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AUTHOR(S): Schön S. Levy

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

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MINERALOGIC ALTERATION HISTORY AND PALEOHYDROLOGY
AT YUCCA MOUNTAIN, NEVADA

Schon S. Levy

Earth and Environmental Sciences Division

Los Alamos National Laboratory

Los Alamos NM 87545

505-667-9504

ABSTRACT

The importance of paleohydrology to the Yucca Mountain Site Characterization Project derives from the role water will play in radioactive-waste repository performance. Changes in hydrologic conditions during the lifetime of the repository may be estimated by investigating past hydrologic variations, including changes in the static water-level position. Based on the distribution of vitric and zeolitized tuffs and the structural history of the site, the highest water levels were reached and receded downward 11.6 to 12.8 myr ago. Since that time, the water level at central Yucca Mountain has probably not risen more than about 60 m above its present position. The history of the high potentiometric gradient running through northern Yucca Mountain may be partly elucidated by the study of tridymite distribution in rocks that have experienced saturated conditions for varying periods of time.

INTRODUCTION

The importance of paleohydrology to the Yucca Mountain Site Characterization Project (YMSCP) derives from the role water is expected to play in high-level radioactive-waste repository performance. Water will interact with the waste packages and with the geologic repository and will act as a transport medium for radionuclides. During the course of site characterization, the present-day disposition and movement of water at the potential repository site

will be investigated. The existing hydrologic conditions will be judged on the basis of numerical models as acceptable or not acceptable for waste isolation requirements. The nature and magnitude of changes in hydrologic conditions that might be expected during the regulated lifetime of the repository must also be estimated and evaluated. One approach to this information need is to investigate past hydrologic variations -- to determine the paleohydrology of Yucca Mountain and surrounding areas.

One aspect of paleohydrology is the history of changes in the static water level (SWL). Both regional and local hydrologic conditions contribute to the SWL configuration. Hydrologic changes large enough to cause a major shift in the SWL position around Yucca Mountain during the next 10 000 years could alter the subsurface pathways and the pattern and timing of surface discharge for water travelling from the repository. Other effects could include changes in the degree of saturation within the repository, with resultant changes in water-rock and water-waste package interactions. It should also be recognized that hydrologic changes with effects on radionuclide mobility can probably also occur in the absence of major SWL readjustment. The existence of perched-water and active-recharge zones at Rainier Mesa, 40 km NE of Yucca Mountain, is an example.¹ This makes it clear that the study of Yucca Mountain paleohydrology must not be restricted to the sole concept of SWL change.

Many techniques are being used or proposed by YMSCP participants to study the paleohydrology of the potential repository site. Table I is a nonexhaustive list of techniques or characterization studies applicable to paleohydrologic questions. Results to date suggest that a combination of techniques and studies will be required to produce a comprehensive reconstruction of Yucca Mountain hydrologic history. This paper describes progress in understanding the relationship between mineralogic alteration history and hydrologic history based on mineral distribution, textural analysis, and supporting structural geologic data.

DESCRIPTION OF WORK

Data Collection

Data analysis was based primarily on interim summaries of drill core and

cutting x-ray mineralogic data^{2,3,4} plus new x-ray data collected specifically to investigate tridymite distribution. Information about mineral distribution was also obtained by petrographic examination of the same drill core and cutting samples. Drill sites are shown in Figure 1. These data were used to generate and test ideas relating to present-day hydrology and paleohydrology.

Basic Principles of Mineralogic Alteration-Paleohydrology Studies

In attempting to correlate mineralogic changes with past or present SWL positions, the researcher must bear in mind that the position and geometry of the SWL are determined by hydraulic parameters and therefore the SWL need not be a geochemical boundary. The connection between SWL position and mineralogic changes related to geochemistry may exist but is always indirect. Such features as paleospring mounds and microtextures related to particulate transport most closely approach being direct indicators of former hydraulic conditions because they are products of aqueous transport and deposition, not of distinctive geochemical conditions.

The mineralogic features under study fall into two general categories: 1) alteration mineralogy, mineral abundance, and mineral chemistry and 2) alteration mineral textures and morphologies. Figure 2 shows some of the spatial variations in alteration mineralogy that might be linked to aspects of a hydrologic regime. As shown in the figure, a potential hydrologic indicator is a combination of a mineralogical variable and one or more spatial distribution parameters. Taken together, these define a three-dimensional pattern of mineral distribution that is related to the hydrologic regime. The amount of time required for mineralogic adjustments to a hydrologic regime and the durability of newly-developed mineralogic characteristics under changing conditions are additional factors of importance in determining the usefulness of a hydrologic indicator. Variations in texture and morphology are less easily generalized and are more meaningfully discussed in the context of individual studies.

Attempts to identify changes in these features that coincide with the present-day SWL are conceptually the simplest and most straightforward investigations. Such studies would seem to be logical first steps in identifying useful mineralogical parameters. To be credible, mineralogical changes should show close and consistent spatial association with the SWL and

should be demonstrably independent of other causes of variability.

Investigations of this type have been difficult to carry out because the tuff mineralogy in the vicinity of the present SWL had already been altered under former hydrologic regimes. The thickness of affected tuff above the present SWL is as much as 150 m. As a consequence, mineralogic variations related to present hydrologic conditions may be largely restricted to minor or trace rock components, minerals with irregular or discontinuous distribution, and textural variations that are not easily characterized or verified.

Progress has been made in reconstructing past alteration and hydrologic conditions. The links between mineralogy and past hydrologic regimes cannot be directly tested, but are established with variable confidence by combinations of data and inference. Research results delineating past hydrologic conditions, including conditions that were in effect millions of years ago, have direct relevance to repository issues. The results provide information about the causes, magnitudes, and rates of hydrologic changes. Even negative or ambiguous results help develop our understanding that complexity in mineralogic patterns is the cumulative effect of a long and varied alteration history with associated hydrologic changes.

RESULTS

The upper 2000-m section of Yucca Mountain consists predominantly of Miocene silicic ash-flow tuffs. The pyroclastic units of interest in this paper, in order of increasing depth from the surface to about 800 to 1000 m, are the Tiva Canyon Member of the Paintbrush Tuff, the Topopah Spring Member of the Paintbrush Tuff, the tuff of Calico Hills, the Prow Pass Member of the Crater Flat Tuff, and the Bullfrog Member of the Crater Flat Tuff. These units are present in all of the Yucca Mountain drill holes (Figure 3). Several minor or local units have been omitted from the list. An additional unit not present in existing drill holes, the Rainier Mesa Member (Tmr) of the Timber Mountain Tuff, is younger than the Paintbrush Tuff and is relevant for the age constraints the Tmr outcrop pattern places on tectonism affecting the older units.

Yucca Mountain was progressively tilted and faulted during Miocene time so that the Paintbrush Tuff and older units are inclined in an easterly to northeasterly direction. Older units are more steeply inclined and show

greater fault offsets than younger units. Some of the inclination is primary and results from pyroclastic deposition on tilted surfaces.⁵ Along a transect of the mountain between G-3 and Ue25a#1, the top of the Crater Flat Tuff drops to the NE by 365 m. Structural relations are commonly key elements in paleohydrologic interpretations.

Volcanic glass pyroclasts were the main original constituents of the tuffs, with variable smaller amounts of phenocrysts and crystalline lithic inclusions. Soon after deposition, each of the units except the tuff of Calico Hills developed a central moderately- to densely-welded portion sandwiched between upper and lower nonwelded zones. This welding pattern reflects the greater heat retention in the middle of a thick pyroclastic unit where welding occurs by viscous flow of the glass particles. The welded portions of the units were further modified by syngenetic devitrification of the hot glass. Devitrified tuffs are completely crystalline and contain an assemblage of mostly alkali feldspar and silica minerals.

Zeolitization

The most extensive post-cooling mineralogic change affecting the rocks at Yucca Mountain has been the zeolitization of nonwelded glassy tuffs. In the affected rocks, the glassy component was altered to the zeolite clinoptilolite with or without lesser amounts of mordenite (another zeolite mineral), clays, silica minerals, carbonates, Fe-Mn oxides and hydroxides, and other minor phases. Rocks in the deeper parts of Yucca Mountain have been subjected to differing and additional alteration.⁶

Most zeolites and zeolitized tuffs appear to be products of diagenetic alteration in which the original glass dissolved and the zeolites precipitated at ambient temperatures in a water-rich environment. The distribution of diagenetically altered zeolitic rocks is important evidence for the paleohydrologic interpretations in this paper. Yucca Mountain also contains zeolites of moderate-temperature hydrothermal origin linked to post-emplacment cooling of a pyroclastic unit.⁷

The downward transition from vitric to zeolitized tuffs is a gross feature common to all Yucca Mountain drill holes. As described below, the exact position of the vitric-zeolitic transition in any given hole cannot be precisely fixed, but the persistence of this feature across the mountain makes

it an attractive candidate for investigation as a hydrologic indicator.

Researchers studying zeolitization in the Yucca Mountain region have made a variety of inferences about the hydrologic regimes in which zeolitization occurred. Most studies predating the Yucca Mountain Project attribute zeolitization to unsaturated-zone hydrologic processes: either from localized active recharge creating a zone of near-saturation and rock alteration above the SWL, or from permeability barriers responsible for the formation of local or regional perched water tables and associated alteration.^{1,8,9} Yucca Mountain researchers recognize a few probable examples of perched-water alteration but tend to favor alteration at or below a SWL.^{2,9,10,11} The Yucca Mountain glass- and zeolite-distribution data provide no support for the existence or former existence of a regional perched water table. Known examples of probable perched-water zeolitization are of much smaller vertical and lateral extent than the main mass of zeolitized tuffs. The working hypothesis is that most zeolitization occurred around or below the SWL in place at the time of alteration. As described below, numerous factors make the vitric-zeolitic transition a much less precisely definable position than the position of the SWL at any given time. Therefore, the concept of vitric tuffs being subject to zeolitization around or below the SWL must cover at least a small range of localized hydrologic conditions.

Even without a consensus on the relationship between the transition zone and the SWL position at the time of alteration, researchers generally agree that zeolitization required the presence of abundant water over a long period of time.^{1,2,4,8,9} The underlying assumption is that glass in nonwelded tuffs is preserved only where the rocks have not been subjected to prolonged saturation. This could be a valuable interpretive tool for the Yucca Mountain project because it might be possible to estimate the highest elevation ever occupied by the SWL.

The present SWL lies within zeolitic or devitrified tuffs more than 100 m below the boundary that separates most vitric tuffs from most zeolitic tuffs. There are uncertainties associated with any attempt to correlate the boundary between vitric and zeolitized tuffs with a past SWL position. An inherent problem in equating the configuration of vitric-zeolitic boundaries with a past SWL is that the position of the mineralogic boundary cannot be defined or measured in so straightforward a manner as the position of a SWL. The free-water surface in a borehole can be directly observed and readily measured

to the nearest 0.1 m. In contrast, the vitric-zeolitic boundary is actually a transition zone with vertical extent up to 10 m or more from the first appearance of zeolite to the last disappearance of glass. The boundary can be defined at a certain weight percent content of zeolite, which is reasonable for estimating amounts of zeolite available to interact with radionuclides but has no demonstrated genetic significance.

Another problem of definition stems from the fact that the generalized upper boundary of zeolitic rocks at Yucca Mountain transgresses the more highly inclined stratigraphic boundaries of the pyroclastic units. Because the pyroclastic section originally consisted of alternating intervals of mostly devitrified welded tuffs and vitric nonwelded tuffs, the position of the zeolitic boundary in some places is artificially fixed at an original boundary between devitrified and vitric tuff. The zeolitic boundary in such a place may be lower than the hydrologic boundary existing at the time of alteration. Drill holes in which the position of the zeolitic boundary may have been constrained by parent lithology include 25a-1, G-2, G-3, H-5, and H-6 (Figure 1). In addition, it has been estimated that zeolitization requires periods of the order of 10^4 yr,¹² and it is not known how much the SWL might fluctuate during this time and what effects the fluctuation might have on the development of the transition zone.

The zeolitization chronology of the Crater Flat, Calico Hills, and Paintbrush tuffs has been partly reconstructed from information about the distribution of zeolitized rocks in these units at Yucca Mountain, the progressive tilting and faulting of the mountain, and microscopic evidence of tilting recorded by textural features called geopetal fillings in zeolitized rocks. Two key pieces of evidence suggest that zeolitization in most of the Prow Pass tuff took place before the Topopah Spring tuff was deposited. First, the Prow Pass tuff is the youngest pyroclastic unit that is largely zeolitized in all Yucca Mountain drill holes. The vitric-zeolitic transition lies within the Prow Pass tuff in the three holes -- G-3, H-3, and H-5 -- where the Prow Pass tuff is structurally high and also in H-6 on the drowndropped western side of a N-S fault zone about 2 km southwest of H-5 (Figure 1). In H-6, both the stratigraphic top of the Prow Pass tuff and the vitric-zeolitic transition are about 40 m lower than in H-5.

The picture that emerges from this information is of alteration in a flat-lying or slightly-inclined Prow Pass tuff, producing a vitric-zeolitic

transition zone of relatively flat orientation. Subsequent deformation produced the more steeply inclined and faulted features seen today. In southern and western Yucca Mountain the Prow Pass tuff is at a higher elevation and the vitric-zeolitic transition within the unit has been preserved, whereas in the eastern part of the mountain the tuff unit is at a lower elevation and the vitric-zeolitic transition has been overprinted by later zeolitization.

The second key piece of evidence is the chronology of tectonic tilting and faulting. Tilting and faulting were at least intermittently active until the Rainier Mesa tuff was deposited.^{4,10} The cumulative offset of the Prow Pass tuff is greater than in the two overlying younger units because tilting occurred after each of the three units was deposited. By the time the Topopah Spring tuff was deposited, the Prow Pass tuff was already tilted close to its present attitude. The Prow Pass unit around G-3 and H-3 probably was structurally high enough to be above the SWL. The maximum duration of zeolitization around G-3 and H-3 would have been the age difference between the Prow Pass and Topopah Spring tuffs, about 0.3 myr.¹³

The history of tectonic tilting and the age of the Rainier Mesa tuff constrain the timing of the later zeolitization in the remaining glassy portion of the Prow Pass tuff, the tuff of Calico Hills, and the lower nonwelded part of the Topopah Spring tuff in the structurally low central-eastern part of Yucca Mountain. A temporal connection between tilting and zeolitization has been established by microtextural studies of geopetal fillings.^{4,10} Geopetal fillings in the zeolitized rocks around Yucca Mountain are layered deposits of opal and zeolite within small pores in the altered rocks. These deposits were formed by colloidal silica and aluminosilicate particles settling out of water and the layers were horizontal at the time of deposition. Many of the pores in which fillings were deposited are cavities formed by dissolution of the last remaining glass shards in the zeolitized rocks. These textural relations indicate that the geopetal fillings postdate most of the zeolitic alteration, at least on a local scale.

The orientations of geopetal layers have been measured in thin section and found to constitute a record of tectonic tilting. Tilting has been recorded by the geopetal fillings in the lower Topopah Spring tuff in G-4, a few meters below the vitric-zeolitic transition in the structurally low part of the mountain. These are the youngest rocks affected by pervasive zeolitization.

The 11.6-myr age of the untilted Rainier Mesa tuff locally overlying the older units places a minimum age limit on the timing of tectonic tilting¹⁴ and, by inference, of zeolitization.

The Paintbrush Tuff and older rocks at H-6 have been downdropped relative to the H-5 section along a N-S-trending fault zone between the two holes. This offset has placed unaltered vitric, nonwelded tuffs in H-6 at a lower elevation than the vitric-zeolitic transition in the central-eastern drill holes. Exact elevation differences between the vitric-zeolitic transitions at the two locations cannot be determined because the transition in H-6 is artificially fixed at the base of a 43-m devitrified zone,¹⁵ but the vitric nonwelded rocks above the devitrified zone in the hole are about 16 m lower than the vitric-zeolitic transition in G-4. The vitric tuff in H-6 remains unaltered because a significant part of the fault offset occurred only after the SWL had dropped well below the zeolitic transition. Thus, the timing of SWL drop can be constrained by the chronology of faulting which is in turn constrained by igneous chronology.

Fault offset of the Tiva Canyon tuff (12.7 myr), measured north of H-5, is about 15 m, whereas offset of a 10-myr unit at the same site is less than 2 m.⁵ In Solitario Canyon west of G-3, the Tiva Canyon tuff is offset by about 30 m and deposits of the 11.6-myr Rainier Mesa tuff are displaced less than 5 m. Therefore, the increment of fault offset that dropped the vitric tuffs in H-6 below the zeolitic transition in G-4 probably occurred no later than 11.6 myr ago. The maximum age limit on the timing of offset may be the 12.7-myr Tiva Canyon age and the offset cannot be any older than the 12.8-myr age of the Topopah Spring tuff. The establishment of the SWL within the lower Topopah Spring tuff in the central-eastern part of Yucca Mountain, the zeolitization in that unit, and the subsequent lowering of the SWL also took place during this time interval but before the downdropping of the H-6 section.

Significant events in the history of the saturated-zone boundary at Yucca Mountain during the last 13 myr are summarized schematically in Figure 4. Based on the present distribution of vitric and zeolitized nonwelded tuffs, the vitric-zeolitic transition in the central-eastern part of Yucca Mountain probably marks the highest SWL established at the mountain during the last 12.8 myr. The SWL remained at its highest position no more than 1.2 myr. Subsequent water levels may have existed at higher elevations than the present

SWL (about 120 m below the zeolitic transition in G-4), but have not been any higher than 16 m below the zeolitic transition and perhaps no higher than 59 m below the transition (adding the 43-m thickness of the devitrified zone in H-6 to the 16-m depth of glassy tuff below the transition). This reconstruction does not apply to the vicinity of drill hole G-2 because available data are insufficient to justify a northward extrapolation.

Tridymite Distribution

Tridymite is a crystalline silica polymorph that is a minor constituent of devitrified tuffs in the Yucca Mountain region. The tridymite distribution at Yucca Mountain is an example of a possible SWL-related mineral distribution pattern tentatively identified from drill-hole sample sets collected to characterize the site mineralogy. No samples were collected specifically to test hypotheses about tridymite distribution, and it has not been possible to obtain additional samples pertinent to this question. Samples on hand that were not included in earlier studies have been analyzed to provide a more stringent test of the tridymite-SWL relationship.

Based on drill-hole x-ray diffraction data sets from Yucca Mountain proper and from several sites east of the mountain, it has been suggested that tridymite is not found below the present SWL.^{3,16} The absence of tridymite below the SWL has been attributed to recrystallization (presumably to quartz) in the presence of water. The published Yucca Mountain data do, however, document an exception in drill hole J-13.³ These indications of a possible pattern, even if imperfect, merit a more detailed investigation including examination of tridymite occurrences on a unit-by-unit basis.

The pyroclastic units in which tridymite is found, in order of increasing age and depth, are the Tiva Canyon and Topopah Spring Members of the Paintbrush Tuff and the Prow Pass and Bullfrog Members of the Crater Flat Tuff. Within the Tiva Canyon and Topopah Spring Members, tridymite is mostly in lithophysal zones within densely-welded, devitrified tuff. Crystals up to 0.1 mm long occur in small aggregates within the groundmass of the tuffs or as void fillings in gas cavities and fractures. Tridymite in Prow Pass and Bullfrog devitrified tuffs is in small lithophysae and cavities formed by the recrystallization of pumice clasts and may be in the groundmass as well. Individual crystals are less than 0.05 mm long.

Because the Tiva Canyon tuff is above the SWL at all Yucca Mountain and eastern drill sites and is partly above the SWL in VH-1, there is no basis for comparison of mineral content in this unit above and below the SWL. Tridymite has been detected by x-ray diffraction in seven of eight drill holes from which Tiva Canyon samples have been analyzed.

Of the thirteen drill holes for which Topopah Spring whole-sample x-ray diffraction data are available, twelve contain detectable tridymite. Samples from the exceptional hole, H-6, contain small concentrations of optically identifiable tridymite. Two drill holes east and west of Yucca Mountain contain tridymite below the SWL. Tridymite in J-13 occurs from about 38 m above to about 54 m below the SWL. In VH-1, where the Topopah Spring section is entirely in the saturated zone, tridymite is present as much as 175 m below the SWL.

Fewer data are available for the Prow Pass and Bullfrog tuffs. Tridymite has been detected by XRD in the Prow Pass tuff in holes G-3 and H-3 (out of eleven holes with relevant data) and in the Bullfrog tuff in G-3 (out of five holes with data). The fine-grained character and low abundance of tridymite in these units make it difficult to check optically for tridymite present in amounts below the XRD detection limit (<2 wt. %).³ G-3 and H-3 are also the only holes in which the Prow Pass section is entirely above the SWL, and G-3 is the only hole in which any of the Bullfrog tuff is above the SWL. The one-km proximity of the two holes and the uncertainty inherent in negative data make it difficult to eliminate original lateral variability in tridymite content or sampling shortcomings as alternative explanations for the restricted occurrence of the mineral. These uncertainties will be reduced when new samples are available. For the purpose of discussion, the distribution data are assumed to be representative and to reflect post-crystallization conditions.

The deepest documented tridymite occurrences in the Crater Flat Tuff in G-3 and H-3 are located, respectively, 119 m and 172 m above the SWL. These large vertical separations between mineral occurrence and SWL weaken both the credibility and the value of any suggested connection between tridymite distribution and the present water table. A connection with a former, higher SWL remains possible and might be documentable in a combined context with other paleohydrologic indicators. For example, combined data on tridymite and clinoptilolite distribution, coupled with an understanding of zeolitization

chronology, may make it possible to interpret the paleohydrologic significance of tridymite.

The deepest tridymite occurrences in the Crater Flat Tuff are approximately 60 m (G-3) and 30 m (H-3) below the vitric-zeolitic transition zone. Hydrologic conditions favorable to zeolitization around Yucca Mountain must have lasted long enough for the vitric nonwelded tuffs above and below the tridymite-bearing rocks to be altered but not long enough for the tridymite to recrystallize. The maximum duration of water-rich conditions associated with this early zeolitization episode has been estimated from the conceptual model of zeolitization to be about 0.3 myr.

The later episode of zeolitization affecting the low-lying tuffs of central-eastern Yucca Mountain lasted up to about 1.2 myr from the deposition of the Topopah Spring tuff to the deposition of the Rainier Mesa tuff. In this location, the maximum cumulative exposure of the Crater Flat Tuff to water-rich conditions represented by the two periods of zeolitization was about 1.5 myr. Because most or all of the Crater Flat Tuff is currently below the SWL in this area (G-1, G-4, H-4, 25a-1, and J-13), the absolute maximum possible exposure could have been as much as 13 myr, the age of the unit. The difference between these two time estimates is so large that additional duration-limiting data are needed to make tridymite recrystallization a useful paleohydrologic indicator. Possible sources of additional data might be drill holes in which the Crater Flat Tuff is situated at elevations intermediate between the high positions of G-3 and H-3 and the central-eastern drill-hole locations where the unit is presently below the SWL. The goal would be to obtain samples from several locations where the Crater Flat Tuff was low enough to have experienced both zeolitization episodes but high enough to be above the present SWL. In these locations, the Crater Flat Tuff would have been exposed to water-rich conditions for variable time periods less than 13 myr. The consistent absence of tridymite from the Crater Flat Tuff in such holes would tend to favor an exposure time closer to the lower estimate. H-5 is the only existing drill hole with the potential to supply some of the needed information, as soon as new samples from the relevant units can be collected and analyzed.

One use of a tridymite paleohydrologic indicator would be to help investigate the history of the high potentiometric gradient across northern Yucca Mountain that separates a region of relatively high SWL (generally west

of the Solitario Canyon fault) from the lower SWL of central and southern Yucca Mountain.¹⁷ This large-scale feature is thought to indicate the presence of low-permeability rocks in the saturated zone beneath parts of Yucca Mountain, but has also been cited as evidence for major in-progress hydrologic changes in response to changing tectonic stresses. With a combination of existing and new data, it may be possible to estimate how long the SWL west of the mountain has maintained its position.

CONCLUSIONS

A preliminary conceptual history of the changing SWL has been constructed from a combination of mineral distribution data, textural data, igneous chronology, and structural information. The mineralogic data required to detect and test potential indicators are more numerous and detailed than what has been routinely collected for general rock characterization. Data from existing drill holes have been and will remain critical to the formulation of the hydrologic history. As more information becomes available from new drill holes, the confidence in preliminary interpretations should increase.

Several mineralogic parameters, including zeolites and tridymite, show some promise as paleohydrologic indicators. The interpretation of SWL history suggests that large and rapid changes in SWL position preceded by a short time the renewal of silicic volcanism (Rainier Mesa tuff) at the Timber Mountain caldera north of Yucca Mountain. The evidence from illite/smectite studies suggests that the Timber Mountain caldera strongly affected the pattern of deep saturated-zone flow below Yucca Mountain,⁶ so the possibility of volcano-tectonic effects higher in the saturated zone deserves further investigation.

The examination of tridymite distribution data has identified an information gap related to the locations of existing drill holes. Drill sites are located either on the crest of the mountain or in washes near the base of the mountain. The surface locations from which certain tridymite-bearing zones could be intersected by vertical drilling tend to be hillslopes that would require greater preparation as drill sites. Adits from the surface might offer opportunities for obtaining appropriate samples, although geographic coverage would be more limited than for drill hole-derived samples.

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This paper is a Level III milestone for WBS element 1.2.3.2.1.1.2. Study Plan YMP-LANL-SP 8.3.1.3.2.2, RO is Quality Assurance Level I and contains the applicable quality assurance procedures. Previously unpublished data cited in this paper are contained in notebook TWS-ESS-1-10/82-19, page 202-203. Non-quantitative x-ray diffraction analyses performed for this paper used unmodified commercial software but were not generated under an approved software quality assurance program.

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TABLE I STUDIES APPLICABLE TO PALEOHYDROLOGY AT YUCCA MOUNTAIN

1. Distribution patterns of major, minor, and trace minerals; variations in fracture fillings.
2. Position and geometry of SWL versus position and geometry of vitric-zeolitic transition in tuff.
3. Chemical tracers, e.g., chloride minerals.
4. Glass hydration, leaching, and/or dissolution evidence.
5. Presence and distribution of gels and colloidal material.
6. Patterns of mineral composition variation: major, minor, trace elements, isotopes.
7. Changes in secondary-mineral texture or morphology.
8. Paleospring discharge sites.
9. Paleoecology, e.g., packrat midden studies.

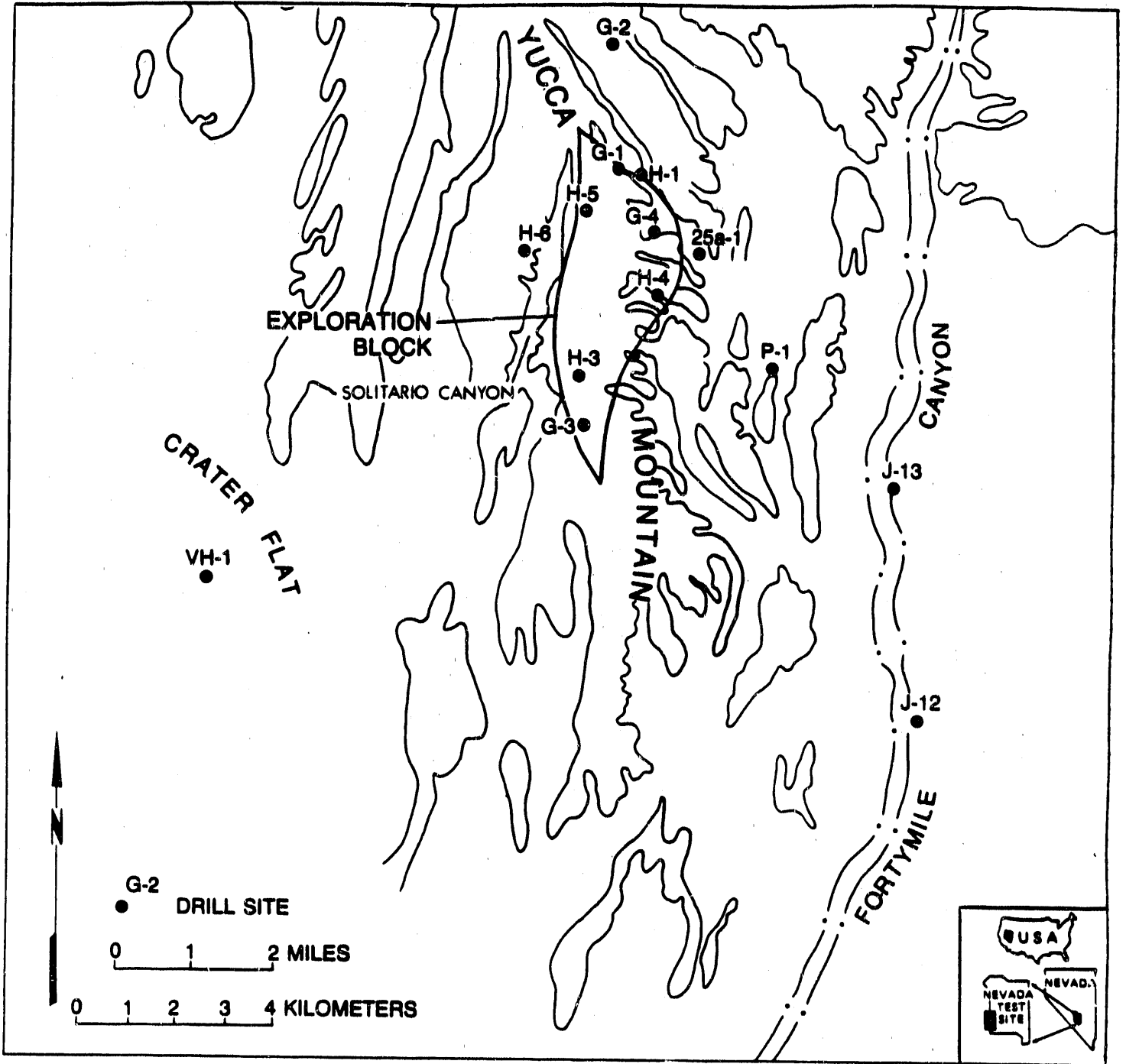
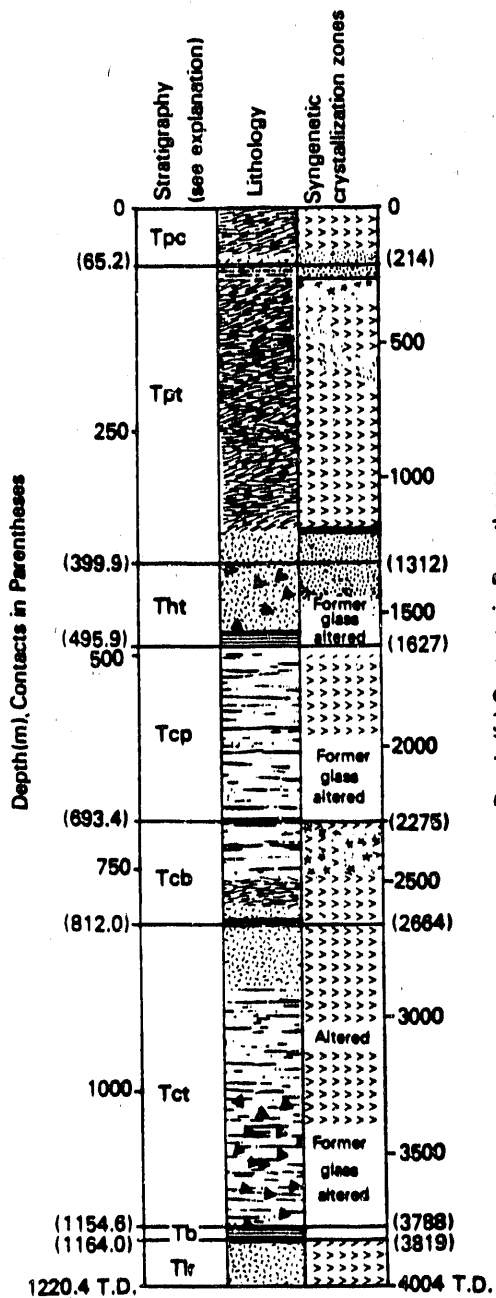


Fig. 1: Location map of Yucca Mountain

MINERALOGICAL PARAMETER x SPATIAL DISTRIBUTION PARAMETER x TIME = HYDROLOGIC INDICATOR

- presence/absence of minerals
- mineral textures
- mineral crystallinity
- mineral composition framework
- exchangeable cations zoning
- scale-dependence
- range and variability
- abrupt boundaries/ gradual trends

Figure 2 POSSIBLE FACTORS LINKING ALTERATION MINERALOGY TO PALEOHYDROLOGY



EXPLANATION

STRATIGRAPHY

Tpc	Tiva Canyon Member	Paintbrush Tuff
Tpp	Pah Canyon Member	
Tpt	Topopah Spring Member	
Tht	Tuff of Calico Hills	Crater Flat Tuff
Tcp	Prow Pass Member	
Tcb	Bullfrog Member	
Tct	Tram Member	
Tb	Bedded Tuff	
Tlr	Lithic Ridge Tuff (Lithic-rich tuff of G-1)	

LITHOLOGY : WELDING ZONES, BEDS, ETC.

	Moderately to densely welded ash-flow tuff
	Partly to moderately welded ash-flow tuff
	Non- to partly welded ash-flow tuff
	Abundant lithic inclusions in tuff
	Bedded tuff; tuffaceous sediments

SYNGENETIC CRYSTALLIZATION ZONES OF ASH-FLOW TUFFS

	Vitrophyre (also densely welded)
	Vitric (glassy)
	Devitrified (microcrystalline quartzo - feldspathic)
	Vapor phase zone (crystals in pumice)
	Lithophysal (crystals in near- spherical cavities)

Fig. 3.
Stratigraphy and lithology of drill hole USW H-4.4

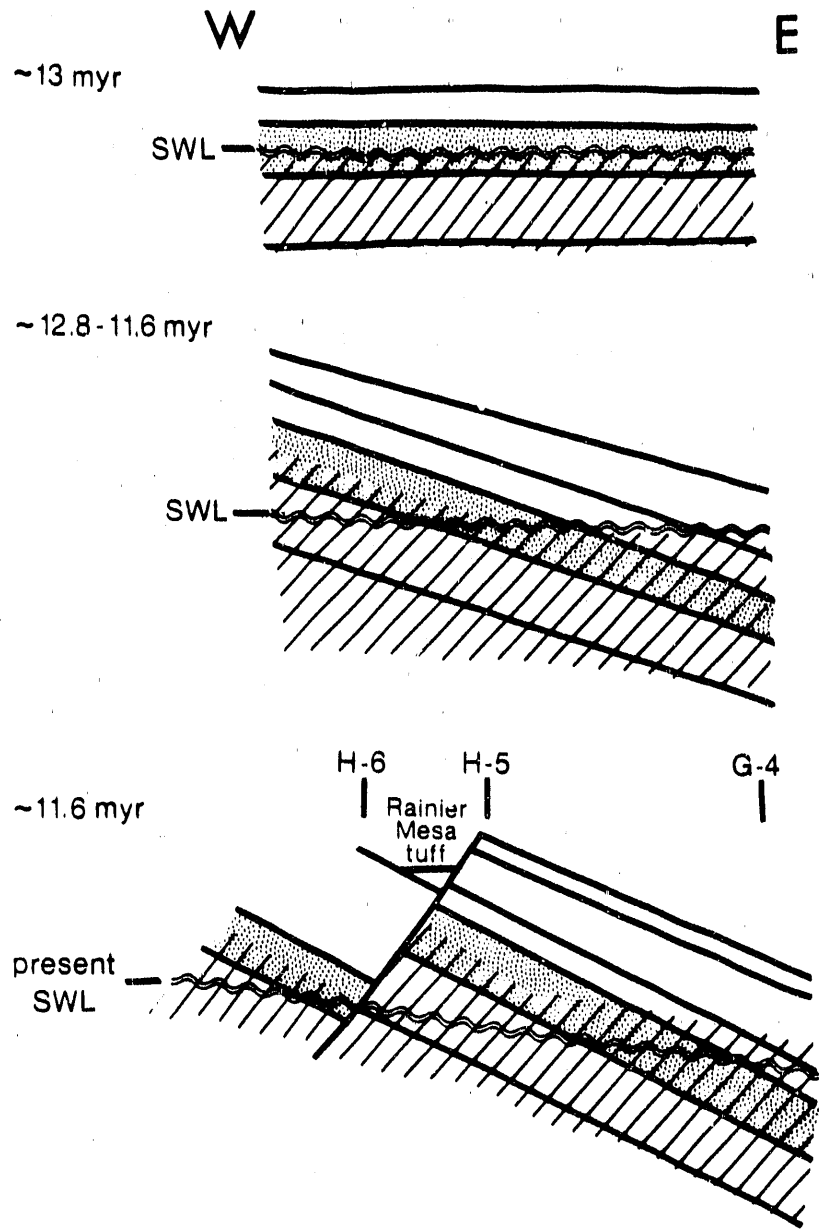


FIGURE 4 Generalized representation of alteration history, not to scale. The Prow Pass tuff is shown in stippled pattern. Diagonal hachures depict zeolitized tuffs. Projected drill hole positions are approximate.

END

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