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CHEMICAL VARIABILITY OF ZEOLITES AT A POTENTIAL NUCLEAR WASTE REPOSITORY, YUCCA MOUNTAIN, NEVADA

D. E. Broxton

ABSTRACT

The compositions of clinoptilolites and their host tuffs have been examined by electron microprobe and x-ray fluorescence, respectively, to determine their variability at a potential nuclear waste repository, Yucca Mountain, Nevada. Because of their sorptive properties, these zeolites could provide important geologic barriers to radionuclide migration. Variations in clinoptilolite composition can strongly affect the mineral's thermal and ion-exchange properties, thus influencing its behavior in the repository environment.

Clinoptilolites and heulandites closest to the proposed repository have calcium-rich compositions (60-90 mol.% Ca) and silica-to-aluminum ratios that concentrate between 4.0 and 4.6. In contrast, clinoptilolites and their host tuffs deeper in the volcanic sequence have highly variable compositions that vary vertically and laterally. Deeper-occurring clinoptilolites in the eastern part of Yucca Mountain are characterized by calcic-potassic compositions and tend to become more calcium-rich with depth. Clinoptilolites at equivalent stratigraphic levels on the western side of Yucca Mountain have sodic-potassic compositions and tend to become more sodium-rich with depth. Despite their differences in exchangeable cation compositions these two deeper-occurring compositional suites have similar silica-to-aluminum ratios, concentrating between 4.4 and 5.0.

The chemical variability of clinoptilolites and their host tuffs at Yucca Mountain suggest that their physical and chemical properties

will also vary. Compositionally-dependant clinoptilolite properties important for repository performance assessment include expansion/contraction behavior, hydration/dehydration behavior, and ion-exchange properties. Used in conjunction with experimental results, the data presented here can be used to model the behavior of these clinoptilolite properties in the repository environment.

INTRODUCTION

Yucca Mountain is located along the southwest border of the Nevada Test Site, 28 km east of Beatty, Nevada (Fig. 1). Ash-flow and bedded tuffs at Yucca Mountain are being studied by the U.S. Department of Energy and its subcontractors to determine their suitability to host a potential underground high-level nuclear waste repository. These studies are supported by the Nevada Nuclear Waste Storage Investigations (NNWSI) Project as part of the Civilian Radioactive Waste Management Program. The NNWSI Project is managed by the Waste Management Project Office of the U.S. Department of Energy (DOE), Nevada Operations Office. NNWSI Project work is sponsored by the Office of Geologic Repositories of the DOE Office of Civilian Radioactive Waste Management.

A major consideration for choosing Yucca Mountain as a potential repository site is the presence of abundant zeolites in the thick Tertiary tuffs. The principal zeolites at Yucca Mountain are clinoptilolite, heulandite, mordenite, and analcime. These zeolites could provide important geologic barriers to nuclear waste migration because of their ability to exchange their constituent cations with some important radionuclides without a major change in structure and because of their ability to gain and lose water reversibly. Factors affecting the ability of these zeolites to selectively remove radioactive species from solution include: (1) cation species (size, charge, hydration), (2) temperature, (3) concentration of species in solution, and (4) zeolite structural characteristics (Breck, 1974). Several countries including the United States, Canada, Great Britain, France, Bulgaria, Hungary, Japan, West Germany, and the Soviet Union have capitalized on the ion-exchange properties of clinoptilolite to remove radionuclides, such as Cs^{137}, Sr^{90}, Tl^{204}, As^{110}, Ca^{45} from waste solutions. Studies presently under way show that Yucca Mountain zeolitic tuffs are selective for strontium, cesium, barium, neptunium, uranium, and plutonium (Daniels et al., 1982; U.S. Department of Energy, 1984).

This paper examines the chemical variability of clinoptilolites, the most abundant zeolite at Yucca Mountain. Experimental studies have shown that the chemical and physical properties of clinoptilolite can vary significantly with composition. Data from this study can be used in conjunction with experimental studies to predict the behavior of clinoptilolites under repository conditions.

GEOLOGIC SETTING OF THE REPOSITORY

Yucca Mountain is an east-tilted Basin and Range uplift located on the southern flank of the Miocene-Pliocene Timber Mountain-Oasis Valley caldera complex (Byers et al., 1976; Christiansen et al., 1977). Rhyolite and quartz latite ash-flow tuffs are the dominant lithology and range in aggregate thickness from 1.2 to over 1.8 km. Zeolites are best developed in nonwelded tuffs and in the nonwelded tops and bottoms of ash flows that have densely welded, devitrified interiors. The zeolites formed by replacement of volcanic glass during diagenesis of the tuffs. Where altered, the zeolitic tuffs form mappable intervals that can be correlated laterally throughout most of Yucca Mountain.

The potential repository is sited in the unsaturated zone in the lower half of the Topopah Spring Member of the Paintbrush Tuff (Fig. 2). The repository host rock is densely welded and devitrified to a thermally stable assemblage of alkali feldspar and silica minerals. Zeolitic tuffs occur in several stratigraphic intervals between the repository and the watertable, providing probable barriers to radionuclide migration in the unsaturated zone. Additional zeolitic tuffs below the watertable provide potential barriers to radionuclide migration through the saturated zone. Individual beds of zeolite-bearing tuffs commonly range in thickness from 10 to 150 m and contain 50-75% clinoptilolite in the upper part of the volcanic sequence (Bish and Vaniman, 1985).

MATERIALS AND METHODS

Except for a few outcrop samples, mineral and bulk-rock analyses were performed on core and, to a lesser extent, cuttings collected from drill holes shown in Fig. 1. Mineral compositions were determined on an automated Cameca electron microprobe operated at 15 kev with a 15 to 20 nanoamp beam current. Standards consisted of a set of natural feldspars and other minerals. Wavelength-dispersive x-ray counts were collected for 10 to 20 s or 30,000 counts. Compositions were corrected for differential matrix effects using the methods of Bence and Albee (1968).

Sodium was counted first in the analytical sequence because it tends to migrate from the region excited by the electron beam. The beam was rastered to a diameter of 15 to 25 microns to minimize sodium migration. Despite this precaution, sodium loss remained a significant problem for the analysis of clinoptilolite and the reported sodium concentrations may be low by 5-20% of the amount present. Moving the sample beneath the electron beam decreases sodium loss, but crystals large enough to allow sample movement during analysis are limited.

Bulk-rock major elements were analyzed with an automated Rigaku wavelength-dispersive x-ray fluorescence (XRF) spectrophotometer. Samples were crushed and homogenized (10 g), dried at 900°C, and a 1-g split was fused with 9 g of lithium tetraborate flux. A library of x-ray intensities for standard rocks was used to calculate elemental concentrations (Valentine, 1983). Bulk-rock sodium was determined for a separate sample split by atomic absorption spectrophotometry and/or plasma emission spectrometry because of sodium loss during the drying procedure for XRF samples.

RESULTS AND DISCUSSION

Representative compositions for clinoptilolite-group minerals are given in Table I. Triangular diagrams showing variations in exchangeable-cation compositions are presented in Figs. 3, 4, and 6. Histograms of Si/Al ratios in these minerals are presented in Fig. 5. Based upon composition and mode of occurrence, these zeolites can be divided into (1) an upper group of clinoptilolites and heulandites that have limited distribution and uniform calcium-rich compositions (Fig. 3), and (2) a lower group of clinoptilolites that occur in thick, widespread zones of alteration and have highly variable compositions (Fig.4). The upper group contains volumetrically small amounts of zeolites but is important because of the proximity of these zeolites to the repository. The lower group includes thick zeolitic tuffs both above and below the watertable.

The upper group of calcic clinoptilolites occurs below the repository horizon in fractures (Carlos, 1985) and in a thin (0.2-1.0 m) but nearly continuous zone of zeolite and smectite alteration concentrated at the top of the basal vitrophyre in the Topopah Spring Member of the Paintbrush Tuff (Levy, 1984). Despite their scattered distribution in local zones of alteration, the minerals in this group are invariably calcium-rich (Fig. 3) and have silica-to-alumina ratios ranging between 4.0 and 5.0 (Fig. 5). Magnesium contents of these zeolites are relatively high, ranging from 0.6 to 1.5% MgO by weight. Some of these zeolites have a thermal stability characteristic of heulandite (Mumpton, 1960; Levy, 1984), while others have a thermal stability intermediate between heulandite and clinoptilolite (Group 2 of Boles, 1972).

The lower group of clinoptilolites occurs in nonwelded tuffs in which diagenetic alteration has completely replaced original volcanic glass with zeolites. These zeolite-rich tuffs occur at well-defined stratigraphic intervals including: (1) the interval extending from the base of the Topopah Spring Member, through the tuff of Calico Hills, and into the top of the Prow Pass Member, (2) the interval at the base of the Prow Pass Member and top of the Bullfrog Member, and (3) the interval at the base of the Bullfrog Member and top of the Tram Member (Fig. 2). Clinoptilolite compositions in this lower group vary systematically both vertically and laterally (Fig. 4). On the eastern side of Yucca Mountain clinoptilolite compositions are calcic-potassic and show a strong calcium enrichment trend with depth. In contrast, clinoptilolites on the western side of Yucca Mountain are sodic-potassic and tend to become more sodium rich with depth. A transition zone which separates the two suites has compositions similar to both suites. Silica-to-aluminum ratios are similar for both compositional suites (Fig. 5) concentrating between 4.4 and 5.0. However, the silica-to-alumina ratios in the eastern clinoptilolite suite are bimodal with a small population of samples having ratios between 2.8 and 3.6. This smaller population of samples with low silica-to-alumina ratios is associated with the most calcic clinoptilolites in the deepest parts of the eastern suite.

Radionuclide-transport models generally distinguish between transport processes in the unsaturated and saturated zones. Figure 6 shows only those clinoptilolite compositions (lower group) that are likely to be encountered below the repository block in the unsaturated zone. On the western side of the repository unsaturated-zone clinoptilolites are potassic-sodic containing between 40 and 70 mol.% potassium as exchangeable cations. The eastern side of the repository block coincides with the transition zone for all clinoptilolites shown in Fig. 4 and has variable exchangeable cation composition. Part of the clinoptilolites in the eastern part of the repository block have potassic-sodic compositions similar to those to the west. However, others are calcic-potassic, containing only 15-45 mol.% potassium.

Representative bulk-rock compositions for zeolitic tuffs from Yucca Mountain are given in Table II. For comparison, tuff compositions from the eastern part of Yucca Mountain are paired with tuff compositions from the west. A triangular plot of alkalis and alkaline earths shows that bulk-rock compositions vary from east to west in manner similar to clinoptilolite compositions (Fig. 7). Zeolitic tuffs from eastern Yucca Mountain are relatively calcium-rich and deviate more from unaltered tuff compositions than tuffs to the west. Groundwater compositions in the saturated zone also vary laterally in manner similar to clinoptilolite and bulk-rock compositions (Benson et al., 1983; Ogard and Kerrisk, 1984). These groundwaters become more calcic and less sodic eastward. The more calcic groundwaters may be partially derived from Paleozoic carbonate aquifers underlying the volcanic rocks, or the groundwater may become more calcic after ion exchange with calcium-rich zeolitic tuffs in the eastern part of Yucca Mountain.

The physical and chemical properties of clinoptilolites and their host tuffs at Yucca Mountain will probably vary with composition. For example, experimental studies have shown that thermal and ion-exchange properties of clinoptilolite, both of which are of particular interest for repository performance assessment, are strongly influenced by compositional differences. Variations in physical and chemical properties of clinoptilolites and clinoptilolite-bearing tuffs may affect their behavior in the repository setting.

The thermal properties of clinoptilolite are strongly affected by exchangeable-cation compositions (Bish, 1984 and 1985). Compositionally-dependant thermal properties in clinoptilolite include: (1) contraction and expansion behavior, (2) dehydration and rehydration properties, and (3) mineral stability. These thermal properties are important because during the thermal pulse induced by radioactive-waste decay clinoptilolites will be heated to varying degrees depending upon their proximity to the repository. Modelling of the thermal pulse is not yet completed, but heating above ambient temperatures will probably affect (1) clinoptilolite in fractures near the repository, (2) clinoptilolite and heulandite associated with alteration at the top of the Topopah Spring basal vitrophyre, and (3) clinoptilolite-rich tuffs at the base of the Topopah Spring Member and in the tuff of Calico Hills.

In a changing thermal environment, unit-cell volumes of clinoptilolites expand and contract in manner governed by the size, amount, and charge of the exchangeable cations (Bish, 1984). Significant volume changes in zeolites could affect fluid flow paths by opening fractures sealed by zeolites and by increasing permeabilities or opening new fractures in tuffs containing large amounts of zeolites. Sodium clinoptilolites decrease in volume by about 8% when heated from 25°C to 300°C in unsaturated conditions (Fig. 8a). Calcic and potassic clinoptilolites are reduced in volume 3.6% and 1.6%, respectively, under the same conditions. Although Yucca Mountain clinoptilolites have mixed rather than pure end-member compositions, their contraction and expansion behavior should be governed by the dominant cations in exchangeable sites. The clinoptilolites closest to the repository, in fractures and at the top of the Topopah Spring basal vitrophyre, are calcium-rich and contain only subordinate sodium and potassium. During the thermal pulse, these calcium-rich clinoptilolites will probably change volume by less than 4%. The potassic-sodic and calcic-potassic clinoptilolites in unsaturated zeolite-rich tuffs at the base of the Topopah Spring Member and in the tuff of Calico Hills (Fig. 6) will probably undergo considerably less volume change because of their potassium-rich compositions and because of their greater distance from the repository.

The dehydration properties of clinoptilolites also are strongly affected by the nature of their exchangeable cations. Dehydration effects should be greatest in clinoptilolites near the repository during the heating and cooling cycle associated with the thermal pulse. Bish (1985) demonstrated that water loss in clinoptilolites is rapid between 50°C and 130°C and slower at higher temperatures (Fig. 8b). Calcic clinoptilolites give up about 27% of their original water upon heating to 100°C, whereas sodic and potassic clinoptilolites lose 29% and 35%, respectively. These data suggest that clinoptilolites may be a significant source of water in the repository near-field environment if temperatures approach 100°C (Bish, 1985). These partially-dehydrated zeolites could also act as significant sinks for water during the cooling portion of the thermal pulse.

Ion exchange capacities in zeolites are largely controlled by the silica-to-aluminum ratios of their structural framework (Sherry, 1969; Breck, 1974). Substitution of Al^{3+} for Si^{4+} causes a charge deficiency in the mineral framework that requires a greater number of exchangeable cations to maintain electrical balance. Therefore, zeolites with low silica-to-alumina ratios have the high ion-exchange capacities. For example, heulandite with a silica-to-alumina ratio of 3.5 has a theoretical ion-exchange capacity 15% greater than clinoptilolite with a silica-to-alumina ratio of 5.0 (Mumpton, 1981; Table 1). Yucca Mountain clinoptilolites and heulandites have variable silica-to-alumina ratios ranging from 2.8 to 6.0 (Fig. 5). The calcic clinoptilolites and heulandites in fractures near the repository and in the thin zone of zeolites at the top of the Topopah Spring vitrophyre tend to have slightly lower silica-to-alumina ratios than clinoptilolites deeper in the volcanic pile and, therefore, should have slightly higher ion-exchange capacities. The deeper clinoptilolites have similar silica-to-aluminum ratios despite their large variations in exchangeable cation compositions (Fig. 5) and probably have similar ion-exchange capacities. The calcic clinoptilolites or heulandites in the deepest clinoptilolite-bearing rocks in the eastern part of Yucca Mountain are unusual in that they have very low silica-to-alumina ratios (2.8 to 3.6) compared to other clinoptilolites found at similar depths. These unusual zeolites should have relatively high ion-exchange capacities but would only be effective in sorbing radionuclides being transported deep within the saturated zone on the eastern side of Yucca Mountain.

The ion-exchange selectivity of zeolites for radionuclides can be strongly affected by cations already in the exchangeable cation positions (Breck, 1974). Ames (1960) determined that the cation selectivity for clinoptilolite is Cs Rb K Ba Sr Na Ca Fe Al Mg Li. This selectivity sequence is only qualitatively correct because selectivity can vary with degree of exchange and the nature of cation speciation in solution (Breck, 1974). However, it does demonstrate that clinoptilolites in contact with groundwater solutions will tend to selectively sorb and retain radionuclides with large ionic radii. Also, clinoptilolites already occupied by relatively large exchangeable cations (e.g., potassium) may be less likely to exchange with radionuclides with smaller ionic radii (e.g., Sr), effectively reducing the ion-exchange capacity of the zeolites for these elements.

In the unsaturated zone, the calcic clinoptilolites nearest to the repository (upper group) should be highly selective for many important radionuclides including cesium, rubidium, barium, and strontium. The selectivity of heulandite for radionuclides is less well-known, but it and other sorptive minerals such as smectites and manganese oxides are commonly associated with the calcic clinoptilolites and should provide additional sorptive barriers near the repository. In the lower part of the unsaturated zone, potassic-sodic and potassic-calcic clinoptilolites (Fig. 6) occur in thick zones containing 50-75% clinoptilolite, forming major sorptive barriers between the repository and the watertable. Between 40 and 70% of exchangeable cation sites in these clinoptilolites are occupied by potassium in the western part of the repository. Some clinoptilolites in the eastern part of the repository contain only 15-40% potassium as exchangeable cations. The potassium in these clinoptilolites may exchange readily with cesium or rubidium but may exchange poorly with cations of small ionic radius such as strontium and barium. Simple exchange within these clinoptilolites may be further complicated by cation-sieving effects in which large cations such as potassium may be locked into certain structural positions during crystallization of the mineral (Breck, 1974). Nevertheless, these clinoptilolites, particularly those on the east side of the repository, also contain significant concentrations of sodium and calcium which should exchange more readily with a wider variety of radionuclides. Batch-sorption experiments have shown that Yucca Mountain zeolitic tuffs are highly sorptive of cationic radionuclides (Daniels et al., 1982; U.S. Department of Energy, 1984) despite their potassium-rich clinoptilolite compositions. Ultimately, variations in ion-exchange selectivity with clinoptilolite composition may be relatively unimportant given the large volumes of zeolites that groundwaters must pass through along transport pathways. However, this remains to be demonstrated.

In the saturated zone, the potassium contents of clinoptilolites decrease systematically with depth. Calcium and sodium become progressively enriched with depth on the eastern and western sides of Yucca Mountain, respectively. Because of their low potassium contents, these clinoptilolites should have generally similar selectivity properties and better ion-exchange capacities for some small-radii radionuclides than zeolites in the unsaturated zone.

CONCLUSIONS

The compositions of Yucca Mountain clinoptilolites and their host tuffs are highly variable. Clinoptilolites and heulandites in fractures near the repository and in a thin, altered zone at the top of the Topopah Spring basal vitrophyre have consistent calcium-rich compositions. Below this level, clinoptilolites in thick zones of diagenetic alteration on the east side of Yucca Mountain have calcic-potassic compositions and become more calcium rich with depth. Clinoptilolites in stratigraphically equivalent tuffs to the west have sodic-potassic compositions and become more sodic with depth.

Clinoptilolite properties important for repository performance assessment include thermal expansion/contraction behavior, hydration/dehydration behavior, and ion-exchange properties. These properties can be significantly affected by clinoptilolite compositions. The compositional variations for clinoptilolites found by this study suggest that the properties will vary vertically and laterally at Yucca Mountain. Used in conjunction with experimental data, the clinoptilolite compositions presented here can be used to model the behavior of clinoptilolites in the repository environment and along transport pathways.

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LIST OF FIGURES

Table I. REPRESENTATIVE CLINOPTILOLITE COMPOSITIONS, YUCCA MOUNTAIN, NEVADA

	Unsaturated Zone			Saturated Zone	
Rock Unit	Topopah Spring Mbr., Paintbrush Tuff, Top of Basal Vitrophyre	Tuff of Calico Hills, East Side of Repository Block	Tuff of Calico Hills, West Side of Repository Block	Prow Pass Mbr., Crater Flat Tuff, East Side of Repository Block	Prow Pass Mbr., Crater Flat Tuff, West Side of Repository Block
Sample No.[a]	J-13-1335	UE25a#1-132[illegible]	USW G-1-1774	UE 25a#1-2087	USW G-1-2083
SiO_2	66.0	66.1	68.1	64.1	67.3
TiO_2	0.02	0.03	0.00	0.00	0.00
Al_2O_3	13.1	11.6	12.2	12.0	11.7
Fe_2O_3 [b]	0.47	0.02	0.00	0.00	0.00
MgO	0.51	0.38	0.09	0.71	0.07
CaO	4.49	4.01	1.11	3.78	0.78
BaO	0.04	0.15	0.03	0.05	0.08
Na_2O	1.07	0.67	2.84	0.47	3.13
K_2O	1.05	1.78	4.20	1.54	3.34
TOTAL	86.7	84.7	88.5	82.7	86.4
			CATION PERCENT		
Si	72.6	74.8	71.9	74.3	72.8
Ti	0.02	0.03	0.00	0.00	0.00
Al	17.0	15.5	15.2	16.4	14.9
Fe^{+3}	0.39	0.02	0.00	0.00	0.00
Mg	0.84	0.64	0.14	1.23	0.11
Ca	5.30	4.87	1.26	4.70	0.91
Ba	0.02	0.07	0.01	0.02	0.03
Na	2.28	1.47	5.82	1.06	6.57
K	1.48	2.57	5.66	2.28	4.61
			Si/Al		
	4.3	4.8	4.7	4.5	4.9
			Mol.% EXCHANGEABLE CATIONS		
K	15	27	44	25	38
Na	23	15	45	11	54
Ca+Mg	62	58	11	64	8

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[a] Sample number consists of drill hole designation followed by depth of sample in feet beneath the surface.

[b] Total iron calculated as Fe_2O_3

TABLE II. REPRESENTATIVE BULK-ROCK COMPOSITIONS FOR DIAGENETICALLY ALTERED TUFFS, YUCCA MOUNTAIN, NEVADA

Rock Unit	Topopah Spring Member, Paintbrush Tuff	Tuff of Calico Hills		Prow Pass Member, Crater Flat Tuff		Bullfrog Member, Crater Flat Tuff	
	Zeolite- and Clay-Rich Zone at Top of Basal Vitrophyre	A. Nonwelded Zeolitic Tuff, East Side of Repository Block	B. Nonwelded Zeolitic Tuff, West Side of Repository Block	A. Nonwelded Zeolitic Tuff, East Side of Repository Block	B. Nonwelded Zeolitic Tuff, West Side of Repository Block	A. Nonwelded Zeolitic Tuff, East Side of Repository Block	B. Nonwelded Zeolitic Tuff, West Side of Repository Block
Sample No.[a]	USW G-4-1314	UE25a#1-1667	USW G-1-1771	USW G-4-2226	USW GU3-1986B	UE25b/1H-2879A	USW G-3-2577
SiO_2	70.2	72.1	71.8	66.4	67.9	67.3	66.3
TiO_2	0.1[illegible]	0.08	0.10	0.14	0.10	0.25	0.12
Al_2O_3	16.7	11.3	11.8	13.2	12.4	13.2	12.9
Fe_2O_3[b]	1.44	1.00	1.40	1.45	1.23	1.82	1.32
MnO	0.09	0.05	0.04	0.05	0.07	0.04	0.10
MgO	0.90	0.12	0.24	0.25	0.11	1.30	0.27
CaO	3.51	2.67	1.20	2.43	0.87	3.13	2.34
Na_2O	1.90	1.47	2.79	2.15	3.44	1.18	2.43
K_2O	0.72	3.47	3.76	3.78	3.72	3.75	3.61
P_2O_5	0.02	0.02	0.00	0.01	0.02	0.09	0.02
LOI[c]	5.91	7.68	5.64	9.40	10.2	7.24	9.83
TOTAL	101.5	99.9	98.8	99.2	100.1	99.2	99.3
CATION PERCENT							
Si	69.6	74.7	72.7	69.8	70.7	69.5	69.8
Ti	0.10	0.06	0.08	0.11	0.08	0.19	0.10
Al	19.5	13.7	14.1	16.3	15.2	16.0	16.1
Fe^{+3}	1.07	0.78	1.07	1.15	0.97	1.42	1.05
Mn	0.06	0.04	0.03	0.04	0.05	0.03	0.07
Mg	1.33	0.19	0.36	0.39	0.17	2.00	0.42
Ca	3.73	2.96	1.30	2.74	0.97	3.46	2.64
Na	3.65	2.95	5.48	4.38	6.94	2.36	4.96
K	0.91	4.59	4.86	5.07	4.94	4.94	4.85
P	0.02	0.02	0.00	0.01	0.02	0.08	0.02

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[a] Sample number consists of drill hole designation followed by depth of sample in feet beneath the surface. Sample analysis USW G-1-1771 from Zielinski (1983).

[b] Total iron as Fe_2O_3.

[c] [illegible], determined by difference in sample weight at room temperature and sample weight at 900°C.

Fig. 1

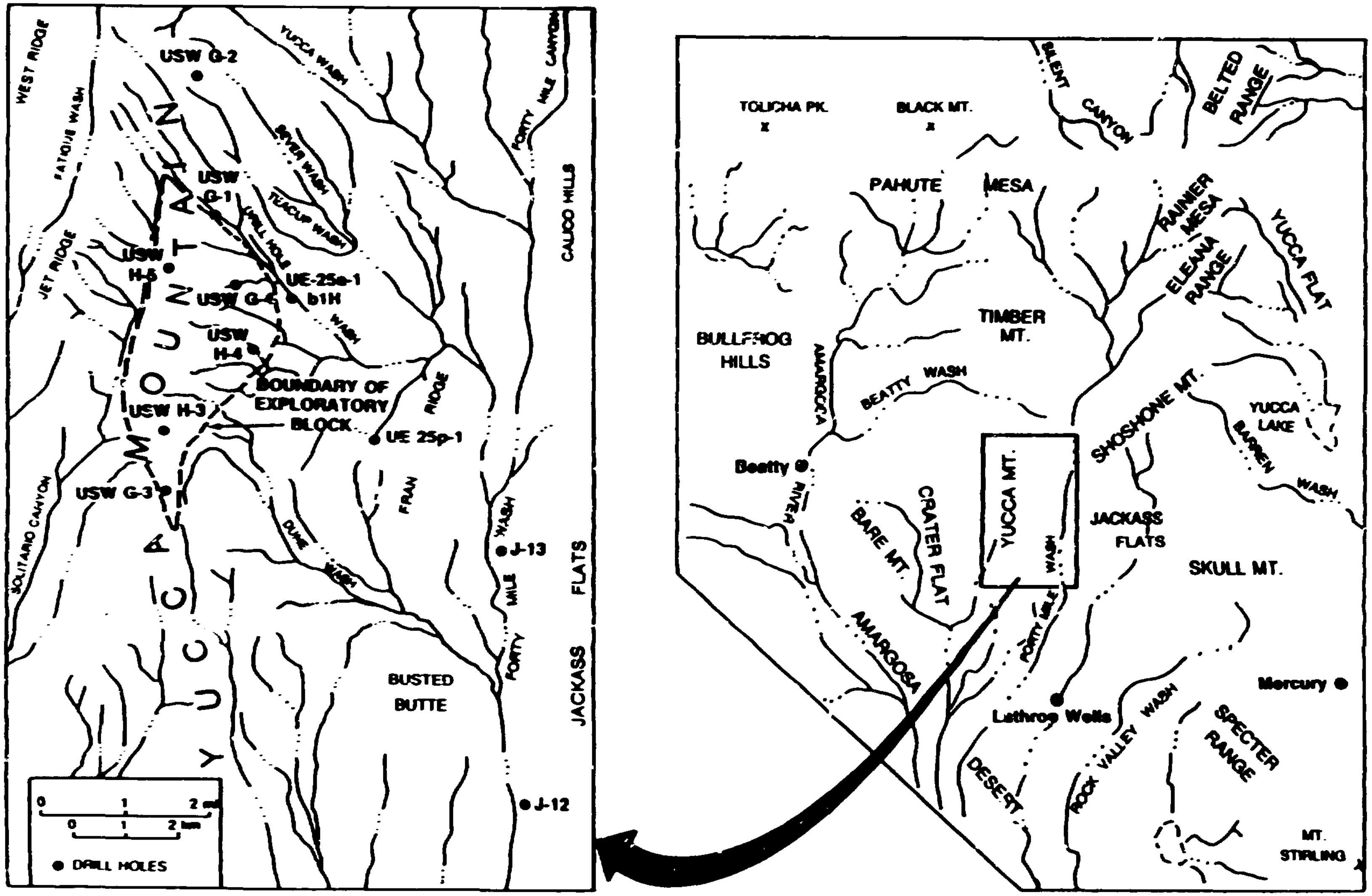

WEST RIDGE
FATIGUE WASH
USW G-2
YUCCA WASH
SEVER WASH
TEACUP WASH
FORTY MILE CANYON
CALICO HILLS
USW G-1
DRILL HOLE WASH
JET RIDGE
USW H-5
UE-25a-1
USW G-4
b1H
USW H-4
BOUNDARY OF EXPLORATORY BLOCK
USW H-3
UE 25p-1
RIDGE
FRAN
USW G-3
SOLITARIO CANYON
DUNE WASH
FORTY MILE WASH
J-13
J-12
YUCCA MOUNTAIN
BUSTED BUTTE
JACKASS FLATS
0 1 2 mi
0 1 2 km
● DRILL HOLES
TOLICHA PK.
BLACK MT.
SILENT CANYON
BELTED RANGE
PAHUTE MESA
RAINIER MESA
YUCCA FLAT
ELEANA RANGE
BULLFROG HILLS
TIMBER MT.
AMARGOSA
BEATTY WASH
SHOSHONE MT.
YUCCA LAKE
BARREN WASH
Beatty
RIVER
BARE MT.
CRATER FLAT
YUCCA MT.
WASH
JACKASS FLATS
SKULL MT.
AMARGOSA
FORTY MILE
Lathrop Wells
Mercury
DESERT
ROCK VALLEY WASH
SPECTER RANGE
MT. STIRLING

Fig. 2

SCHEMATIC CROSS-SECTION OF YUCCA MOUNTAIN SHOW POSITION OF PROPOSED REPOSITORY AND PRINCIPAL ZEOLITIC TUFFS.

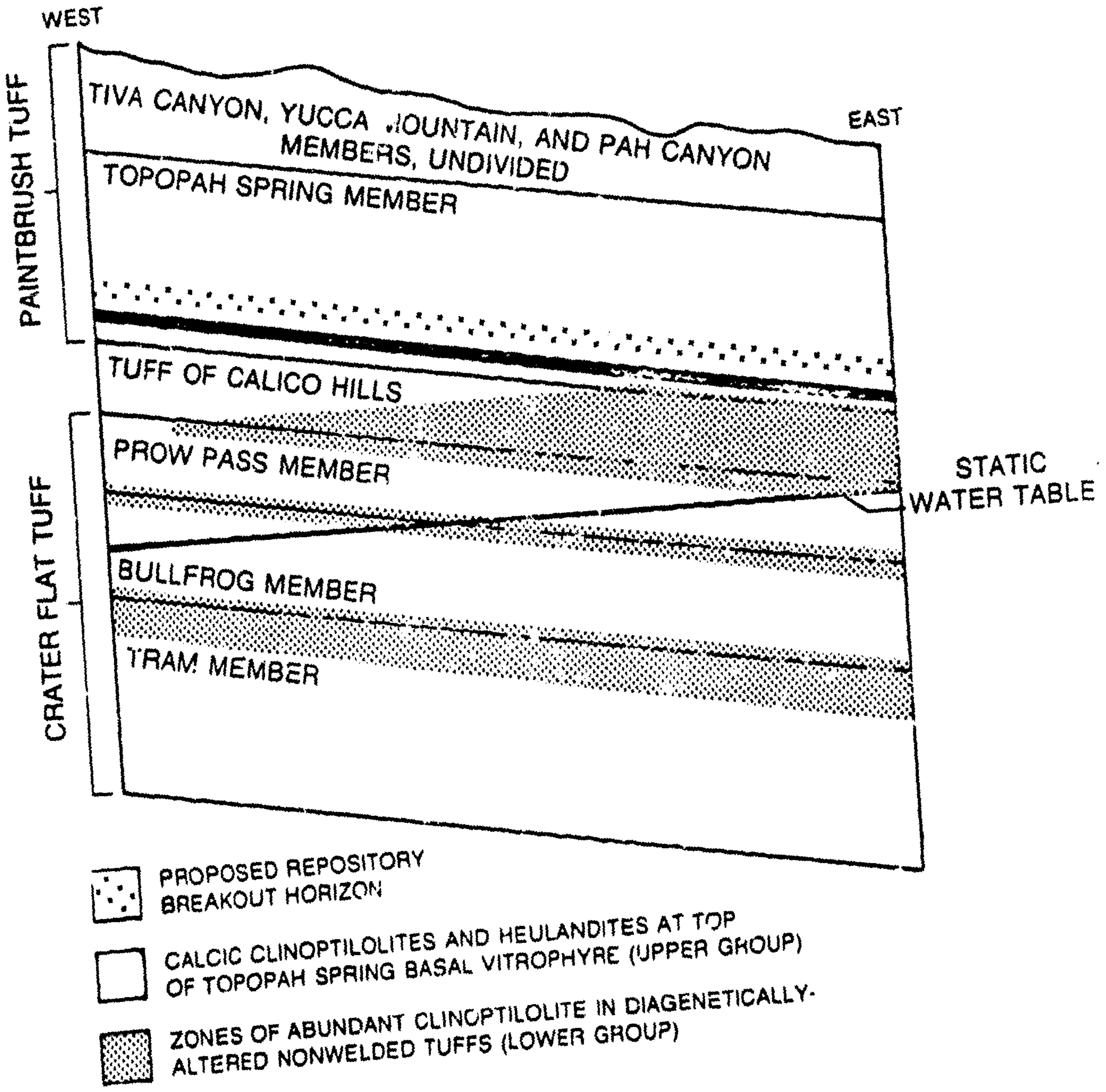


Fig. 3

EXCHANGEABLE-CATIONS IN Ca-CLINOPTILOLITE AND HEULANDITE (UPPER GROUP), YUCCA MOUNTAIN, NEVADA

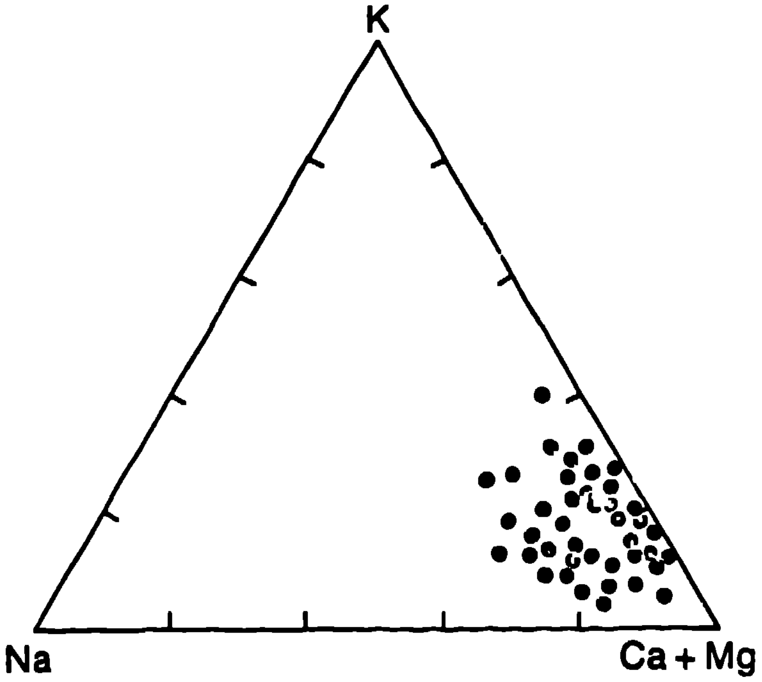
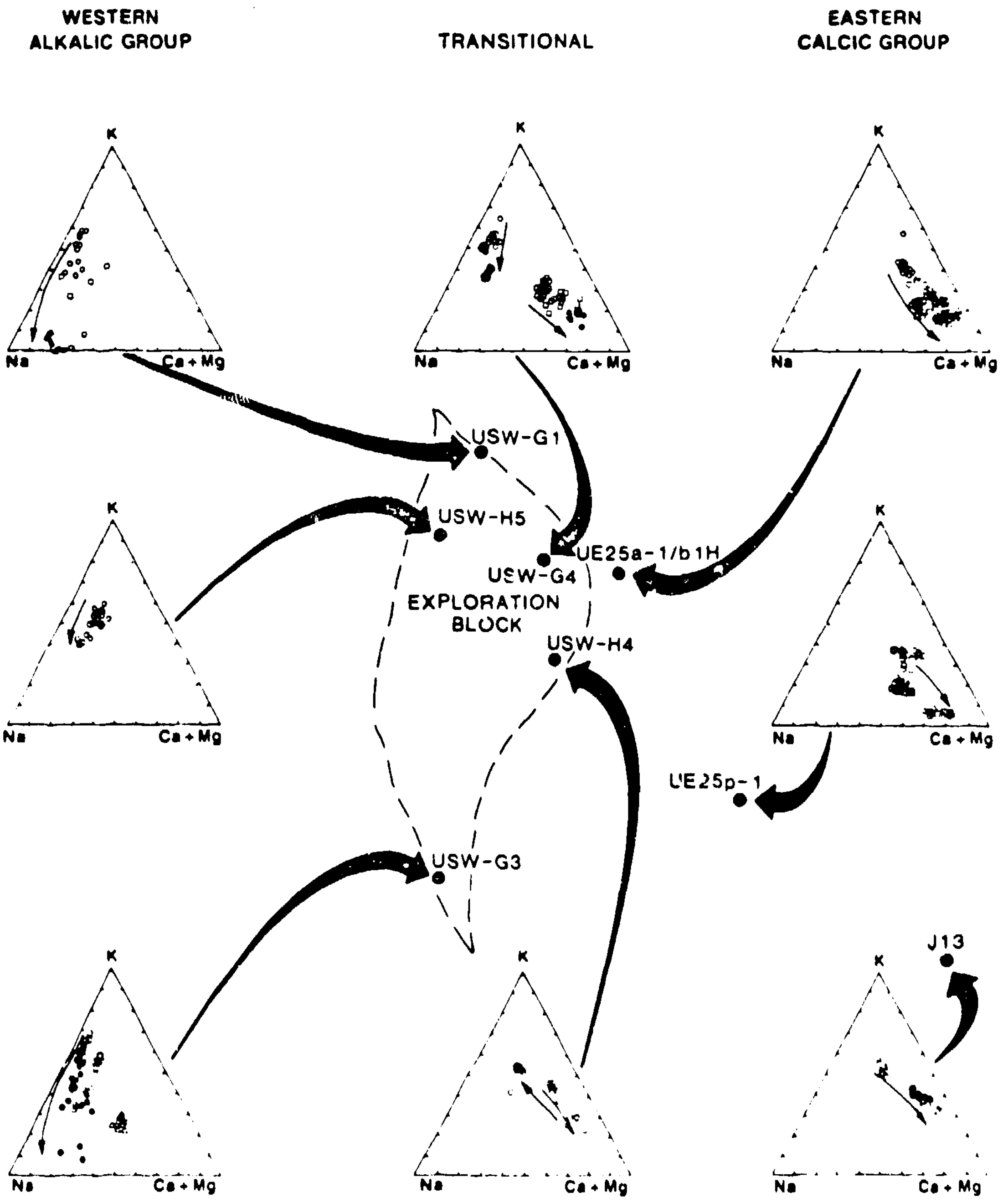


FIG. 6.



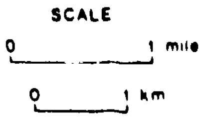
○ NONWELDED BASE OF TOPOPAH SPRING MBR., TUFF OF CALICO HILLS, AND TOP OF PROW PASS MBR.

☐ NONWELDED BASE OF PROW PASS MBR. AND TOP OF BULLFROG MBR.

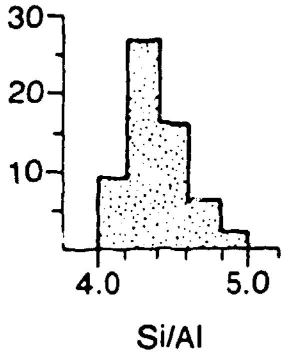
△ NONWELDED TOP OF BULLFROG MBR. AND TRAM MBR.

● PRE-TRAM VOLCANIC ROCKS

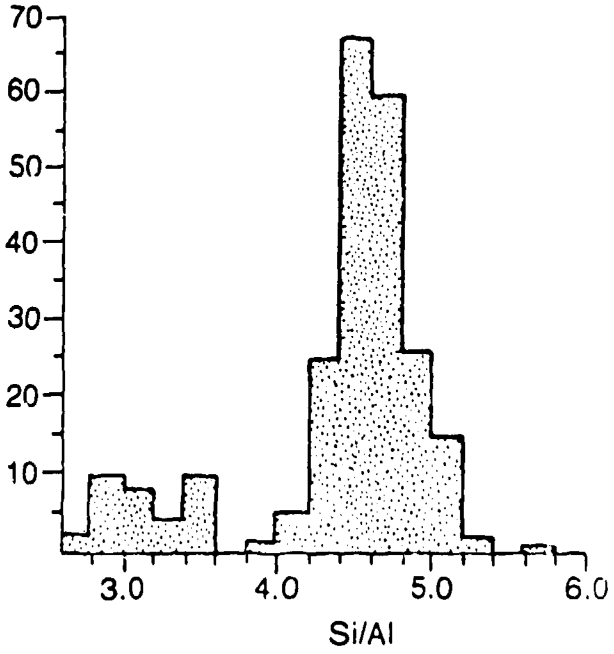
NOTE: SMALL ARROWS WITHIN PLOTS INDICATE CHEMICAL TRENDS WITH INCREASING DEPTH.



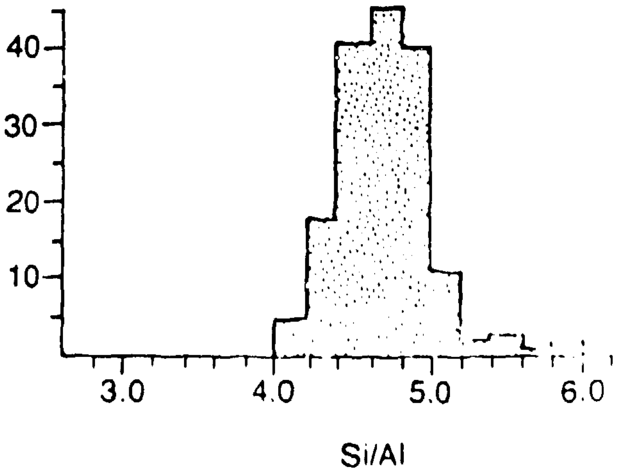
UPPER GROUP OF CALCIC CLINOPTILOLITES AND HEULANDITES



LOWER GROUP OF CLINOPTILOLITES ON EASTERN SIDE OF YUCCA MTN.



LOWER GROUP OF CLINOPTILOLITES ON WESTERN SIDE OF YUCCA MTN.



CLINOPTILOLITE EXCHANGEABLE-CATION COMPOSITIONS BELOW THE REPOSITORY BLOCK IN THE UNSATURATED ZONE

Fig. 6

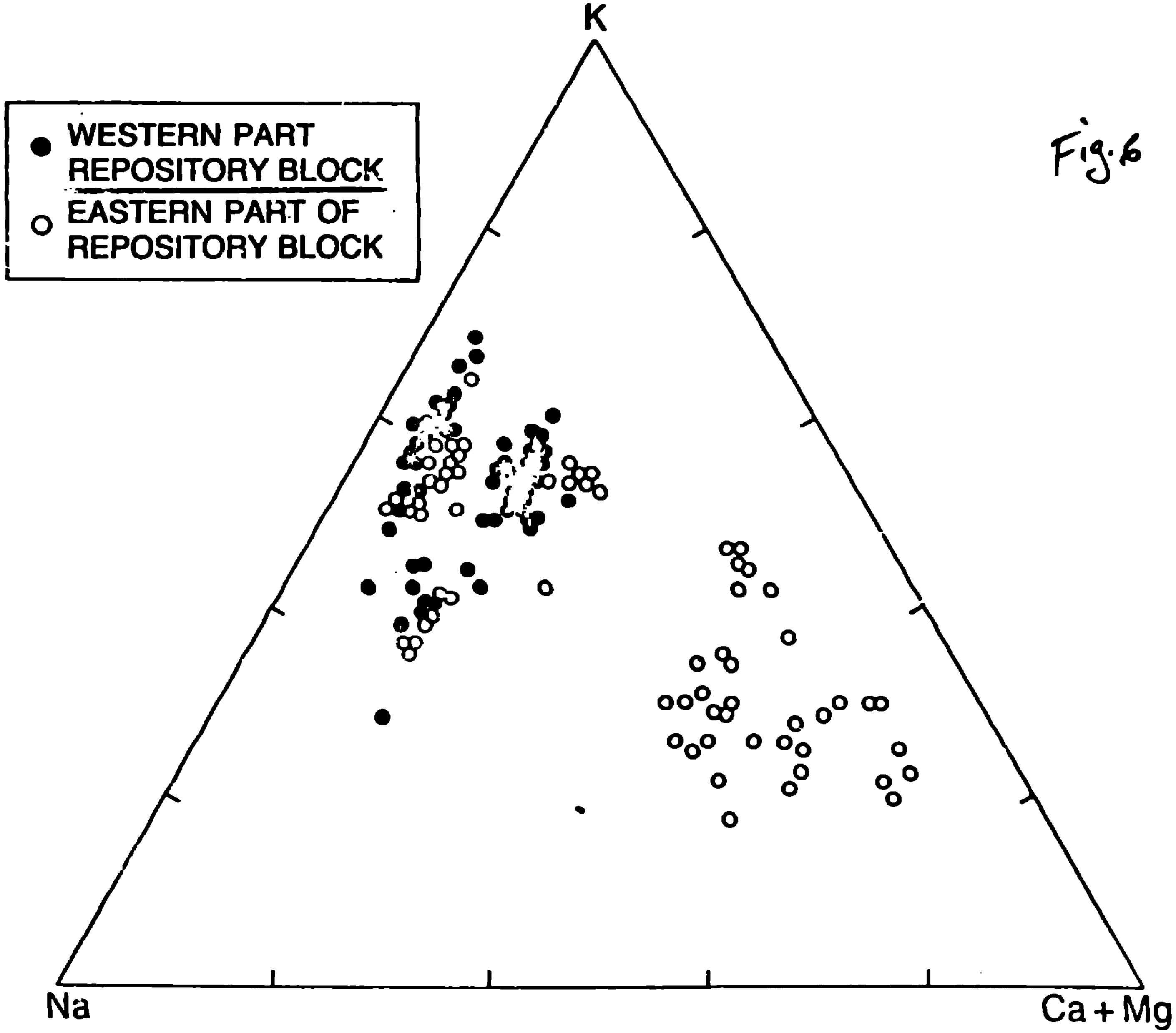


Fig. 7

EXCHANGEABLE-CATION COMPOSTIONS IN BULK ROCKS, YUCCA MOUNTAIN, NEVADA

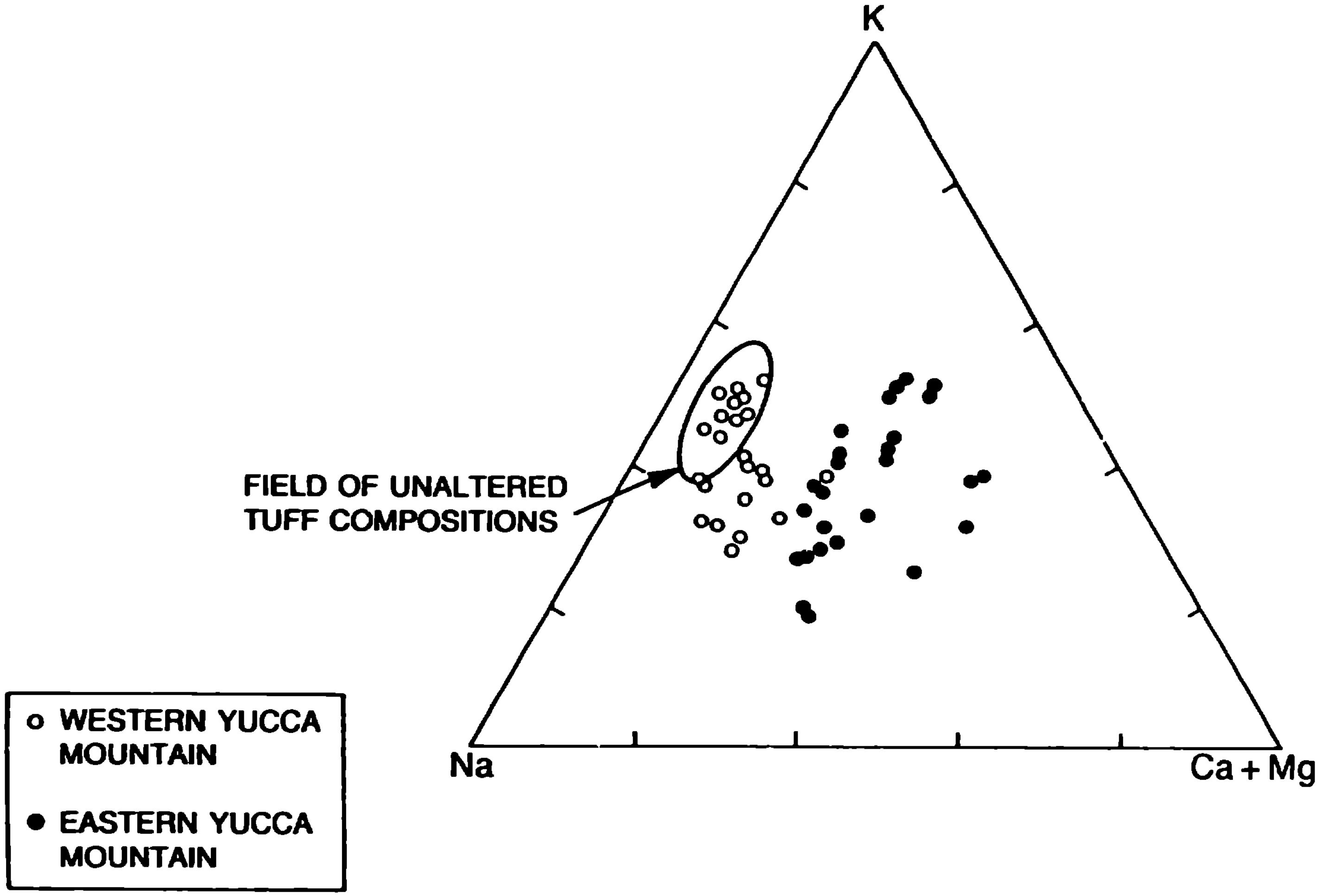
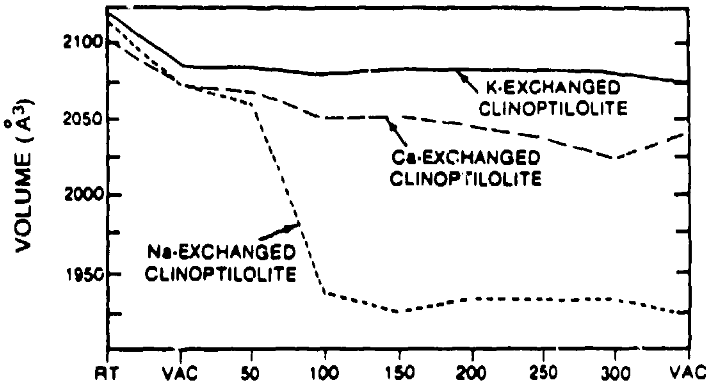


Fig. 8

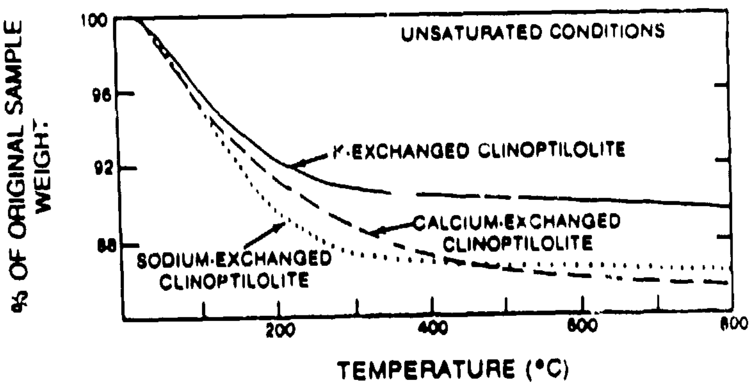
A) CLINOPTILOLITE UNIT-CELL VOLUMES AS A FUNCTION OF COMPOSITION AND TEMPERATURE



FROM BISH, 1984

RT = ROOM TEMPERATURE
VAC = VACUUM

B) DEHYDRATION PROPERTIES OF CLINOPTILOLITE AS A FUNCTION OF COMPOSITION AND TEMPERATURE



FROM BISH 1985