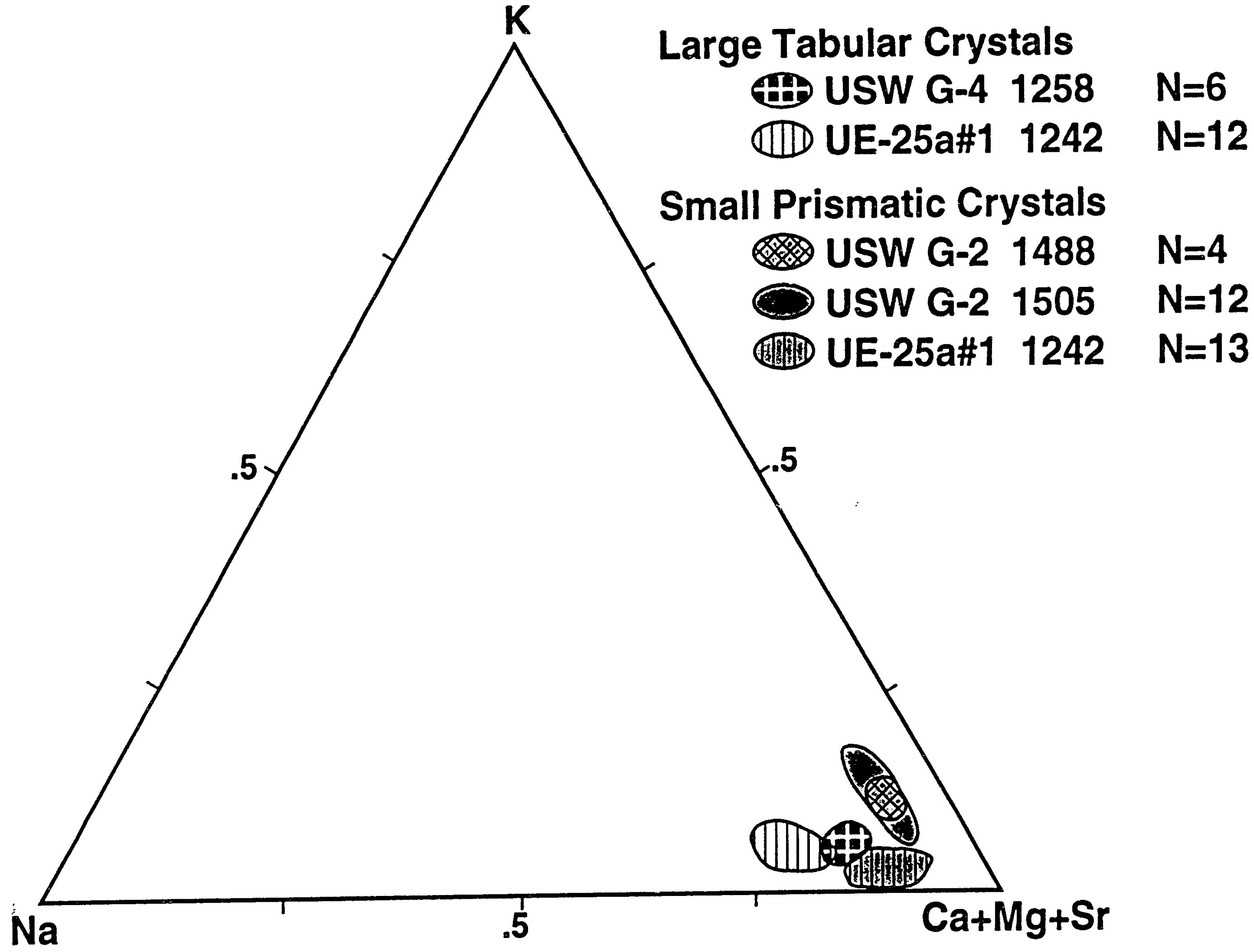


Fig 3

Fig 4



5a


K
Na
Ca+Mg+Sr
.5
.5
.5
Large Tabular Crystals
USW G-4 1258 N=6
UE-25a#1 1242 N=12
Small Prismatic Crystals
USW G-2 1488 N=4
USW G-2 1505 N=12
UE-25a#1 1242 N=13

5b

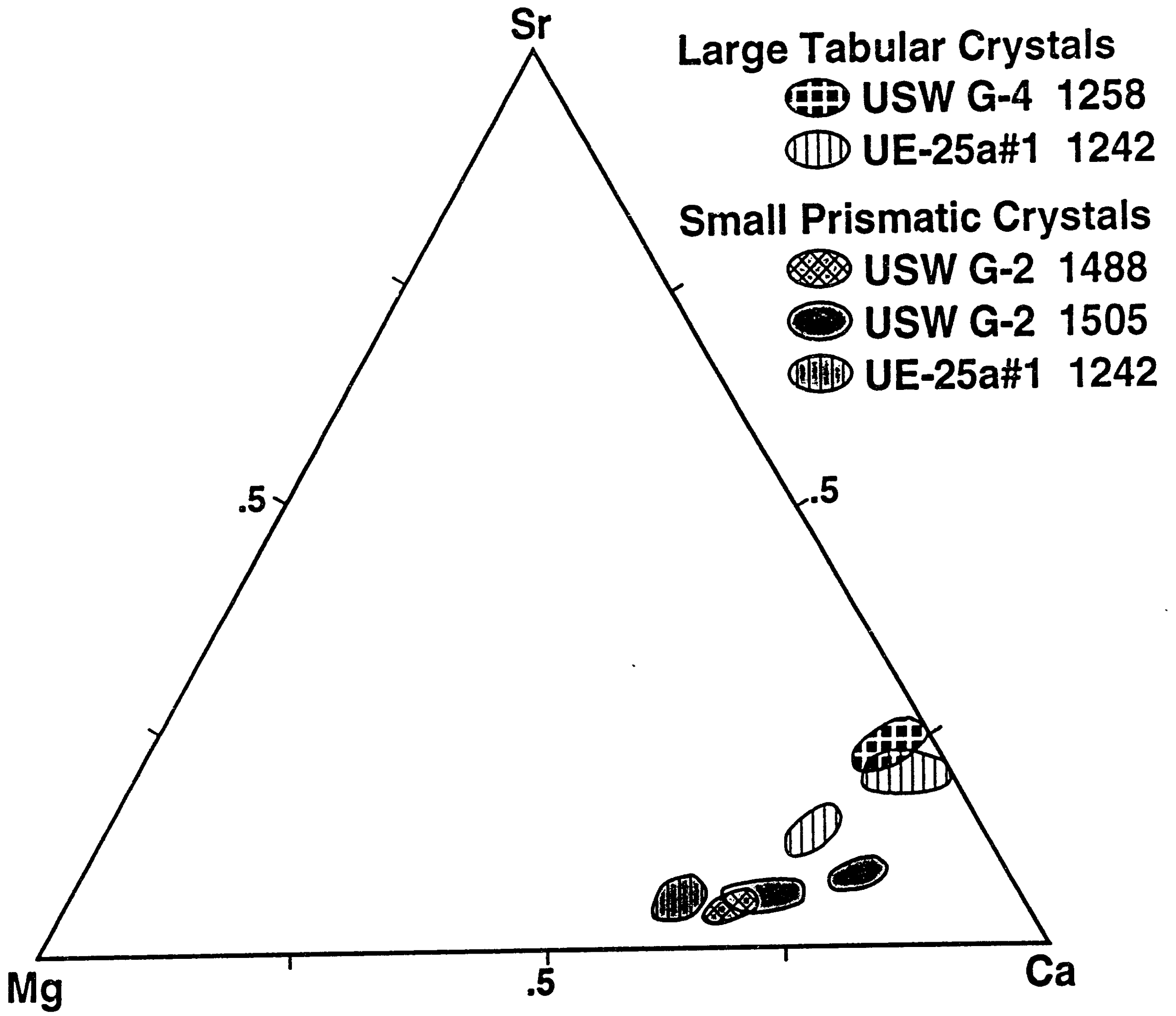

Sr
Mg
Ca
.5
.5
.5
Large Tabular Crystals
USW G-4 1258
UE-25a#1 1242
Small Prismatic Crystals
USW G-2 1488
USW G-2 1505
UE-25a#1 1242

Fig 6

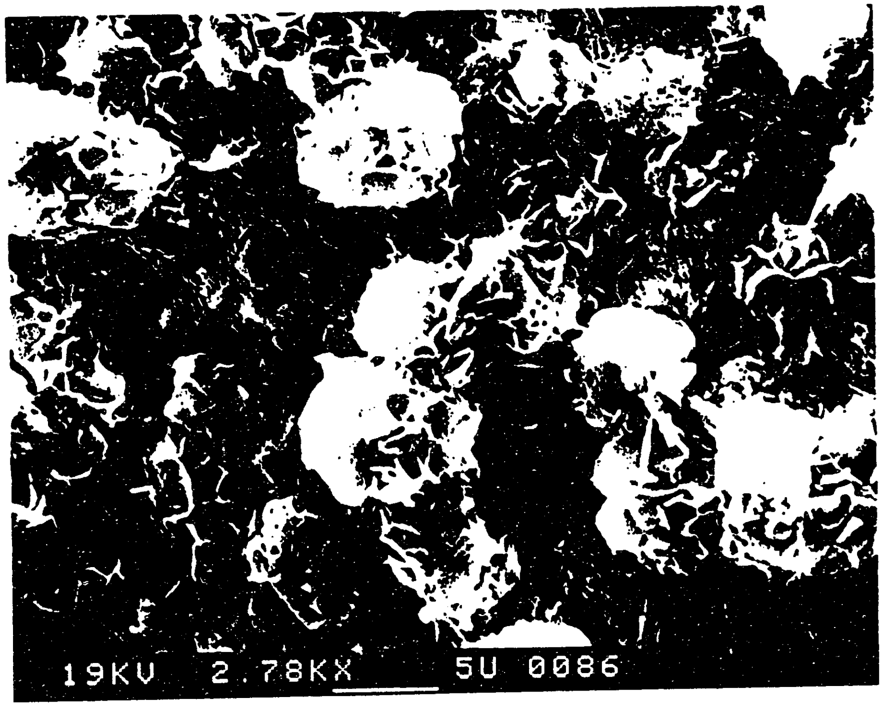


Fig 1

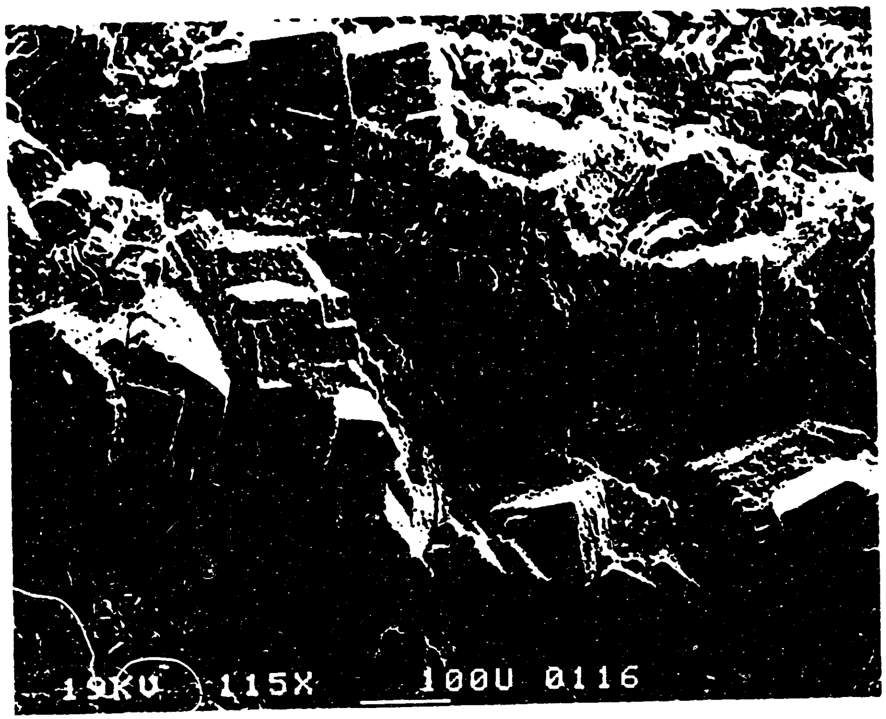


Fig 8

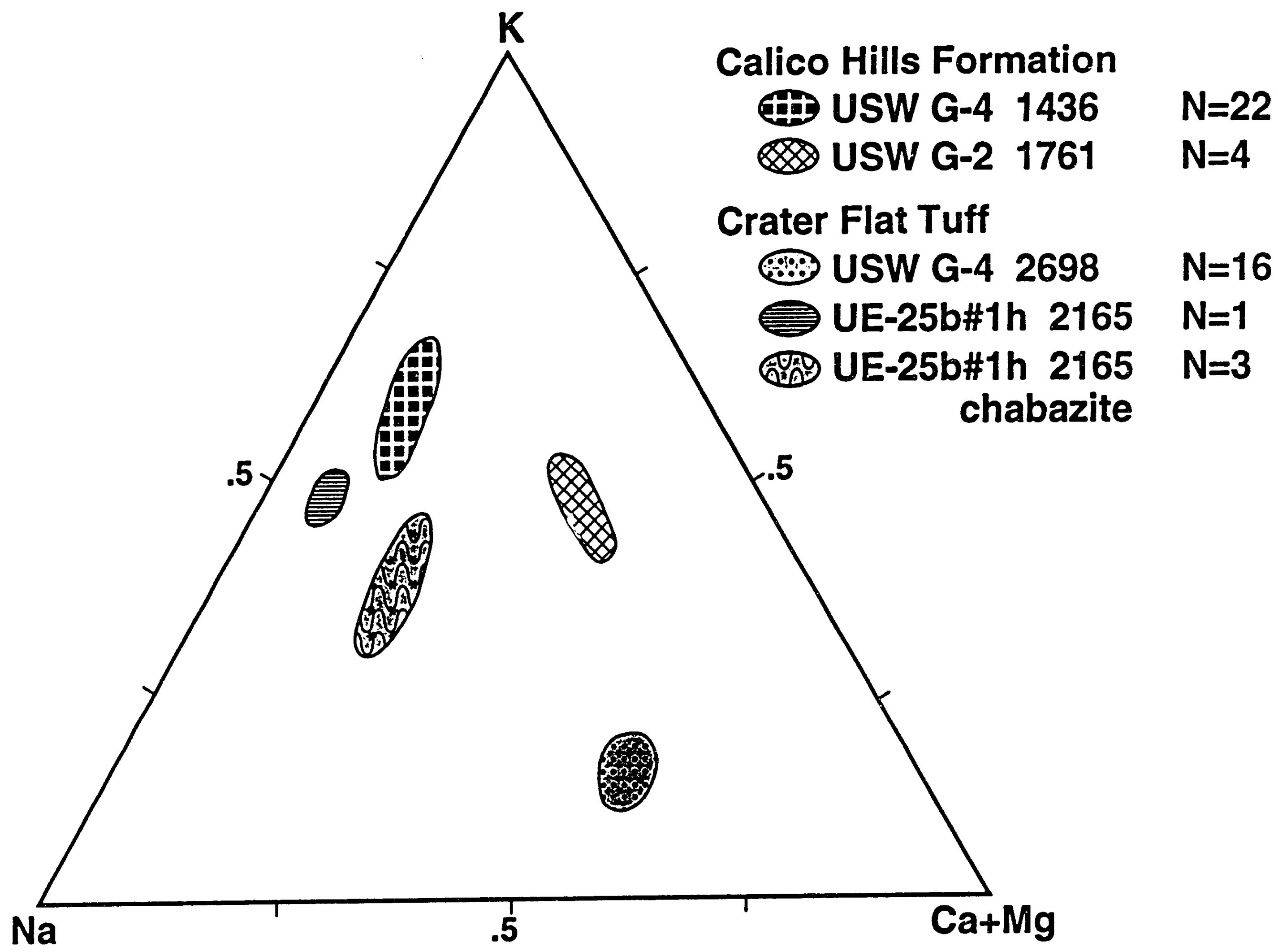

K
Na
Ca+Mg
.5
.5
.5
Calico Hills Formation
USW G-4 1436 N=22
USW G-2 1761 N=4
Crater Flat Tuff
USW G-4 2698 N=16
UE-25b#1h 2165 N=1
UE-25b#1h 2165 N=3
chabazite

Fig 10

Fig 11

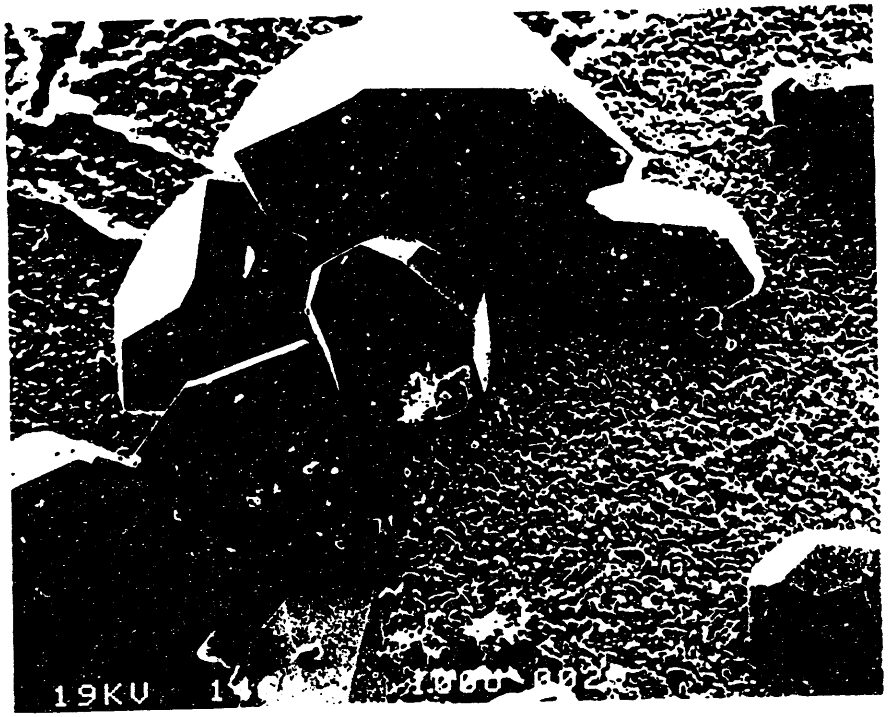


Table 1

Fracture-Coating Minerals

Key to footnotes.

[1] Sample label represents the sample depth in feet.
[2] Clinoptilolite/heulandite group mineral.
[3] Zeolite -- unknown whether clino/heul or mordenite.
[4] Presence uncertain due to peak overlaps with clinoptilolite.
[5] Presence uncertain due to peak overlaps with clinoptilolite and mordenite.
[6] Presence uncertain due to peak overlaps with stellerite.
[7] Presence uncertain due to peak overlaps with feldspar.
[8] Either poorly crystallized cristobalite or opal-C.
[9] Believed to be present but positive ID impossible due to feldspar or tridymite peak overlaps.

[a] Major abundance.
[b] Minor abundance.
[c] Trace abundance.

Qualitative Mineralogy as Determined by XRD for UE-25a#1 and UE-25b1h Fracture Samples

Sample[1]	Smect-ite	Clinopt-ilolite[2]	Morden-ite	Stell-erite	Other Zeolite	Cristob-alite	Opal-CT	Tridy-mite	Quartz	Cal-cite	Other
UE-25a#1											
Topopah Spring Member											
780.6/780.9	---	---	Trace	---	---	---	---	---	Major	Major	
989.2/989.6a	Trace	Trace	---	---	---	---	---	Trace	Major	---	
989.2/989.6b	Trace	Trace	Minor	---	---	---	---	Minor	Major	---	
1100.4/1100.6	Minor	---	Minor	---	---	---	---	---	Major	---	
1105.1/1105.4	---	Major	Major	---	---	Minor	---	---	Minor	---	
1242.7/1243.1	---	Major	Minor	Minor	---	---	Minor	---	Minor	---	
1252.3	Trace	Minor	Major	---	---	---	Minor	---	Minor	---	
1274.5	Major	Major	Trace	---	---	---	Minor	---	Minor	---	
1276.0/1276.2	Major	Minor	Minor	---	---	---	Minor	---	Minor	---	
1282.6	Major	Major	Trace	---	---	---	---	---	---	---	
1296.2	Minor	Major	---	---	Erionite[a]	---	---	---	---	---	
1301.5/1302.0	Minor	Major	---	---	Phillip.[a]	---	---	---	Trace	---	
1309.0/1309.2	Minor	Major	---	---	---	---	Minor	---	---	---	
1318.4/1319.5	Trace	Major	Minor	---	---	---	Minor	---	Trace	---	
1322.9/1323.2	Minor	Major	Minor	---	---	---	Minor	---	Trace	---	
1339.5/1339.7	Minor	Major	Major	---	---	---	Trace	---	Trace	---	
1361.8/1362.0	Minor	Major	Minor	---	---	---	Major	---	Trace	---	
Calico Hills Formation											
1416.4	---	Major	Major	---	---	---	Trace	---	Minor	---	Mn-Oxides[b]
1419.0	Minor	Minor	Major	---	---	---	Trace	---	---	---	
1542.9	======================== Static Water Level ========================										
1643.1	Trace	Major	Major	---	---	---	Minor	---	---	---	
1676.7	Minor	Trace	Major	---	---	---	Trace	---	---	---	
Prow Pass Member											
2036.3/2036.5	Trace	Minor	Major	---	---	---	Trace	---	Minor	---	
2182.2	---	Minor	Major	---	---	---	---	---	Major	---	Mn-Oxides[b]
2212.0/2212.5	---	Trace	Major	---	---	---	---	---	Major	---	Mn-Oxides[b]
2234.3	Minor	Minor	Major	---	---	---	---	---	Minor	---	
2237.6/2237.8	---	Minor	Major	---	---	---	---	---	Minor	---	Mn-Oxides[b]
Bullfrog Member											
2362.3	Major	---	Minor	---	---	---	---	---	Major	---	
2395.4	Major	Minor	Major	---	---	---	Minor	---	Minor	---	
UE-25B1H											
Prow Pass Member											
2008.8/2009.3	---	---	---	---	---	---	---	---	Major	---	Mn-Oxides[b]
2141.5/2141.7a	Trace	Major	Trace	---	---	---	Major	---	Minor	---	
2141.5/2141.7b	Minor	Major	---	---	---	---	Major	---	Minor	---	
2164.7/2165.0	Major	Major	Minor	---	Chabaz.[b]	Minor	Major	---	Minor	---	
Tram unit											
3185	Trace	---	---	---	---	---	---	---	Minor	Major	Mn-Oxides[b]

Qualitative Mineralogy as Determined by XRD for USW G-1 Fracture Samples

Sample[1]	Smectite	Clinoptilolite[2]	Mordenite	Stellerite	Other Zeolite	Cristobalite	Opal-CT	Tridymite	Quartz	Calcite	Other
Topopah Spring Member											
425.5/425.7	---	---	---	---	---	---	Minor	---	Trace	Major	
625.0/625.2	Major	Major	---	---	---	---	---	---	Minor	---	
686.6/686.7	Trace	---	---	Major	---	---	---	---	Trace	---	
726.0/726.4	---	---	---	Major	---	---	---	---	Trace	---	
942.4/942.8	---	---	---	Major	---	---	---	---	Trace	---	
980.9/981.1	Trace	---	---	Major	---	---	---	---	---	---	
1104.3/1104.5	Trace	---	---	---	---	Minor	---	Minor	Major	---	
1136.9/1137.2	Major	---	---	---	---	Major	---	Minor	Major	---	
1156.0/1156.4	Major	Trace[3]	---	---	---	Minor	---	Minor	Major	---	
1165.5/1165.8	Major	Trace[3]	---	---	---	---	---	Minor	Major	---	Mn-Oxides[a]
1225.6/1225.9	Major	Trace	---	Major	---	---	---	---	Minor	---	
1265.3/1265.8	---	---	---	Trace	---	---	---	---	Trace	Major	
1281.8/1282.0	Trace	Major	---	???[4]	---	Minor	---	---	Trace	Major	
1297.0/1297.2	Major	---	---	---	---	---	Major	---	Minor	---	
1337.0/1337.5	Major	Major	---	---	---	---	Major	---	Minor	---	Mn-Oxides[b]
1356.0/1356.3	Trace	Major	---	---	---	---	Major	---	Minor	---	
Prow Pass Member											
1875.7	=========	=========	=========	=========	Static Water Level	=========	=========	=========	=========		
1921.1/1921.2	Trace	---	---	---	---	---	---	---	Major	---	
Bullfrog Member											
2243.1/2243.5	---	Minor	Major	---	---	---	Minor	---	Trace	---	
2281.6/2282.0	Minor	Minor	Major	---	---	---	Minor	---	Minor	---	Mn-Oxides[a]
2306.4/2306.6	---	---	Major	---	---	---	---	---	---	---	
2506.6/2506.8	---	---	---	---	---	---	---	---	Major	---	
2564.4/2564.8	---	Trace	---	---	---	---	Major	---	Trace	---	
2578.5	Minor	---	Trace	---	---	---	---	---	Major	---	Mn-Oxides[b]
Tram unit											
2790.9	Minor	---	---	---	---	---	---	---	Major	---	Mn-Oxides[b]
2807.0	Minor	---	---	---	---	---	---	---	Major	---	Mn-Oxides[b]
2905.1/2905.2	---	---	---	---	---	---	---	---	Major	---	Mn-Oxides[b]
2920.1/2921.1	---	---	---	---	---	---	---	---	Major	---	Mn-Oxides[a]
2937.2/2937.6a	---	---	---	---	---	---	---	---	Trace	Major	
2937.2/2937.6b	---	---	---	---	---	---	---	---	Trace	Major	
2963.7	---	---	---	---	---	---	---	---	Major	Trace	Mn-Oxides[a]

Qualitative Mineralogy as Determined by XRD for USW G-2 Fractures

Sample[1]	Smectite	Clinoptilolite[2]	Mordenite	Stellerite	Other Zeolite	Cristobalite	Opal-CT	Tridymite	Quartz	Calcite	Other
Yucca Mountain Member											
331.5/332.5	Major	---	---	---	---	Major	---	---	---	---	Mn-Oxides[a]
Topopah Spring Member											
1178.4/1178.7	Trace	---	---	---	---	---	---	Minor	Major	---	
1282.0/1282.1	Trace	---	Trace[3]	---	---	---	---	Major	Major	---	
1447 lithoph	Minor	---	Minor	---	---	Major	---	Minor	Minor	---	
1447 breccia	Minor	Minor	Minor	???[5]	---	Major	---	Trace	Major	Major	
1449	Minor	Major	Major	Major	---	???[6]	---	---	Minor	---	
1456	Trace	Trace	Major	---	---	???[7]	---	Trace	Minor	---	
1488.2	Minor	---	Trace	???[5]	---	---	---	???[6]	Major	---	
1505.0/1505.2	Minor	Trace	Major	Major	---	???[6]	---	???[6]	Major	---	
1516.7/1517.0	Trace	---	Major	Major	---	???[6]	---	---	Minor	---	
1534.4	Trace	Trace	Major	Trace	---	Minor	---	---	Minor	---	
1568.8/1569.0a	Trace	Major	Minor	Major	---	Minor	---	---	Trace	---	
1568.8/1569.0b	Trace	Major	Trace	Major	---	Minor	---	---	Major	---	
1581.0/1582.2	Trace	Minor	Major	Major	---	???[6]	---	---	Minor	---	
1603.6/1604.0	Minor	Major	Major	???[5]	---	???[6]	---	---	Minor	---	Mn-Oxides[a]
1629.7/1630.0	Minor	Major	Trace?	???[5]	---	Minor	---	---	Minor	---	
1631.2/1631.4	Major	---	Trace	---	---	Major	---	---	Major	---	Mn-Oxides[b]
1636.7/1636.8	Major	Minor	---	---	---	---	---	---	Trace	---	
1643.8/1644.0	Major	Minor	---	---	---	---	---	---	---	---	
1644.0/1644.4a	Minor	Major	---	---	---	---	---	---	---	---	
1644.0/1644.4b	Major	Major	---	---	---	---	---	---	---	---	
1653.4	Major	Major	---	Trace[5]	---	---	Minor	---	Trace	---	
1656.8/1657.2	Major	Major	---	---	---	---	---	---	Minor	---	
1669	Major	Major	Trace	---	---	---	Major	---	---	---	
1680.7	Minor	Major	---	---	---	---	Major[8]	---	Minor	---	
1687.6	Minor	Major	Trace	---	---	---	Major	---	Minor	---	
Bedded Tuffs											
1722.1	=========	=========	=========	=========	Static Water Level	=========	=========	=========	=========		
Calico Hills Formation											
1757.6/1757.9	---	Minor	Major	---	---	---	Trace	---	---	---	
1762.7/1762.9	Minor	Trace	---	---	---	---	Major	---	---	---	
1867.7	---	Minor	Major	---	---	---	---	---	---	---	Mn-Oxides[b]
2005.0/2005.4a	---	Minor	Major	---	---	---	Major	---	Major	---	
2005.0/2005.4b	Trace	Minor	Major	---	---	---	Minor	---	Major	---	
2027.7/2028.0	Trace	Minor	Major	---	---	---	Trace	---	Trace	---	
2067.5/2067.7	Minor	Minor	Major	---	---	---	Minor	---	Trace	---	
2069.6/2069.9	Trace	Minor	Major	---	---	---	Minor	---	---	---	
2085.0/2085.4	---	Major	Major	---	---	---	Minor	---	---	---	
2091.6/2091.8	Trace	Minor	Major	---	---	---	Trace	---	---	---	
2122.6/2123.0	---	Trace	Major	---	---	---	---	---	---	---	
2281.1	Minor	Minor	Major	---	---	---	Trace	---	Trace	---	
2282.9	Trace	Trace	Major	---	---	Major	---	---	---	---	
Prow Pass Member											
2722.2	Minor	---	---	---	---	---	---	---	Major	---	Mn-Oxides[a]
2751.6	Major	---	Trace	---	---	---	---	---	Major	---	
2762.0	Trace	---	---	---	---	---	---	---	Major	---	Mn-Oxides[a]
2812.1	Trace	---	---	---	---	---	---	---	Major	---	Fe-Oxides[a]
2853.0/2853.3	Minor	---	---	---	---	---	---	---	Major	---	Fe-Oxides[b]
2862.6/2863.2	Minor	---	---	---	---	---	---	---	Minor	---	Mn-Oxides[a]
2872.8/2873.3	Trace	---	---	---	---	---	---	---	Major	---	Mn-Oxides[a]
2878.0/2878.1	Trace	---	---	---	---	---	---	---	Major	---	Mn-Oxides[a]
2884.9	Major	---	---	---	---	---	---	---	Major	---	Fe-Oxides[b]
2894.4	---	---	---	---	---	---	---	---	Minor	---	Mn-Oxides[a]
2926.7	Minor	---	---	---	---	---	---	---	Major	---	Mn-Oxides[b]
3000.2	Major	---	---	---	---	---	---	---	Major	---	Fe-Oxides[a]
3137.0/3137.3	---	---	Trace	---	Analcime[a]	---	---	---	Minor	---	
3168.0/3168.3	Major	Minor	Trace	---	---	---	---	---	Major	---	Fe-Oxides[a]
Bullfrog Member											
3397.4/3397.7	Trace	---	---	---	---	---	---	---	Major	---	Mn-Oxides[a]
3407.0/3407.4	Trace	---	---	---	---	---	---	---	Major	---	Fe-Oxides[a]
3420.6/3420.9	Trace	---	---	---	---	---	---	---	Minor	---	Mn-Oxides[a]

Qualitative Mineralogy as Determined by XRD for USW GU-3 Fracture Samples

Sample[1]	Smectite	Clinoptilolite[2]	Mordenite	Stellerite	Other Zeolite	Cristobalite	Opal-CT	Tridymite	Quartz	Calcite	Other
Tiva Canyon Member											
88.1	---	---	---	---	---	---	---	Minor	---	---	Sepiolite[a]
154.5	Minor	---	---	---	---	---	---	---	---	Major	Palygorskite[a]
244.8	---	---	---	---	---	---	---	---	---	---	Palygorskite[a]
319.0	---	Major	---	---	---	---	Minor	---	Minor	---	
337.4	Major	Minor	---	---	---	---	Minor	---	---	---	
Topopah Spring Member											
470.0	---	---	---	---	---	---	---	---	---	Major	Sepiolite[b]
479.7/480.3	---	---	---	---	---	---	---	---	---	Major	Sepiolite[a]
520.8	---	---	---	---	---	---	---	Trace	---	---	Sep+Palyg[a]
579.1/579.5	Trace	---	---	---	---	---	---	Major	Trace	---	
687.8/688.3	---	---	Trace	---	---	---	Trace	---	---	---	Fluorite[a]
687.7/688.3b	---	---	---	---	---	---	---	---	---	---	Fluorite[a]
799.7/800.0	Minor	---	---	---	---	???[9]	---	Minor	Major	---	Hemaitite[b]
802.4	Major	---	Major	---	---	---	---	Minor	Trace	---	
804.0/804.3	Minor	---	---	---	---	Minor	---	Major	Major	---	Mn-Oxides[a]
811.0/811.1	Major	---	Trace[3]	---	---	Minor	---	Minor	Major	---	
818.6/819.0	Major	---	---	---	---	???[9]	---	Minor	Major	---	Mn-Oxides[a]
829.4/829.8a	---	---	---	---	---	---	---	---	Trace	Minor	Palygorskite[a]
829.4/829.8b	Trace	---	---	---	---	Minor	---	---	Minor	Major	
846.0/846.2	---	---	---	---	---	---	---	Minor	Major	---	
876.0/876.2	Trace	---	---	---	---	---	---	---	Major	---	
944.5/944.9	---	---	---	---	---	---	---	Major	Major	---	
945.5/945.7	---	---	---	---	---	Trace??	---	Minor	Major	Trace??	
973.0/973.1	---	---	---	---	---	---	---	Minor	Major	---	
976.0/976.5	Major	---	---	---	---	Minor	---	Minor	Minor	---	
981.0/981.5	Major	---	---	---	---	???[9]	---	Major	Major	---	Mn-Oxides[b]
987.5/988.0	Minor	---	---	---	---	Minor	---	Major	Major	---	Fe+Mn Oxides[b]
1006.3/1006.6	---	---	---	---	---	---	---	Minor	Major	---	
1072.5/1072.7a	---	---	---	---	---	---	---	---	Minor	Major	Fluorite[a]
1072.5/1072.7b	---	---	---	---	---	---	---	---	Minor	Trace	Fluorite[a]
1162.7/1163.0	Major	---	Minor	---	---	Trace	---	---	Minor	---	
1189.3/1189.6	Minor	Major	---	---	Erionite[b]	---	Minor	---	Major	---	
1200.1/1200.6a	Minor	Minor	---	---	Phillip.[a]	---	---	---	---	---	
1200.1/1200.6b	Minor	Minor	---	---	Phillip.[a]	---	---	---	Minor	---	
1210.2/1210.6	Major	---	Trace[3]	---	---	Minor	---	---	Minor	---	Fluorite[a]
1232.0/1232.1	Major	---	---	---	---	Minor	---	---	---	---	Fluorite[a]
Prow Pass Member											
1713.7/1714.2	Trace	---	---	---	---	---	---	---	Major	Major	
1714.2	Trace	---	Major	---	---	Minor	---	---	Minor	Minor	Fluorite[a]
1936.8/1937.1	---	Major	---	---	---	---	Minor	---	---	---	
Bullfrog Member											
2013.4/2013.7	Major	Minor	---	---	---	---	---	---	Minor	---	
2013.4/2013.7b	Minor	Major	---	---	---	---	Minor	---	---	---	
2094.7	Trace	---	---	---	---	---	---	---	Major	---	
2198.0/2198.3	Major	---	Major	---	---	Trace?	---	---	Minor	---	
2208.0	---	---	Major	---	---	---	---	---	---	---	
2291.2/2291.4	Minor	---	Major	---	---	Trace	---	---	Minor	---	
2326.4	Minor	---	Major	---	---	Trace?	---	---	Minor	---	
2385.5/2385.8	Major	???	Trace	---	---	---	---	---	Major	---	
2431.8/2432.0	Trace	---	Major	---	---	Minor	---	---	Minor	---	
2461.6	=========================				Static Water Level			======================			
2502.0/2502.2	Minor	---	Major	---	---	---	---	---	Minor	---	
2635.0/2635.4	Minor	Minor	Minor	---	---	Trace?	---	---	Major	---	Mn-Oxides[b]
Tram unit											
3238.7/3239.0	Trace	---	Trace	---	---	---	---	---	Major	---	Mn-Oxides[a]
3263.7/3264.0	Major	Major	---	---	---	Trace?	---	---	Trace	---	

Qualitative Mineralogy as Determined by XRD for USW G-4 Fracture Samples

Sample[1]	Smect-ite	Clinopt-ilolite[2]	Morden-ite	Stell-erite	Other Zeolite	Cristob-alite	Opal-CT	Tridy-mite	Quartz	Cal-cite	Other
Tiva Canyon Member											
64.3/64.5	---	---	---	---	---	---	Major	---	Minor	---	Palygorskite[a]
70.1/70.5	---	---	Minor	---	---	Major	---	Major	Minor	---	Palygorskite[a]
72.0/72.2	---	---	Minor	---	---	Major	---	---	Major	---	Palygorskite[a]
82.6/83.0	---	---	Minor	---	---	Major	---	---	Major	---	Mn-Oxides[b]
Topopah Spring Member											
349.0/349.3	Minor	---	Major	---	---	Minor	---	Minor	---	---	
669.9/670.3	Trace	---	---	---	---	Trace	---	---	Trace	Major	
777.8/778.0	Trace	---	---	---	---	???	---	Major	Major	---	
810.7/811.2	Major	---	Major	---	---	---	---	---	Minor	---	
887.2/887.4	Minor	---	---	---	---	???	---	Minor	Major	---	
984.0/984.4	Trace	---	---	---	---	???	---	Minor	Major	---	
1001.4/1001.8	Minor	---	---	---	---	Minor	---	Trace	Major	---	Hematite[b]
1008.1/1008.3	Trace	---	Minor[3]	---	---	Minor	---	---	Major	---	Hematite[b]
1038.0/1038.7	Major	---	Trace	---	---	Minor	---	Major	Major	---	
1072A type-1	---	---	---	---	---	---	---	Minor	Major	---	
1072B type-2	Minor	---	Minor	---	---	Minor	---	Minor	Major	---	
1083 Fract#3	Major	---	---	---	---	Major	---	Major	Minor	---	
1148.2/1148.4	Major	---	---	---	---	Minor	---	---	Major	---	
1160.1/1160.2	Trace	---	---	---	---	Minor	---	Trace	Major	---	
1173.0/1173.2	Trace	---	Major	---	---	Minor	---	---	Minor	---	
1201.6/1201.8	Trace	---	---	---	---	???	---	Minor	Major	---	Mn-Oxides[b]
1244.5/1244.8	Minor	---	---	---	---	Minor	---	---	Major	---	
1254 Fract#1	Trace	Major	Minor	---	---	Minor[8]	---	---	Minor	---	
1254 Fract#3	---	Major	Trace	---	---	Minor[8]	---	---	Minor	---	Mn-Oxides[b]
1258.0/1258.1	Minor	Major	---	---	---	Minor[8]	---	---	Minor	---	Mn-Oxides[b]
1309.0/1309.4	---	Major	---	---	---	---	---	---	---	---	
1341 Blue	Minor	Major	Trace	---	---	---	Minor	---	---	---	
1341 Beige	Minor	Major	---	---	---	---	Minor	---	---	---	
1341 Cream	Major	Minor	---	---	---	---	Minor	---	---	---	
1350.1/1350.3	Major	Major	Trace	---	---	---	Trace	---	Trace	---	
1362.1/1362.3	Major	Minor	Trace	---	---	---	Minor	---	---	---	
1381.2/1381.5	---	Major	Trace	---	---	---	Major	---	Trace	---	
Calico Hills Formation											
1436	---	Major	---	---	---	---	---	---	---	---	
1513	---	Major	Minor	---	---	Minor	---	Minor	Minor	---	
1542	Trace	Major	Major	---	---	Trace	---	---	Minor	---	
1643	---	Major	Major	---	---	---	---	---	---	---	
1670.7/1671.2	---	Minor	Minor	---	---	---	---	---	Trace	---	Mn-Oxides[a]
1694	Trace	Major	Major	---	---	Minor	---	Minor	Minor	---	
1707	---	Major	Major	---	---	---	---	---	---	---	
1716	Minor	Major	Major	---	---	Trace	---	Trace	Major	---	
Prow Pass Member											
1763 white	Major	Minor	---	---	---	Trace	---	---	---	---	
1763 orange	Major	Major	Minor	---	---	Trace	---	---	Trace	---	
1770.0	========================				Static Water Level			=====================			
1788	---	---	Major	---	---	---	---	---	---	---	
1970	---	Minor	Major	---	---	---	---	---	Minor	---	
1991 orange	Trace	Minor	Major	---	---	Trace	---	---	Minor	---	
1991.4	Major	Major	Minor	---	---	???[8]	---	---	Minor	---	Mn-Oxides[a]
2062	---	Minor	Major	---	---	---	---	---	Minor	---	
2071	---	Major	Major	---	---	---	---	---	Major	---	
2099.3/2099.4	---	Major	Minor	---	---	Minor	---	---	Trace	---	Mn-Oxides[a]
2100 horiz	---	Major	---	---	---	---	---	---	Minor	---	
2100 white	---	Minor	Major	---	---	---	---	---	Trace	---	
2101 white	---	Minor	Major	---	---	---	---	---	Trace	---	
2101 beige	---	Minor	Major	---	---	---	---	---	Minor	---	
2135	---	---	---	---	---	Major	---	---	---	---	
2147 white	---	Major	Major	---	---	---	---	---	Trace	---	
2147 pink	---	Minor	Major	---	---	---	---	---	Minor	---	

USW G-4 Continued

Sample[1]	Smectite	Clinoptilolite[2]	Mordenite	Stellerite	Other Zeolite	Cristobalite	Opal-CT	Tridymite	Quartz	Calcite	Other
Bullfrog Member											
2248	---	Major	Major	---	---	---	---	---	Trace	---	
2344	---	---	---	---	---	Trace	---	---	Major	---	
2578	---	---	---	---	---	Trace	---	---	Major	Major	
2615.8/2615.9	Trace	---	---	---	---	---	---	---	Major	---	Mn-Oxides[a]
2689	Major	---	---	---	---	---	---	---	Major	---	
2698	---	Major	Major	---	---	Minor	Minor	---	---	---	
2728	---	Trace	Major	---	---	---	---	---	Trace	---	
Tram unit											
2793	---	Major	Minor	---	---	---	---	---	---	---	
2823	Minor	Minor	Major	---	---	---	---	---	Minor	---	
2832	Major	Major	Major	---	---	---	---	---	Minor	---	
2854.5/2854.7	Trace	---	---	---	---	---	---	---	Major	---	Mn-Oxides[a]
2917	Trace	---	---	---	---	---	---	---	Major	---	Mn-Oxides[a]
2920.5/2920.6	Minor	---	---	---	---	---	---	---	Major	---	Hematite[b]
2931	Major	---	Major	---	---	---	---	---	Major	---	
2947.3	Trace	---	---	---	---	---	---	---	Major	---	Mn-Oxides[a]
2954.8/2955.1	Minor	---	---	---	---	---	---	---	Major	---	Mn-Oxides[a]
2967.4/2967.5	Trace	---	---	---	---	---	---	---	Major	---	Mn-Oxides[a]
2985.6/2986.0	Minor	---	---	---	---	---	---	---	Major	---	Mn-Oxides[b]

TABLE 2. FRACTURE-LINING ZEOLITES IN THE PAINTBRUSH TUFF.

	Heulandite						Stellerite		Phillipsite
	USW G-4	UE25a#1	UE25a#1	UE25a#1	USW G-2	USW G-2	USW G-2	USW G-2	USW GU-3
	1258	1242	1242	1242	1488	1505	1488	1505	1200
	Tabular	Most Tabular	Few Tabular	Prismatic	Prismatic	Prismatic			
SiO_2	62.29	63.04	64.42	64.63	64.37	64.97	63.94	64.73	64.44
Al_2O_3	14.52	14.74	14.93	14.85	15.07	15.14	15.10	15.71	16.73
Fe_2O_3	-	-	-	-	-	-	-	-	-
MgO	0.39	0.10	0.76	1.80	1.47	1.21	-	-	-
CaO	5.12	5.38	5.25	4.60	5.09	5.28	7.93	8.34	6.08
SrO	2.77	2.33	1.99	0.88	0.83	0.87	-	-	0.26
BaO	-	-	-	-	-	-	-	-	-
Na_2O	0.63	1.03	0.79	0.53	0.33	0.35	0.11	0.13	1.80
K_2O	0.38	0.46	0.39	0.25	0.76	0.85	0.17	0.10	2.38
Total	86.10	87.08	88.53	87.54	87.92	88.67	87.25	89.01	91.69
Si	28.25	28.25	28.25	28.32	28.21	28.26	28.19	28.02	12.25
Al	7.76	7.78	7.72	7.67	7.78	7.76	7.85	8.01	3.75
Mg	0.26	0.07	0.50	1.18	0.96	0.78	-	-	-
Ca	2.49	2.58	2.47	2.16	2.39	2.46	3.75	3.87	1.24
Sr	0.73	0.61	0.51	0.22	0.21	0.22		-	0.03
Na	0.55	0.89	0.67	0.45	0.28	0.30	0.09	0.11	0.66
K	0.22	0.26	0.22	0.14	0.42	0.47	0.10	0.06	0.58
#Oxygen	72	72	72	72	72	72	72	72	32
Si/Al	3.64	3.63	3.66	3.69	3.62	3.64	3.59	3.50	3.27

TABLE 3. CHEMISTRY OF FRACTURE-LINING ZEOLITES IN CALICO HILLS FORMATION AND CRATER FLAT TUFF

	Calico Hills Formation				Crater Flat Tuff			
	USW G-2 1761 Clinoptilolite		USW G-4 1436 Clinoptilolite		USW G-4 2698 Clinoptilolite	Co-existing in Single Fracture UE25b1h 2165 Clinoptilolite	Co-existing in Single Fracture UE25b1h 2165 Chabazite	USW G-2 3137 Analcime
SiO_2	67.74	69.33	69.31	69.91	70.74	71.75	62.94	60.25
Al_2O_3	13.45	12.85	12.14	12.45	12.77	12.26	16.04	19.95
Fe_2O_3	-	0.06	-	-	-	0.12	-	-
MgO	0.06	0.08	-	-	0.16	0.05	-	-
CaO	3.67	3.07	1.03	1.25	4.43	0.84	2.59	-
SrO	-	-	-	-	-	-	-	-
BaO	-	-	-	-	-	-	-	-
Na_2O	1.03	0.99	2.33	2.35	1.48	2.94	3.78	11.38
K_2O	3.25	3.90	6.31	5.79	1.13	4.55	3.60	-
Total	89.20	90.28	91.12	91.75	90.71	92.51	88.95	91.38
Si	29.32	29.66	29.80	29.76	29.75	30.03	9.27	2.17
Al	6.86	6.48	6.15	6.25	6.33	6.05	2.78	0.85
Fe	-	0.02	-	-	-	0.04	-	-
Mg	0.04	0.05	-	-	0.10	0.03	-	-
Ca	1.70	1.41	0.47	0.57	2.00	0.38	0.41	-
Na	0.86	0.82	1.94	1.94	1.21	2.39	1.08	0.80
K	1.79	2.13	3.46	3.14	0.61	2.43	0.68	-
#Oxygen	72	72	72	72	72	72	24	6
Si/Al	4.27	4.58	4.84	4.76	4.70	4.97	3.33	2.55

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