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AUTHOR(S): D. T. Vaniman and D. L. Bish

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THE IMPORTANCE OF ZEOLITES IN THE POTENTIAL HIGH-LEVEL RADIOACTIVE WASTE REPOSITORY AT YUCCA MOUNTAIN, NEVADA

D. T. Vaniman and D. L. Bish

Los Alamos National Laboratory, MS D462, Los Alamos, New Mexico 87545

ABSTRACT

Zeolitic rocks play an important role in retarding the migration of radionuclides that occur in solution as simple cations (Cs, Sr, Ba). However, the interaction of zeolites with complex transuranic species in solution provides little if any advantage over other common silicate minerals. The most important consequences of zeolite occurrences near a high-level radioactive waste repository environment are likely to be their response to thermal loading and their impact on site hydrology. Partial zeolite dehydration during the early thermal pulse from the repository and rehydration as the repository slowly cools can have an important impact on the water budget of a repository in unsaturated rocks, provided that the long-term heating does not result in zeolite destabilization.

INTRODUCTION

The tuffs of Yucca Mountain, Nevada, are being evaluated by the U.S. Department of Energy as a potential site for the nation's first high-level radioactive waste repository (Figure 1). For the purposes of this paper, these tuffs can be considered to consist of three principal rock types. The two most abundant rock types are (1) densely welded rocks in which feldspar and silica minerals predominate and (2) poorly welded rocks which have been extensively zeolitized. The third rock type is vitric tuff, both vitrophyric and nonwelded; although not abundant throughout Yucca Mountain, vitric rocks occur close to the potential repository horizon. Vitric rocks are also important as potential precursors to zeolitization.

The presence of zeolites first drew attention to tuffs as possible hosts for radioactive waste disposal. The two most abundant zeolites, clinoptilolite and mordenite, have been viewed as important natural barriers against radionuclide migration. However, recent sorption studies (Triay et al., 1993) show that the effectiveness of zeolites as cation exchangers is severely limitied for many of the radionuclides of greatest concern. Nevertheless, zeolites at Yucca Mountain are important in a repository setting for three major reasons.

First Reason

Both clinoptilolite and mordenite have high cation-exchange capacities and are highly selective for several common radionuclides, particularly Cs, Ba, and Sr. It is important to recognize that these elements constitute only a subset of the radioactive species that may be emplaced at Yucca Mountain. Kerrisk (1985) categorized the radionuclides of potential concern as actinides and their decay products (Np, U, Pu, Am, Cm, Th, Ra, and Pa), fission products (Cs, Sr, Ba, Tc, Sn, Sm, Se, Zr, Y, Nb, and I), and activation products from fuel-element cladding (Zr, Ni, C). The actinides and their decay products are the radionuclides of greatest concern; for these elements, cation exchange is not an important retardation mechanism (Triay et al., 1993). The potential importance of zeolites as cation exchangers is further diminshed by the relatively short half-lives of most radioisotpes of Cs, Ba, and Sr; these short-lived radionuclides will have largely decayed by the time the storage canisters are likely to fail. Nevertheless, at least one isotope of Cs (^{135}Cs) has a half-life long enough to be of concern. The sorptive capacities of zeolites for the abundant but short-lived Sr, Ba, and Cs should also not be discounted. The short-lived nuclides of these elements account for 2/3 to 3/4 of the total waste activity at 100 years (Kerrisk, 1985) and the presence of zeolites provides assurance against significant movement of these radionuclides if there are any unforseen early canister failures.

Second Reason

The abundance of zeolites with low thermal stability near the potential repository horizon has led to questions about the advisability of placing large amounts of heat-generating waste nearby (Smyth, 1982). These questions are receiving new attention following recent proposals for increasing the heat load in order to keep the repository relatively dry for about 200,000 years (Buscheck and Nitao, 1993). The proposed increase in head load could extend the boiling isotherm out as much as 210 m above and 160 m below the potential repository in the first 2,000 years of repository lifetime. The thermal history is dynamic, with a drying front that first migrates away from and then collapses back toward the waste horizon. Zeolite transformations should be considered in space and time as a part of the total potential rock alteration at variable temperature and p(H_2O).

Third Reason

Zeolitic rocks tend to be highly saturated even above the water table and are therefore sources of or sumps for water displaced in the repository thermal aureole. Models of a potential repository with high thermal loading (Buscheck and Nitao, 1993) indicate extensive drying of zeolitized rocks beneath the repository, with thermal perturbation extending down to the water table.

In brief, although the zeolites at Yucca Mountain are potentially beneficial for their sorptive abilities and potential imbibition of waste-carrying waters, their low thermal stability may limit the maximum rock temperatures and thus the total waste loading in the potential repository.

ZEOLITE DISTRIBUTIONS AT YUCCA MOUNTAIN

Zeolitic alteration of nonwelded, initially glassy tuffs is extensive at Yucca Mountain. Such tuffs are pervasively altered beneath the water table and are commonly zeolitized to elevations of about 100 m above the water table. Figure 2 shows the distribution (weight percent) of zeolites, other minerals, and glass with depth in drill core UE-25a#1, just to the east of the potential repository block at Yucca Mountain (Figure 1). Clinoptilolite is the most abundant zeolite present near the static water level (SWL); mordenite is second in abundance in many drill cores, but is not as ubiquitous as clinoptilolite. Other drill cores show that analcime occurs several hundred meters beneath the water table, at depths too great to be influenced by repository thermal effects or by waste releases.

Beneath the SWL, zeolitic rocks tend to form non-transmissive intervals between those tuff units formed of anhydrous tectosilicates (principally quartz and alkali feldspars); the latter intervals have relatively high rates of fracture transmission in pumping tests (~5-15 l/sec; Benson et al., 1983). The extent to which these saturated rocks must be relied on in blocking waste movement is yet to be determined. However, the rocks above the static water level are closest to the potential repository and are the units most likely to encounter any waste releases. For these reasons, the primary emphasis in current site characterization is on the unsaturated zone, including the unsaturated zeolitic intervals.

Figure 3 is an east-west cross section along Antler Ridge, near the middle of the potential repository block (Figure 1). This cross-section shows that the first occurrence of significant abundances of zeolites ranges from about 100 m to 250 m beneath the potential repository. Zeolitic rocks interfinger with vitric nonwelded rocks beneath much of the repository, in a manner that is yet poorly known. One of the goals of current drilling studies is to better define the distribution of zeolitic rocks in the unsaturated zone, and in particular the interrelations between zeolitic and vitric nonwelded rocks.

Zeolites occur in other intervals than those shown in Figure 3. Clinoptilolite and mordenite both occur in fractures throughout the unsaturated zone, especially in the abundant fractures within those rocks formed of anhydrous tectosilicates. Stellerite also occurs in some fractures, from the vitrophyre beneath the potential repository up toward the surface at Yucca Mountain (Carlos et al., in prep). The thin (<5 m) altered top of this vitrophyre contains a series of zeolites not found elsewhere at Yucca Mountain, including heulandite, phillipsite, chabazite, and erionite. Although of great interest for understanding the alteration history of Yucca Mountain, and of potential importance where fracture transport may occur down to and between the major clinoptilolite-rich intervals, the zeolites in these other occurrences are several orders of magnitude less abundant than the clinoptilolite-mordenite association and are not dealt with in this paper.

RADIONUCLIDE SORPTION

Both clinoptilolite and mordenite have cation exchange capacities up to 2.0 meq/g for many simple cations. Cation exchange can be important for retarding the migration of simple cationic radioactive wastes. The radionuclides most readily sorbed by zeolites are $^{137}Cs^{+}$ (half-life 30.3 yr) and its short-lived daughter $^{137m}Ba^{2+}$ (2.55 min), $^{135}Cs^{+}$ ($2.3x10^{6}$ yr), $^{90}Sr^{2+}$ (29.1 yr), $^{59,63}Ni^{2+}$ (~$7.6x10^{4}$ and 100 yr), and $^{226}Ra^{2+}$ ($1.6x10^{3}$ yr). Except for ^{135}Cs, ^{59}Ni, and ^{226}Ra, these radionuclides have half-lives so short that they are unlikely to survive canister containment and encounter any of the natural barriers around the potential repository. With a half-life of $2.3x10^{6}$ yr, $^{135}Cs^{+}$ is most likely to remain a significant hazard when stored in waste canisters that will provide reliable containment for less than a few thousand years. There has been sufficient study, both in the laboratory and in the field, to allow confidence that any radioactive Cs leaked from waste canisters at Yucca Mountain will be blocked from any significant movement by the first zeolitized rocks it encounters. Equilibrium sorption coefficients, K_D, for Cs are generally 1×10^{3} to 6×10^{4} ml/g in zeolitic rocks, and transport calculations have suggested that K_D values greater than 1×10^{2} ml/g yield more than adequate isolation of radionuclides over the lifetime of the potential repository (Birdsell et al., 1990). However, clinoptilolite and mordenite do not have high K_D values for complex cations, such as NpO_2^{+} and UO_2^{2+}, or anions, such as I^{-}, $NpO_2CO_3^{-}$, and TcO_4^{-}. Spent-fuel wastes include isotopes of elements such as Np, U, Th, Pu, I, and C that in general are not strongly sorbed by clinoptilolite or mordenite (Kerrisk, 1985). For these elements, a more complete assessment of interaction with rock and water at the Yucca Mountain site is being pursued to determine how the site will perform. Overall, retardation of radionuclides cannot rely solely on clinoptilolite and mordenite but will also depend on interactions with other minerals, particularly Fe and Mn oxides, and on precipitation and complexation reactions. An example of recent research in this direction is Triay et al. (1993), in which surface-area-normalized retardation factors (K_a) were found to be about two orders of magnitude higher for quartz and hematite than for clinoptilolite. Their results illustrate (1) the importance of pH (retardation increases markedly in the pH range 6-8) and (2) the lack of a significant cation-exchange effect in retardation of complex Np species (NpO_2^+, $NpO_2CO_3^-$) by zeolites.

THERMAL EFFECTS

The importance of zeolites at Yucca Mountain extends beyond their role as traps for waste. Clinoptilolite, mordenite, and both vitrophyric and nonwelded glass are the most abundant hydrous phases near the potential repository at Yucca Mountain. At saturation, clinoptilolite contains 16.6% water by weight and mordenite contains 13.2%; the glasses are perlitic and contain about 3% to 5% water. Studies of the vitric rocks suggest that release and uptake of water occurs in the glasses, but at higher temperatures and more sluggishly than in zeolites. More immediate response to heating is seen in loss or gain of water from glass surfaces and from pore space in the vitric rocks. In this regard, there are major differences between the densely welded vitrophyres and the vitric nonwelded rocks (Figure 3). The vitrophyres have very low porosity (~7%) with correspondingly low abundance of internal wetted surfaces; vitric nonwelded rocks, however, have variable but generally high porosity (av. 37%) with correspondingly high abundance of wetted grain surfaces (Klavetter and Peters, 1986; Loeven, 1993). Because of the high wettable surface area in the nonwelded vitric rocks, these rocks are more likely to undergo extensive alteration, at a given temperature, where heating occurs under saturated conditions.

Clinoptilolite and, to a lesser extent, mordenite are sensitive to minor changes in temperature and/or partial pressure of water (Bish, 1990a). Temperature increases on the order of tens of °C can cause both zeolites to evolve water, and clinoptilolite in particular undergoes a reduction in molar volume related to the amount of water evolved. Smyth (1982) proposed that heating could "provide both a pathway (shrinkage fractures) and a driving force (fluid pressure) for release of radionuclides to the biosphere." He also suggested that clinoptilolite and mordenite could react to analcime at temperatures as low as 95°C, giving rise to a volume reduction and evolution of water. However, dehydration reactions depend on water vapor pressure and low-temperature dehydration appears to be rapidly reversible even after prolonged heating; conversely, reactions that form less hydrous zeolites such as analcime are likely to be sluggish where the heated tuffs are unsaturated. However, clinoptilolite and mordenite will respond to changes in the partial pressure of water when heated under the partially (to completely) saturated conditions existing in the massive zeolitic horizons. More importantly, gradual re-introduction of water as liquid or vapor after heating will probably restore the zeolites to their original state, provided that the long-term stability limits of the zeolites are not exceeded in the thermal aureole around the repository. It should be noted, however, that rehydration of the zeolites to initial condition is a <u>mineralogic</u> feature and does not insure that the inter-grain hydrologic properties of zeolitized <u>rock</u> will return to the state they were in prior to heating. The kinetics of zeolite dehydration and rehydration are very fast; clinoptilolite typically rehydrates within a few tens of minutes after dehydration (Kranz et al., 1989). A significant aspect of this dehydration and rehydration is the potential to develop stresses equivalent to those that now exist at Yucca Mountain. Dehydration-induced contraction of zeolitic tuffs could decrease horizontal stresses significantly and increase the likelihood of normal faulting at the site (Kranz et al., 1989).

Predictions of the temperatures and p(H_2O) conditions in the potential repository depend on a variety of factors, including the age of the high-level waste, the distribution and abundance of the waste in the repository, the intital saturation of the tuffs, the ventilation of the repository, and the rate of rainfall recharge into the unsaturated tuffs. Thermal models of the potential repository depend greatly on the amount and type of waste emplaced. At a nominal waste loading of 57 kW/acre the maximum distance to the 95°C isotherm is about 50 m at 1,000 years, with heat rapidly decaying as the waste ages (Buscheck and Nitao, 1992). Another option being considered at Yucca Mountain is the possibility of higher heat loadings with an extended "dry-out" period. To generate sufficient heat, a thermal load of 114 kW/acre has been envisaged, where the maximum range to the 95°C isotherm is about 210 m above the repository and 160 m below at 2,000 years (Buscheck and Nitao, 1993). The schematic distribution of this hotter aureole around the repository is illustrated in Figure 4.

Significantly, these calculations suggest that the zone with temperatures higher than 95°C will be partially to completely dehydrated, reducing the likelihood of zeolite transformation. Recent studies using illite/smectite geothermometry and observed mineral transformations with depth at Yucca Mountain suggest that clinoptilolite reacted above 100°C and mordenite reacted above 130°C, both of them eventually transforming to analcime (Bish and Aronson, 1992). These reactions almost certainly occurred under saturated conditions; reactions at $p(H_2O)$ less than saturation are likely to be much more sluggish. Prediction of potential mineral reactions in a repository environment must be closely linked to $T-P(H_2O)$ models of the repository as a function of time.

Because zeolites provide an important reservoir for water in the unsaturated zone, reversible dehydration of clinoptilolite and mordenite will be an important consequence of the emplacement of hot radioactive waste at the Yucca Mountain site. At present there are few data to constrain the dehydration behavior of clinoptilolite or mordenite in terms of temperature, $p(H_2O)$, and time. However, studies of the dependence of the water adsorption capacity of heulandite on temperature and $p(H_2O)$ provide a conceptual basis for considering how clinoptilolite may respond to changes in these conditions. We emphasize that the heulandite data provide nothing more than a conceptual basis for considering how clinoptilolite and mordenite may respond in terms of coupled response to temperature and $p(H_2O)$. The concept is illustrated in Figure 5, modified from Simonot-Grange (1979), showing the relationship between $p(H_2O)$, the "filling coefficient" Θ of water in heulandite (i.e., the amount of water in the zeolite relative to the maximum allowed by the zeolite structure), and isotherms that are reversible at temperatures and $p(H_2O)$ conditions where heulandite does not transform to metaheulandite. Simonot-Grange (1979) placed the transition from heulandite, with reversible dehydration, to irreversibly dehydrated metaheulandite at the locus of temperature-$p(H_2O)$ conditions where Θ drops below 0.49. This is reflected in the change in slope of the heulandite 240°C curve, where the heulandite structure is transformed to metaheulandite. We have extrapolated the isotherms of Simonot-Grange beyond 10 kPa to address conditions more like those anticipated in a geologic repository environment (dashed isotherm segments in Figure 5). These isotherms curve toward the bottom of the figure as they approach the a Θ value of 1.0 and $p(H_2O)$ values approach those of a water-saturated atmosphere. The arrow drawn on Figure 5 represents possible heating and cooling pathways for zeolites in the unsaturated zone at Yucca Mountain. These pathways are constrained by the vapor pressure of water at $p(H_2O)$ < atmospheric pressure (~95 kPa at the elevation of the potential repository). At $p(H_2O)$ > atmospheric pressure, the pathways may curve upward in the manner shown, dependent on the site's ability to sustain overpressure. This ability is poorly known, as indicated by the question marks along the pathways in this regime.

Figure 5 is useful for visualizing the effects of temperature and $p(H_2O)$ on zeolite dehydration, but there are several factors that limit its application to Yucca Mountain. First, heulandite is relatively rare at Yucca Mountain (although the zeolitized top of the vitrophyre below the repository is heulandite-rich; Figure 3). Clinoptilolite and, to lesser extent, mordenite are the more abundant zeolites, and although farther from the repository, these zeolitized rocks occupy an important position along downward pathways (Figure 4). Desorption isotherms at 20°C suggest that clinoptilolite will evolve more water and mordenite less water than heulandite at a given $p(H_2O)$ (Yamanaka et al., 1989), but neither clinoptilolite nor mordenite will irreversibly dehydrate to a "meta" phase in the temperature range where heulandite transforms to metaheulandite. Second, the portion of Figure 5 extending above 10 kPa was extrapolated from the data of Simonot-Grange (1979); actual data for the full $p(H_2O)$ range anticipated at Yucca Mountain and specific to clinoptilolite and mordenite are needed. Finally, kinetic effects on possible structural transformations of clinoptilolite or mordenite are not considered. We have found that long-term heating of clinoptilolite can result in formation of a new "B" phase somewhat comparable to the heulandite-metaheulandite transformation (Bish, 1990b), although no loss of water adsorption capacity occurs in the clinoptilolite transformation. It is evident that kinetic effects should be considered in evaluating zeolite stability.

The possibility of zeolite recrystallization must be investigated more rigorously at Yucca Mountain should the hotter repository designs be selected. At 114 kW/acre, the lower "dry-out" zone around the repository will develop at the far limit of the most important vitric/zeolitic unit beneath the potential repository, with temperatures above boiling (~96°C at the elevation of Yucca Mountain) reaching this maximum distance about ~2,000 years after waste emplacement. This isotherm is then predicted to migrate slowly back toward the repository over the next ~8,000 years, with a return to pre-heating saturation (~70% saturation) occurring at the repository only after ~200,000 years (Buscheck and Nitao, 1993). These models indicate that the zeolitized rocks will remain below full saturation throughout this period because of drainage toward the static water level; however, silica migration and precipitation is a predicted phenomenon (Rimstidt et al., 1989) that may seal some portions of the unsaturated zone and prevent effective drainage.

An understanding of the coupled effects of temperature and p(H_2O) on mineral alteration and rock hydrologic properties is clearly important.

Although alteration of the zeolites within the "dry-out" zone may not occur, the 8,000-year migration of the boiling limit across the vitric tuffs and back toward the potential repository will provide ample opportunity for alteration of the vitric tuff, should conditions of local saturation occur. Extensive glass alteration is likely in this scenario, and the possibilities for large-scale dissolution, precipitation, and especially silica migration may lead to a complex mineralogic and geochemical "redesign" of the site over the first 10,000 years after waste emplacement. Since this is the most critical time for release and migration of radioactive wastes that have not yet decayed, the impetus for detailed zeolite studies, modeling, and field-scale experiments is even greater.

HYDROLOGIC EFFECTS

Zeolitic intervals above the water table at Yucca Mountain are zones of high saturation (av. 92%; Loeven, 1993). Addition of only a small amount of water to these rocks will render them saturated, although their low matrix permeability has the effect of then rendering them more of a barrier to further transport than a means of water through-flow. Fracture flow or flow along throughgoing faults (see Figure 3) is the likeliest means of transport through zeolitic units.

Zeolitic rocks provide two distinct reservoirs for water storage, either in pore space or within zeolites. The liberation of water from both types of reservoirs occurs over a range of conditions, depending on pore size and connectivity in the pore-space reservoir and on variations in the structure of water sites in zeolites. Based on average porosity of 29% in zeolitic rocks at Yucca Mountain, and clinoptilolite saturated density of ~2.2 g/cm^3

with 16.6% water by weight, the proportions of pore water at 92% saturation and zeolitic water in clinoptilolite tuff are 0.27 g/cm^3 and 0.26 g/cm^3 respectively. Mordenite tuff at the same porosity and saturated mineral density would contain 0.21 g/cm^3 of zeolitic water. The pore-space and zeolitic reservoirs contain comparable amounts of water, but the pore spaces must dehydrate significantly before zeolite dehydration occurs.

The vitric nonwelded rocks that interfinger with zeolitized rocks beneath the repository have markedly different hydrologic properties. Although the porosity of the vitric nonwelded rocks is only moderately higher than their zeolitized equivalents (av. 37% vs. 29%; Loeven, 1993), the matrix permeability of the vitric nonwelded tuffs is 4 to 5 orders of magnitude greater than any of the other tuff units, including the zeolitic tuffs (Buscheck and Nitao, 1993). Buscheck and Nitao pointed out that after boiling ceases, the still dried-out and comparatively impermeable zeolitic rocks will prevent fracture transport because they will actively imbibe water that may otherwise pass through fractures (and probably also through faults, unless the fault-zone mineralogy is very different). The zeolitic rocks, dry or wet, are poorly transmissive. However, this is not the case in the nonwelded vitric rocks that lack zeolites and therefore may not rehydrate as aggressively but once rehydrated will be highly transmissive. Because of this difference in hydrologic properties, the asymmetric layering of vitric and zeolitic rocks beneath the potential repository may allow more rapid transport through an otherwise impermeable barrier. Furthermore, within zeolitized horizons, asymmetric hydraulic conductivity will increase the likelihood of lateral transport at decreased saturation (Loeven, 1993) during the prolonged thermal pulse beneath a hot repository.

With a repository design of high heat load, however, it is possible that some aspects of this asymmetry in hydrologic properties will be reduced. As noted in the section on thermal effects, at 114 kW/acre thermal loading extensive alteration of the vitric tuffs may occur as water from the

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overlying rocks moves into the vitric tuffs over the first 2,000 years of heating, and as the condensation front migrates back toward the potential repository through the vitric tuffs over the subsequent 8,000 years. Natural analogs of past zeolitization at Yucca Mountain (Levy, 1991) show that the common products of glass alteration include clinoptilolite, mordenite, silica minerals, and smectite, with lesser amounts of Fe-Mn oxides and hydroxides and calcite. Laboratory experiments on vitric-tuff alteration (Knauss, 1987) suggest that saturated, heated glass will largely alter to clinoptilolite. A major concern for mineralogic evaluation of Yucca Mountain will be adequate prediction of how potential mineralogic alteration will affect water movement and waste interaction. Whether any potential zeolite loss will be more than compensated by zeolite formation will be an important aspect of the site evaluation.

CONCLUSIONS

Cation exchange is not a compelling reason to rely on zeolitic rocks as a natural barrier against the migration of high-level radioactive waste that contains complex ions of the transuranic elements. The importance of zeolites at a high-level waste repository in unsaturated rocks may rest mainly in their potential to partially dehydrate under thermal loads, and to rehydrate as waste-bearing waters pass through the aging repository. This importance must be assessed against the possibility of zeolite destabilization and must consider the possibility of induced alteration, including zeolitization, of presently vitric rocks. At sites such as Yucca Mountain where both vitric and zeolitic rocks occur within range of the potential long-term dehydration zone, it is possible that the inventory of local zeolites may increase over the lifetime of the repository if locally saturated conditions occur in the time-dependent expansion and contraction of the thermal aureole.

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Figure Captions

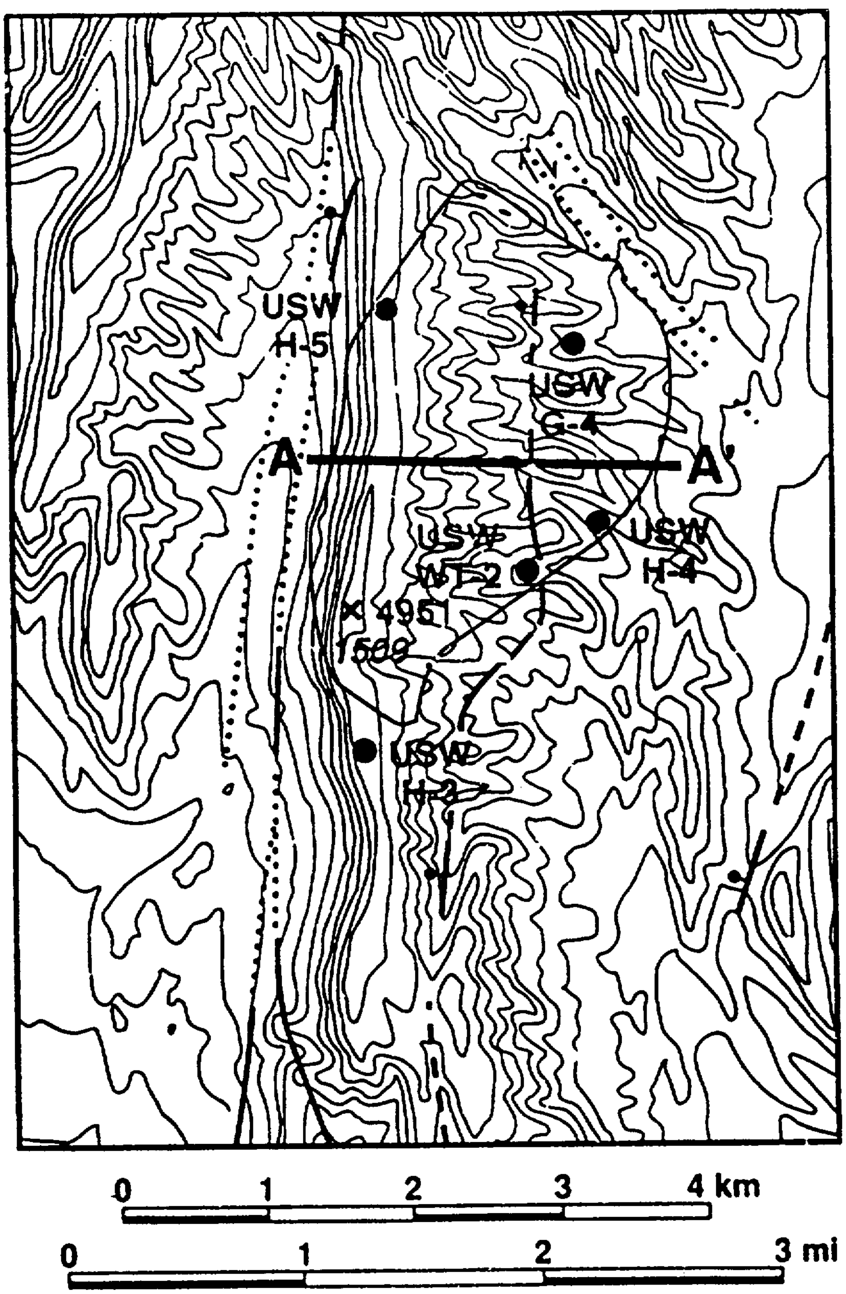
Figure 1: Topographic map of Yucca Mountain, showing the outline of the potential repository (boundary enclosed in heavy line) and the location of cross-section A-A' used in Figures 3 and 4. The locations of several drill holes are also indicated.

Figure 2: Mineral abundances and stratigraphic units in drill core UE-25a#1 (Figure 1). The width of the marker beneath each mineral varies with the abundance of that mineral (weight %) according to the scale shown. The static water level (SWL) is indicated by the horizontal dashed line.

Figure 3: Cross-section A-A' (see Figure 1). The locations of mineral-stratigraphic and glass units are based on X-ray diffraction data from drill cores USW H-3, USW H-4, and USW H-5.

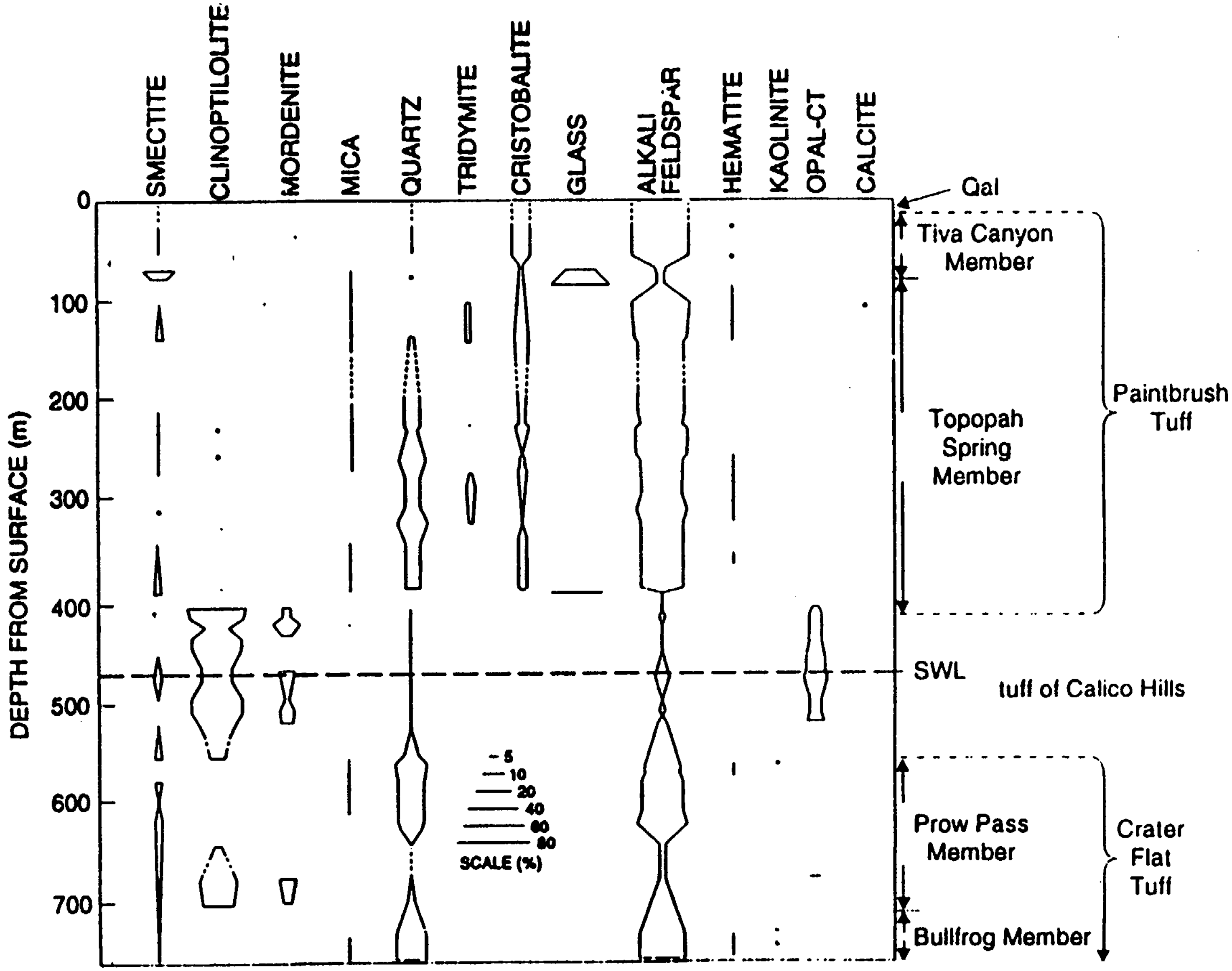
Figure 4: Maximum extent of condensation zones around a "hot" repository loaded at 114 kW/acre with 30-year-old spent nuclear fuel; this maximum thermal aureole extent is at 2,000 years after waste emplacement (thermal concept based on Buscheck and Nitao, 1992, 1993).

Figure 5: Diagram for heulandite showing relations between $p(H_2O)$, fraction Θ of water in heulandite relative to the maximum allowed by crystal structure, and heulandite water-adsorption isotherms (after Simonot-Grange, 1979). The bend in the 240°C isotherm corresponds to structural transformation from heulandite to metaheulandite; the other isotherms curve downward at $\Theta > 0.91$, as isotherms approach saturated $p(H_2O)$ conditions. Data of Simonot-Grange (1979) are for $p(H_2O) < 10$ kPa; our extrapolations of the curves above this pressure are hypothetical. The arrows indicate possible heating and cooling pathways for zeolitic rocks near a repository. The pathways at $p(H_2O) > \sim 95$ kPa depend on the extent to which the unsaturated-zone environment might sustain overpressure.



CONTOUR INTERVAL = 100 FT *(30.5M)*

Figure 1



(b) Drill hole UE-25a#1

Figure 2

CROSS-SECTION OF YUCCA MOUNTAIN ALONG ANTLER RIDGE
(5x vertical exaggeration)

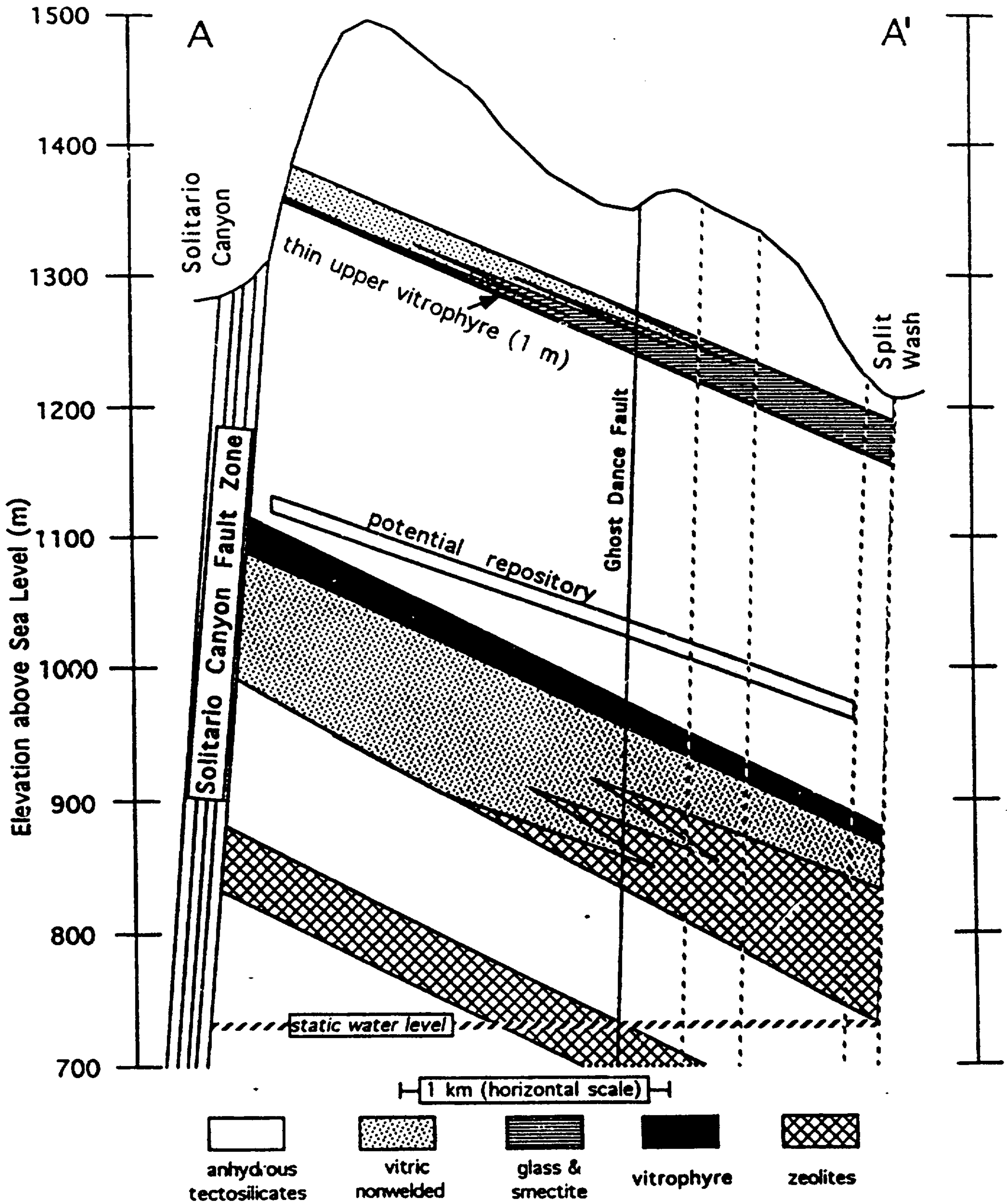


Figure 3

CROSS-SECTION OF YUCCA MOUNTAIN ALONG ANTLER RIDGE
(5x vertical exaggeration)

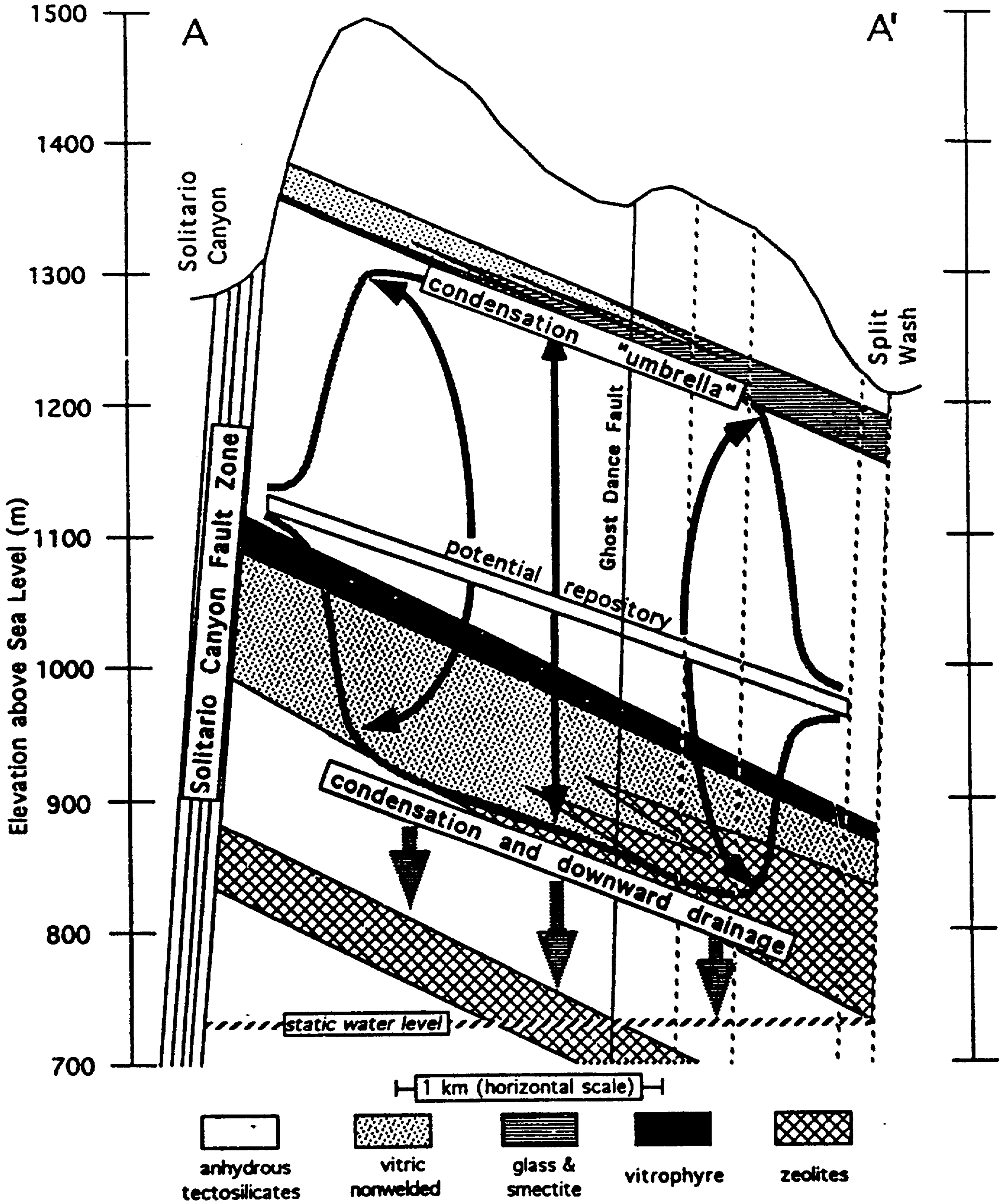
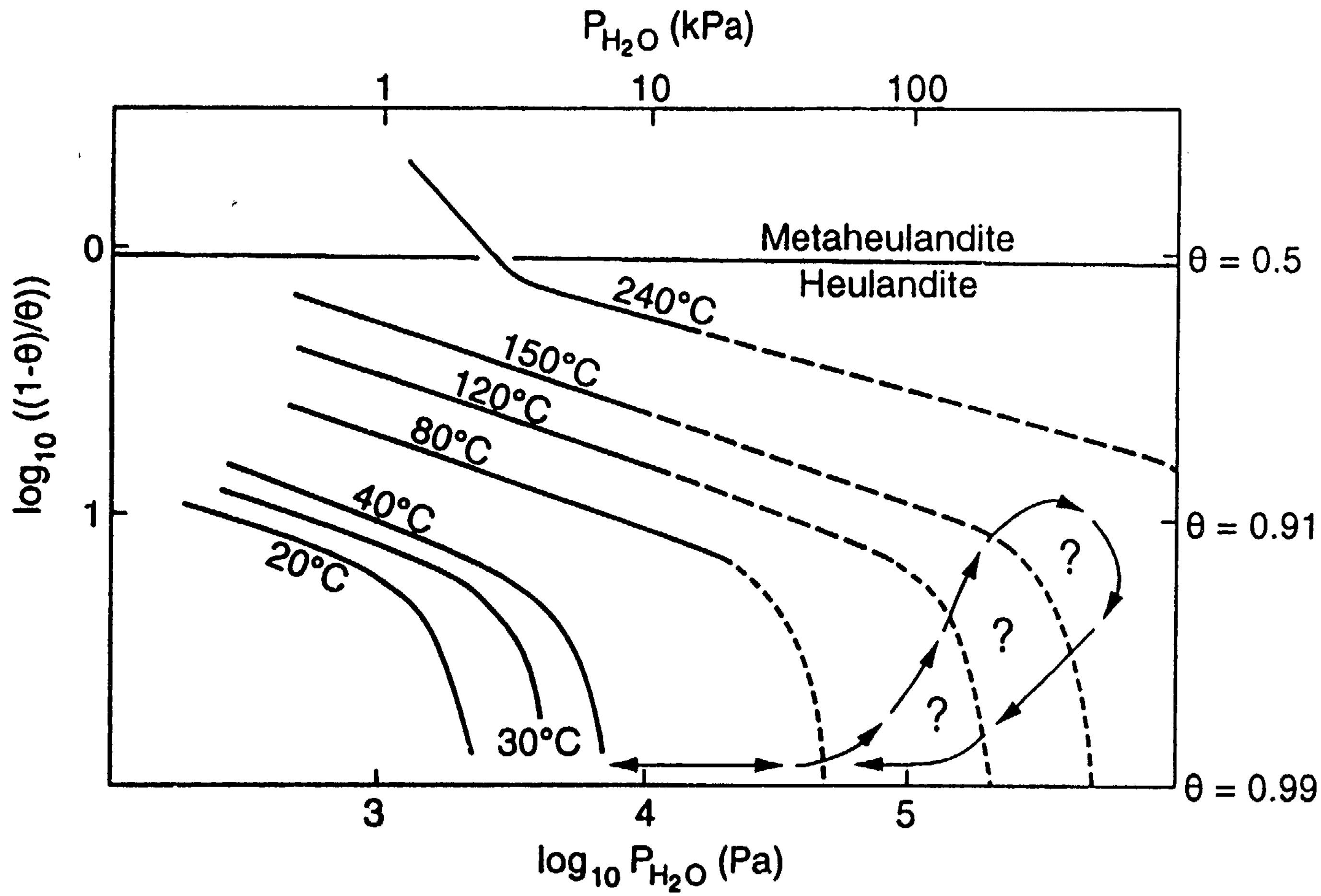


Figure 4



P_{H_2O} (kPa)
1
10
100
0
1
Metaheulandite
Heulandite
$\theta = 0.5$
$\theta = 0.91$
$\theta = 0.99$
240°C
150°C
120°C
80°C
40°C
30°C
20°C
?
?
?
$\log_{10}((1-\theta)/\theta))$
3
4
5
$\log_{10} P_{H_2O}$ (Pa)

Figure 5

END

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