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Potentially Disruptive Hydrologic Features, Events and Processes at the Yucca Mountain Site, Nevada

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ABSTRACT

Yucca Mountain, Nevada, has been selected by the United States to be evaluated as a potential site for the development of a geologic repository for the disposal of spent nuclear fuel and high-level radioactive waste. If the site is determined to be suitable for repository development and construction is authorized, the repository at the Yucca Mountain site is planned to be constructed in unsaturated tuff at a depth of about 250 meters below land surface and at a distance of about 250 meters above the water table. The intent of locating a repository in a thick unsaturated-zone geohydrologic setting, such as occurs at Yucca Mountain under the arid to semi-arid climatic conditions that currently prevail in the region, is to provide a natural setting for the repository system in which little ground water will be available to contact emplaced waste or to transport radioactive material from the repository to the biosphere. In principle, an unsaturated-zone repository will be vulnerable to water entry from both above and below. Consequently, a major effort within the site-characterization program at the Yucca Mountain site is concerned with identifying and evaluating those features, events, and processes, such as increased net infiltration or water-table rise, whose presence or future occurrence could introduce water into a potential repository at the site in quantities sufficient to compromise the waste-isolation capability of the repository system.

INTRODUCTION

Burial in underground repositories sited in suitable geologic settings is considered generally throughout the international community to be the preferred method for the permanent disposal of radioactive waste [1]. The primary function of the geologic setting is to provide a repository host rock and a stable natural setting that, in combination with an appropriately designed engineered-barrier system, will impede the movement of radioactive material from the repository to the biosphere. Siting repositories in thick unsaturated zones in arid regions has been proposed to offer a number of advantages not only for long-term waste isolation but also for repository construction, operation, and waste retrievability [2,3]. The United States (U.S.) currently is proceeding with the concept of an unsaturated-zone repository for the disposal of spent nuclear fuel and high-level radioactive waste. In 1987 the U.S. Congress directed the U.S. Department of Energy (DOE) to evaluate a site in the arid southwestern U.S. at Yucca Mountain, Nevada, to determine the suitability of this site for development of a mined geologic repository. If the site is determined to be suitable and a license is granted by the U.S. Nuclear Regulatory Commission for repository construction and operation, the repository at the Yucca Mountain site is planned to be excavated in unsaturated tuff at a depth of about 250 m below land surface and at a distance of about 250 m above the water table and would have a design capacity for 70,000 metric tons of heavy-metal waste.

Waste isolation in an unsaturated-zone repository under arid climatic conditions would be achieved principally by providing a natural setting in which little ground water would be available to contact emplaced waste and to transport radioactive material to the biosphere. This waste-isolation concept is based on the premise that moving ground water is the primary means by which radionuclides are likely to be transported from a geologic repository to the biosphere and the subsidiary hypotheses that in an unsaturated-zone setting (1) little of the water held in storage by capillarity and adsorption within an unsaturated host medium will be available to contact emplaced waste and (2) under sustained arid climatic conditions, negligible quantities of ground water will be moving through the repository either to contact emplaced waste or to transport radionuclides.

DISCLAIMER

Reliance on this waste-isolation concept implies that a potential failure mode for an unsaturated-zone repository is the presence or occurrence of features, events and processes that could introduce large quantities of water into the repository or its surrounding host rock. A major effort within the site-characterization program that the DOE is conducting at the Yucca Mountain site is being devoted to determining present and past geohydrologic conditions at the site and to assessing possible and expected future changes in these conditions that could impact waste isolation during a nominal 10,000-year or longer repository lifetime. This paper describes the geohydrologic setting of the Yucca Mountain site and presents a summary report of progress achieved to date in identifying and evaluating such features, events, and processes whose presence or occurrence during the next 10,000 years could alter hydrologic conditions within the unsaturated zone sufficiently to compromise the waste-isolation capability of a potential, unsaturated-zone repository at the site.

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GEOHYDROLOGIC SETTING OF THE YUCCA MOUNTAIN SITE

Yucca Mountain is located about 160 km northwest of Las Vegas, Nevada, (Figure 1) in the southern part of the Great Basin. The Great Basin is a subregion within the Basin and Range physiographic province, a broad region of crustal extension in the western and southwestern U.S. and northern Mexico consisting of tilted, fault-block mountain ranges and deep alluvium-filled intermontane basins. The interior of the Great Basin, in particular, is characterized by linear, generally north-trending, fault-bounded mountain ranges separated by broad (20 to 30 km) alluvial valleys and basins. Although crustal extension continues at present within the Great Basin, the rate of extension has slowed from a maximum of about 20 to 30 mm/yr in the interval 10 to 15 ma to about 10 mm/yr since 5 ma, and the locus of active tectonism has migrated westward to the Owens Valley, Death Valley, and Long Valley Caldera regions along the western margin of the Great Basin near the border between Nevada and California [4]. This evidence suggests the concurrent decline of both the rate and magnitude of tectonism in the Yucca Mountain area since the occurrence of the volcanic and structural events that created Yucca Mountain in middle-to-late Miocene time.

Yucca Mountain evolved from a thick depositional apron of predominantly rhyolitic ash-flow and ash-fall tuffs and minor intercalated bedded tuff that were erupted episodically during middle Miocene time (10 to 14 ma) from a caldera complex whose eroded remnants adjoin Yucca Mountain on the north. Faulting and tilting during or immediately succeeding late-stage caldera collapse, together with subsequent erosion, has produced the plexus of north- to northwest-trending, parallel to subparallel ridges and intervening canyons and valleys that constitute the present-day physiography of Yucca Mountain. West-dipping normal faults bound the major north-south ridges and demarcate the western boundaries of individual, usually east-tilted structural blocks within the Yucca Mountain complex.

The potential repository at Yucca Mountain is proposed to be constructed beneath a prominent ridge and east-tilted structural block within the central part of the Yucca Mountain complex (Figure 1). At the site of the potential repository, the ridge, designated the Yucca Crest in Figure 1, attains an altitude of about 1,500 m above sea level and stands more than 300 m above the valley floors to the west and east. The structural block in which the potential repository would be constructed is bounded on the west by a steep erosional escarpment that developed along the trace of a major west-dipping normal fault, on the east by north-trending zones of imbricate normal faults, and on the north by northwest-trending strike-slip faults. Strata within the block dip variably from 5° to 10° to the east.

The stratigraphy of Yucca Mountain consists of unconsolidated surficial materials (alluvial, colluvial, and eolian deposits and thin veneers of residuum) overlying a layered sequence of variably welded, altered, and fractured tuffs of middle-Miocene age. The unconsolidated surficial materials range in thickness from zero on bedrock outcrops to several tens of meters or more in the canyon and valley floors. The Tertiary volcanics section attains an aggregate thickness of 2 km or more and lies unconformably on Paleozoic carbonate rocks.

Based largely on the degrees of welding and alteration of the tuffs, the rock-stratigraphic units within the unsaturated zone and uppermost part of the saturated zone at the Yucca Mountain site have been grouped into informally named hydrogeologic units [5]. In descending order from land surface, with the ranges of thickness of the units indicated in parentheses, these hydrogeologic units are: the Tiva Canyon welded unit (0 to 150 m); the Paintbrush nonwelded unit (20 to 100 m); the Topopah Spring welded unit (290 to 360 m); the Calico Hills nonwelded unit (100 to 400 m); and the Crater Flat undifferentiated unit. The Crater Flat unit designates the sequence of moderately to densely welded tuffs of unspecified thickness that underlie the Calico Hills unit and constitute much of the upper part of the saturated zone beneath the potential repository site. The Tiva Canyon and Topopah Spring welded units are composed of moderately to densely welded, devitrified, fractured (10 to 40 fractures/m^3) ash-flow tuff that is characterized by low rock-matrix porosity (~0.1) and low rock-matrix hydraulic conductivity (~10^{-11} m/s). The Paintbrush nonwelded unit consists of unfractured (~1 fracture/m^3), nonwelded to partially welded ash-fall tuff and bedded tuff of relatively high matrix porosity (~0.4) and high hydraulic conductivity (~10^{-7} m/s). The Calico Hills unit consists of mainly unfractured (2 to 3 fractures/m^3), nonwelded to partially welded ash-flow and ash-fall tuff and bedded tuff of moderate matrix porosity (~0.3). The initially glassy tuffs within the Calico Hills unit, however, have been altered extensively to zeolities and other minerals progressively from south to north in the site area; and the matrix hydraulic conductivity of the unit ranges from about 10^{-7} m/s, where the unit is predominantly vitric, to about 10^{-10} m/s, where it has been zeolitized. The tuffs composing the Crater Flat unit are generally fractured (8 to 25 fractures/m^3) and of moderately low matrix porosity (~0.2) and hydraulic conductivity (~10^{-9} m/s).

The potential repository at Yucca Mountain is proposed to be constructed in densely welded tuff in the lower part of the Topopah Spring welded unit. The units above the potential repository horizon, specifically the Paintbrush nonwelded and Tiva Canyon welded units, together with the unconsolidated surficial materials where present, are hydrologically important because these units control the spatial distribution and flux of ground water that enters the unsaturated zone as net infiltration and percolates downward through the unsaturated zone toward the water table. The Calico Hills nonwelded and Crater Flat undifferentiated units below the potential repository constitute the principal hydrologic and geochemical barriers for water-borne transport of radionuclides from the potential repository to the biosphere. The contrasting hydrologic properties between and within these units are expected to produce distributions of water content and ground-water flux within the unsaturated zone that are likely to be highly variable in both space and time.

The configuration of the water table at the Yucca Mountain site is marked by two distinctive and as yet unexplained features. The water table is virtually flat and stands at an altitude of about 730 m above sea level beneath and to the east and south of the potential repository location. Immediately to the north of the potential repository, however, the water table rises steeply in altitude by about 300 m over a lateral distance of about 3 km. The region of small hydraulic gradient may indicate the presence of high-transmissivity materials, low ground-water flux, or a combination of these two factors. The region of large hydraulic gradient is more enigmatic, although several hypotheses have been advanced to explain its presence [6]. The ground-water flow system within the saturated zone beneath Yucca Mountain is of importance because the most likely route by which radioactive material released from a potential Yucca Mountain repository may reach the biosphere is by vertically downward transport by ground water moving through the unsaturated zone to the water table and subsequently by lateral transport and dispersal in the saturated zone.

Recharge to the ground-water flow system by water percolating downward through the unsaturated zone at Yucca Mountain appears to be virtually negligible. Present-day average annual precipitation at Yucca Mountain ranges from 150 to 170 mm, depending principally on altitude [7].

Average potential evapotranspiration at Yucca Mountain, however, is estimated to be about 1,500 to 1,700 mm [8], which suggests that most of the water incident on Yucca Mountain as precipitation is returned to the atmosphere by evapotranspiration with only a small residual remaining to enter the unsaturated zone as net infiltration. The hydraulic conductivity values for the tuffaceous rocks composing Yucca Mountain imply that vertical ground-water flux through the unsaturated zone must be less than about 1 mm/yr in order to sustain unsaturated conditions within the rock matrix. Preliminary hydrologic modeling [9] that represents ground-water flow as steady-state Darcian flow through an unsaturated rock matrix further indicates that average ground-water fluxes through the unsaturated zone must be in the range from 0.01 to 0.1 mm/yr in order to match the saturation profiles observed in deep boreholes at the site. Studies of water content in the shallow unsaturated zone at the site, however, indicate present-day near-surface fluxes that range from 0.02 mm/yr to as much as 13.4 mm/yr depending on spatial location [10]. These data, together with recent observations of perched-water occurrences in deep unsaturated-zone boreholes, indicate that both the spatial and temporal distributions of water content and ground-water flux are likely to be highly variable within the unsaturated zone at Yucca Mountain. The resultant complexly three-dimensional state of the unsaturated-zone hydrologic system is the product of both present and past geologic and hydrologic processes whose continuance or change will govern future states of the system and their consequent implications for waste isolation in the unsaturated zone at Yucca Mountain.

POTENTIALLY DISRUPTIVE FEATURES, EVENTS, AND PROCESSES

The intent of locating a repository in the unsaturated zone at Yucca Mountain is to provide a geohydrologic setting in which little water will be available to contact emplaced waste and to transport radionuclides from the repository to the biosphere. Although available evidence indicates that such a setting exists within the unsaturated zone at Yucca Mountain under present-day conditions, the critical issue for long-term waste disposal at the site concerns the expectation that the extant geohydrologic setting will be sustained throughout a nominal repository-system lifetime of 10,000 years or more. In this context, the following three sets of features, events, and processes have been identified whose presence or occurrence at Yucca Mountain could alter hydrologic conditions in the unsaturated zone sufficiently to warrant evaluation of their potential future impacts on waste isolation at the site: (1) the presence of preferential flow pathways that could provide conduits for localized ground-water flow into or through the unsaturated zone; (2) the occurrence of future climatic change that could increase net infiltration into the unsaturated zone; and (3) the occurrence of tectonically or climatically induced water-table rise into or near an unaturated-zone repository at the site. Progress achieved to date in evaluating these possible features and occurrences is summarized below.

Preferential Flow Pathways

The geologic setting, consisting of faulted, tilted structural blocks composed of layered sequences of fractured welded tuffs alternating with relatively unfractured nonwelded tuffs, endows the geohydrologic framework at Yucca Mountain with pronounced heterogeneity and anisotropy. Heterogeneity results from the juxtaposition of hydrogeologic units of highly contrasting hydrologic properties at stratigraphic boundaries and fault contacts and from the presence of discontinuities across fractures and faults. Anisotropy is manifest in the tilted, layered stratigraphy and the common alignment of fractures within fracture networks. Within this framework the distribution and movement of water within the unsaturated zone not only is likely to be complexly three dimensional but may be governed locally by nonequilibrium conditions and processes as well [11]. In particular, models of ground-water flow that are based on Darcian concepts of capillarity-driven flow in unsaturated porous-media may not be adequate to account for the inherent heterogeneity. Consequently, an alternative conceptual model has been proposed [12] that considers transient, gravity-driven flow in highly localized preferential flow pathways to be a major, if not dominant, mode of water movement into and through the unsaturated zone at Yucca Mountain. Candidates for such preferential flow pathways include the fracture systems within the welded tuffs, fractured zones associated with the faults that bound and transect the structural blocks, and high-saturation zones within relatively permeable nonwelded tuff units.

Evidence for the presence of preferential flow pathways in the unsaturated zone at Yucca Mountain derives from several sources. The occurrences of perched-water bodies [13], high-saturation zones [14], and anomalous concentrations of ^{3}H [15] and ^{36}Cl [16] that have been observed in boreholes imply that, even under present-day arid climatic conditions, water is being channeled into the unsaturated zone and is able to descend to depths ranging from several tens to hundreds of meters. Presently dry fractures throughout the unsaturated zone contain coatings and fillings of calcite that bears a pedogenic isotopic signature and apparently was precipitated from water that had passed through the soil zone and had continued downward in the fractures [17]. Pneumatic testing in boreholes [18] shows that the fractured tuffs are characterized by high rock-mass bulk permeabilities, which are apparently fracture dominated and indicate that the fractures form extensive integrated and hydraulically connected flow networks. Finally, observations of active localized flow systems and pathways in settings similar to that of Yucca Mountain [19], including spring discharge from apparently fault-controlled perched-water systems and ground-water flow from fractures intersected by tunnels excavated in otherwise unsaturated tuffaceous rocks, provide indirect evidence for the likely presence of pathways for localized ground-water flow within the unsaturated zone at Yucca Mountain.

The implications for waste isolation at a potential Yucca Mountain repository posed by the presence of preferential flow pathways in the unsaturated zone remain to be addressed fully. Such pathways may be viewed as being beneficial if they were to divert downward moving ground water away from the potential repository and its emplaced waste, but would be detrimental if they were to channel flow towards the repository. Because of the limited quantities of water that are available to enter the unsaturated zone under present-day climatic conditions, the presence of potential preferential flow pathways above an unsaturated-zone repository may be viewed as benign unless and until they are activated by an influx of water, for example, from increased net infiltration in response to future climatic change. However, as a consequence of waste-generated heat release following repository development, these flow pathways may figure prominently in redistributing in situ moisture and establishing a thermal-hydrologic flow regime in the unsaturated zone whose effects may dominate and overwhelm any naturally occurring change within the hydrologic system for periods up to or, perhaps, exceeding 1,000 years after repository closure [20].

Future Climatic Change

The thick unsaturated zone at Yucca Mountain owes its presence in part to the arid to semi-arid climatic conditions that prevail in the southern Great Basin. This climatic regime provides little effective moisture (defined as precipitation minus evapotranspiration) to enter the unsaturated zone as net infiltration. Consequently, to the extent that the maintenance of essentially present-day conditions in the unsaturated zone at Yucca Mountain is to be relied on to isolate radioactive waste at the site, the long-term stability of the extant climatic regime emerges as an issue of major concern. However, because climatic change is not strictly a geologic disruptive process, only a brief summary of an approach for evaluating climatic change at Yucca Mountain will be discussed here.

Of primary concern is future climatic change that would increase net infiltration and introduce water into the unsaturated zone in sufficient quantities and rates to reach an unsaturated-zone repository, contribute to waste-package degradation and failure, and transport radionuclides to the biosphere. The central issue of future climatic change, therefore, is threefold: (1) How much water entering at land surface and moving through the unsaturated zone, either as Darcian flow in the rock mass or as episodic or sustained flow in preferential pathways, is too much water? (2) What degree of climatic change, both in magnitude and duration vis-a-vis the present-day climatic regime, would be required to introduce such quantities of water into the unsaturated zone at Yucca Mountain? (3)

What is the likelihood that climatic change of such degree will occur in the Yucca Mountain region during a nominal repository lifetime of 10,000 years?

Performance-assessment evaluations that are being conducted for a potential Yucca Mountain repository will provide a basis for addressing the first question. The second question is difficult to address because the transfer function relating climatic variables to water entry into the unsaturated zone is not straightforward and remains to be determined for the Yucca Mountain site. Once the issues associated with the first two questions are resolved, however, the third question can be addressed, in principle, by climate-modeling studies to estimate the likelihood of occurrence of those global and regional conditions and forcing functions that could combine to generate climatic change of the required degree. This inverse approach for evaluating future climatic change would not necessarily entail the development of detailed climate models but, instead, would focus on examining the plausibility of climatic change based on the specific consequences that such change would have for waste isolation at Yucca Mountain.

An intensive program of paleoenvironmental studies has been undertaken to support reconstructions of climatic and hydrologic conditions and their interrelationship during the Holocene and late Pleistocene Epochs in the Yucca Mountain region. Knowledge of past climatic conditions and change is essential for calibrating and testing models intended to predict future climatic change and to establish bounds on the extremes of naturally induced climatic variation that may be expected in the future. Evaluation of the evidence for changing hydrologic conditions will contribute toward developing the functional relation between climatic change and hydrologic-system response. There is, of course, no assurance that future climates will mimic past climates, especially in view of the uncertain effects of increased concentrations of greenhouse gases in the atmosphere as a result of human activity. Consequently, knowledge of past climatic conditions and change provides a guide to, but not necessarily an analog for, future climatic conditions and change.

Water-Table Rise

By virtue of being located in the unsaturated zone, the potential repository at Yucca Mountain will be subject potentially not only to ground-water entry from above but also to ground-water entry from below. Ascending water would be manifest as local or regional water-table rise that could occur either quasi-statically, for example, in response to climatically induced increased recharge, or dynamically as a consequence of tectonic or hydrothermal processes. The possibility of dynamically induced water-table rise to or above the altitude of the potential repository at Yucca Mountain has emerged as a major source of controversy in assessing the suitability of the site for potential repository development.

In 1989, J.S. Szymanski, who was then with the Department of Energy, released a draft report [21] in which he suggested that upwelling ground water from the saturated zone has breached the surface in the Yucca Mountain area repeatedly in geologically recent times. The principal evidence cited by Szymanski to support this hypothesis is the presence at and near Yucca Mountain of (1) near-surface and subsurface fractures and faults filled with calcite and subordinate opaline silica veins, (2) breccias composed of angular bedrock fragments cemented by calcite and opaline silica, and (3) surface-parallel deposits of calcium carbonate within the soil zone. Szymanski proposed that these deposits were produced by mineral-laden water ascending from the saturated zone and discharging at the surface. Szymanski further proposed that tectonic stress release ("seismic pumping") and (or) hydrothermal convection provided the mechanisms to force water vertically upward from the saturated zone. These mechanisms, however, confront serious obstacles in that to be viable they must be capable of forcing appreciable quantities of water upwards from the water table through several hundred meters of unsaturated rock. Furthermore, the most likely source of water with high calcium-carbonate content is the Paleozoic carbonate rocks that underlie the thick Tertiary volcanic section at Yucca Mountain. In order for water from the carbonate rocks to reach the surface, however, the water would have to ascend through 2 km or more of saturated and unsaturated volcanic rocks.

Because of the negative implications for waste isolation at a potential Yucca Mountain repository posed by this so-called "Szymanski hypothesis," the DOE conducted an intensive review of Szymanski's data and conclusions and supported numerous studies to determine the origin of the calcite-silica deposits cited by Szymanski as evidence. Controversy arose because the DOE investigators maintained that the deposits in question originated from near-surface processes [24] analogous to those responsible for calcrete and caliche formation that is a common occurrence in desert environments [22]. The controversy culminated in a review of the contending hypotheses by a panel convened for the purpose by the U.S. National Research Council, which issued a report [23] that strongly endorsed the interpretation of a pedogenic origin for the near-surface calcite-silica deposits.

The evidence against upwelling ground water as the source of the near-surface calcite-silica deposits derives principally from the morphology of the deposits and their distinctive isotopic composition. These deposits bear little resemblance to the travertine, tufa, and siliceous sinter ("geyserite") deposits that typically form around warm and hot springs by the degassing of CO_2-charged waters ascending from depth. In contrast, the deposits in question consist of fine-grained, micritic calcite; low-temperature opal-CT; numerous root casts, ooids, and pellets; and inclusions of 20 percent or more of detrital material [24], which is consistent with a low-temperature origin by evaporative precipitation of minerals that are dissolved and mobilized locally in meteoric water moving through the soil zone. To ascribe the mineralogy and morphology of these deposits to the surface discharge of deep-seated ground water would seem to entail chemical and physical processes heretofore unobserved in the Yucca Mountain region or elsewhere.

The isotopic composition of the near-surface calcite-silica deposits provides independent evidence for a shallow, pedogenic origin of these deposits. The stable isotopes ^{18}O and ^{16}O (as well as ^{13}C and ^{12}C) are partitioned between calcite and ground water during calcite precipitation and are diagnostic of the composition and temperature of the water from which a particular calcite precipitated. Unless altered by chemical interaction with the rocks through which the water passes, the relative abundance of the isotopes ^{18}O and ^{16}O in ground water generally reflects the isotopic composition of the meteoric water entering the ground-water flow system as recharge and, thus, the environmental conditions under which recharge occurred. The isotope pairs ^{87}Sr and ^{86}Sr and ^{234}U and ^{238}U are not partitioned during calcite precipitation; consequently, the relative abundances of these isotopes are direct indicators of the source of the precipitated calcite.

Measurement of stable-isotope concentrations in water samples obtained from 21 boreholes that penetrate the saturated zone beneath Yucca Mountain yield a mean $\delta^{18}O$ value of -13.52±0.4 ‰ (SMOW) [25], and present-day precipitation at Yucca Mountain has a mean $\delta^{18}O$ value of about -9.4 ‰ (SMOW) [25]. The disparity between the isotopic composition of Yucca Mountain ground water and contemporary precipitation at Yucca Mountain has been interpreted to reflect differences between the climatic regime that prevailed when recharge to the ground-water flow system beneath Yucca Mountain occurred and the climatic regime that currently prevails in the southern Great Basin [25]. These $\delta^{18}O$ data indicate that Yucca Mountain ground water and Yucca Mountain meteoric water represent two isotopically distinct water bodies whose isotopic imprint should be imparted to minerals precipitated from these waters. In particular, if the near-surface calcite-silica deposits at Yucca Mountain were formed by ground water ascending from the saturated zone beneath Yucca Mountain, calcites within these deposits should reflect the $\delta^{18}O$ composition of that water. Water temperatures at the water table beneath Yucca mountain average about 30 °C [26]. If calcite were to precipitate at these temperatures under equilibrium conditions from Yucca Mountain ground water with mean $\delta^{18}O$ = -13.5 ‰, the resulting calcite should have $\delta^{18}O \leq 12$ ‰ [24]. Measurements of $\delta^{18}O$ on calcite samples from the near-surface calcite-silica deposits at Yucca Mountain, however, yield $\delta^{18}O$ values in the range from 19 to 22 ‰ [24]. In order for Yucca Mountain ground water to precipitate calcites with $\delta^{18}O$ values in the range observed for the near-surface calcite samples, calcite precipitation would have to have occurred at temperatures less than 5 °C [24], which is not consistent with the hypothesis that these calcites derived from warm upwelling water from the saturated zone. On the other hand, if the near-surface calcites were to have precipitated at a soil temperature of about 10 °C from water with $\delta^{18}O$ = -9.4 ‰, corresponding to the mean composition of present-day rainfall and snowmelt at Yucca Mountain, the resulting calcite would have a $\delta^{18}O$ value of about 21 ‰ [24], which is consistent with the observed $\delta^{18}O$ values for the near-surface calcites. Although the isotopic composition of calcites formed in the soil zone by carbonate dissolution in and precipitation from infiltrating meteoric water will depend complexly on many factors [27], the $\delta^{18}O$ evidence for the near-surface calcites strongly favor a hypothesis of local pedogenic origin as opposed to direct precipitation from ground water ascending from the saturated zone.

Available strontium isotope data for ground water in the saturated zone beneath Yucca Mountain and for the near-surface calcite-silica deposits also are incompatible with the hypothesis that these deposits derived from water that ascended from the saturated zone. Because of the accuracy with which the isotope ratio $^{87}Sr/^{86}Sr$ can be measured (±0.00005 or better) and because these isotopes are not fractionated during calcite precipitation, the $^{87}Sr/^{86}Sr$ ratio provides a reliable indicator of the water from which a particular calcite precipitated [24]. Measured values of $^{87}Sr/^{86}Sr$ for ground water in the saturated zone beneath Yucca Mountain range from 0.7093 to 0.7113. The near-surface calcite-silica deposits, however, tend to be more radiogenic: $^{87}Sr/^{86}Sr$ values for these calcites range from 0.7116 to 0.7127 [28]. The hypothesis of calcite-silica deposition from upwelling ground water from the saturated zone offers no ready explanation for the apparent ^{87}Sr enrichment in the near-surface deposits. A more reasonable interpretation is that these deposits are of pedogenic origin and that the observed $^{87}Sr/^{86}Sr$ values resulted from the interaction between locally infiltrating meteoric water and surficial material enriched in ^{87}Sr (or depleted in ^{86}Sr) relative to Yucca Mountain ground water [24].

Uranium isotope data also fail to support the hypothesis that the near-surface calcite-silica deposits at Yucca Mountain derived from ground water from the saturated zone beneath Yucca Mountain. Like strontium, the uranium isotopes do not fractionate during calcite precipitation and, thus, are indicators of the source water from which the calcite precipitated. Once uranium is immobilized, for example, by inclusion in calcite, the subsequent radioactive decay will tend towards secular equilibrium, and the $^{234}U/^{238}U$ activity ratio will approach 1.0. In particular, calcites precipitating from ground water will have the same $^{234}U/^{238}U$ activity ratio as the parental ground water. Calculated initial $^{234}U/^{238}U$ activity ratios on calcite samples from the near-surface calcite-silica deposits at Yucca Mountain are all less than 1.5; whereas water from the saturated zone beneath Yucca Mountain has $^{234}U/^{238}U$ activity ratios that range from 5.00 to 6.94 [24]. These data indicate that ground water in the saturated zone is enriched in ^{234}U and could not be the source water for the near-surface calcite deposits. $^{234}U/^{238}U$ activity ratios determined for soils in the Yucca Mountain area generally are less than 1.4 with only a single value as high as 2.0 [29]. These soil data suggest that the observed initial $^{234}U/^{238}U$ activities in the near-surface calcite-silica deposits derived from a pedogenic source. In any case, the $^{234}U/^{238}U$ activity data do not support the hypothesis that the near-surface calcite-silica deposits originated from saturated-zone ground water.

Although the geochemical data cited above do not support the hypothesis of geologically recent water-table rise sufficient to breach the surface at Yucca Mountain, the potential for possible future water-table rise to the level of the potential repository in the unsaturated zone at Yucca Mountain remains to be addressed. In this regard, it is entirely appropriate to seek evidence of former water-table altitudes to guide assessments of the likelihood for and magnitude of changes in water-table altitude that may occur in the future. Two lines of geochemical evidence, which are discussed briefly below, indicate that although the water table beneath Yucca Mountain has been at higher levels in the past, it probably has not stood higher than about 60 to 100 m above its present configuration with respect to the structural and stratigraphic setting of Yucca Mountain since this setting was created by faulting and tilting of the Yucca Mountain block during the interval 11.6 to 12.8 ma.

One line of geochemical evidence for past water-table altitudes derives from the alteration history of the tuffs at Yucca Mountain [30]. Core samples from boreholes indicate that the stratigraphic section at Yucca Mountain is transected laterally by a persistent zone that is about 10 m thick and records a progressive downward transition from unaltered tuff above to altered tuff below. In particular, below the transition zone, initially glassy nonwelded tuffs have been extensively altered, predominantly to the zeolite mineral clinoptilolite and subordinately to mordenite, clays, and other minerals. The alteration appears to have been a diagenetic process in which the original glass pyroclasts were replaced by zeolites under conditions of abundant water and at ambient temperatures. Based on the consequent implication that the zeolitization occurred below the water table at the time of alteration, the present-day configuration of the alteration transition zone embeds a record of former maximum water-table altitudes with respect to present-day structure and stratigraphy at Yucca Mountain. A preliminary reconstruction of this record [30] suggests that maximum water-level altitudes may have been attained at Yucca Mountain in the period 11.6 to 12.8 ma and, since that time, have not been greater than about 60 m above present-day levels for periods sufficiently long (~10^4 yr) to induce zeolitization of the vitric tuffs.

A second line of evidence is provided by analyses of secondary calcite that pervasively, but not ubiquitously, occurs as fracture and vug fillings within both the unsaturated and saturated zones at Yucca Mountain. The data clearly indicate that calcites in the saturated zone are morphologically, chemically, and isotopically distinct from the calcites present in the unsaturated zone [17,31,32], a reflection of both differing precipitation environments and differing source materials. Consequently, the distribution of saturated-zone and unsaturated-zone calcites can be used, in principle, to map the location and altitude of former high-stands of the water table.

Strontium isotope data provide the best example to date for the use of calcite analyses to infer possible former water-table altitudes at Yucca Mountain. $^{87}Sr/^{86}Sr$ values determined [28] for 16 calcite samples obtained from the unsaturated zone at altitudes more than 100 m above the present-day water table range from 0.7115 to 0.7127. This range of values coincides with the range observed for pedogenic calcite at Yucca Mountain and implies that secondary calcite in the unsaturated zone derived from a pedogenic source. In contrast, $^{87}Sr/^{86}Sr$ values for 19 calcite samples from the saturated zone at depths from 250 to 1,275 m below the water table range from 0.7087 to 0.7098, which clearly distinguishes these calcites from those deposited in the unsaturated zone. However, four calcite samples collected from the unsaturated zone within 100 m of the present-day water table yielded $^{87}Sr/^{86}Sr$ values that ranged from 0.7108 to 0.7112. These $^{87}Sr/^{86}Sr$ values are significantly less than the values obtained from samples higher in the unsaturated zone and indicate the presence of a non-pedogenic contribution to strontium in these samples. The most likely candidate source for the anomalous $^{87}Sr/^{86}Sr$ values is ground water from the saturated zone; consequently these data may indicate that the water table at the borehole site from which the samples were taken has been higher by as much as 100 m above the present level at this site. Data from other locations are needed, however, in order to determine whether this apparent anomaly represents a trend over the Yucca Mountain area or is an isolated occurrence.

Evidence for changing water-table altitudes near Yucca Mountain are indicated from examinations of three paleospring deposits that are located about 20 km southwest of the Yucca Mountain site. Uranium-series dating of calcites from these deposits indicate that, although currently inactive, water discharged at these sites at 18 ± 1, 30 ± 3, 45 ± 4, and > 70 ka [33]. Initial $^{234}U/^{238}U$ activity ratios for these calcites range from 2.8 to 3.8 and suggest that water from the ground-water flow system in the volcanic rocks underlying Yucca Mountain supplied the water that formed these deposits. At the present time, the water table is interpolated to be about 80 to 115 m below the spring deposits, thus implying that when these springs were active the water table locally stood at least 80 to 115 m higher than present-day levels. The magnitude of possible changes of water-table altitude beneath Yucca Mountain that may have occurred during times of ground-water discharge from these paleosprings is unknown but, perhaps, could be estimated from ground-water modeling studies.

The geochemically based inferences of former water-table altitudes at Yucca Mountain are indirect but are corroborated in part by data indicating that the potentiometric surface in the regional ground-water flow system has undergone progressive decline since at least mid-Pleistocene time [34]. The data are based on uranium-series dating of vein calcites associated with sites of former spring discharge from the carbonate aquifer. Depending on the degree of hydraulic connection between the two flow systems, lowering of the potentiometric surface in the regional carbonate-rock aquifer would be expected to induce water-table decline in the saturated-zone ground-water flow system overlying the carbonate-rock aquifer beneath Yucca Mountain. These data, based additionally on occurrences of abandoned spring-discharge areas well above the present potentiometric surface [35], imply regional potentiometric-surface declines ranging from tens to possibly hundreds of meters during the Quaternary Period. Possible explanations for such apparent declines include tectonic lowering of the discharge areas, especially in the Death Valley region; tectonic uplift of the abandoned spring sites; water-table lowering due to increased aridity or erosion; or some combination of these processes [34]. The apparent decline of the regional potentiometric surface is consistent with and may have contributed to secular decline of water-table altitudes beneath Yucca Mountain.

SUMMARY AND CONCLUSIONS

The United States has selected Yucca Mountain, Nevada, as a potential site for the Nation's first geologic repository for the disposal of spent nuclear fuel and high-level radioactive waste. The potential repository at Yucca Mountain is planned to be excavated in unsaturated tuffaceous rocks at a depth below land-surface of about 250 m and at a distance above the local water table of about 250 m. Locating a repository in a thick unsaturated-zone geohydrologic setting under arid to semi-arid climatic conditions, such as occur at the Yucca Mountain site, is intended to provide a a natural setting for the potential repository in which little water will be available either to contact emplaced waste or to transport radioactive material from the repository to the biosphere. The concept of siting geologic repositories in natural settings that will restrict the flow of ground water into and out of the repository system is common to virtually all radioactive-waste-disposal programs; however, reliance on a thick unsaturated zone in an arid environment to accomplish this function is unique to the U.S. program.

By virtue of being located in the unsaturated zone, however, a repository at Yucca Mountain will be subject, in principle, to water entry from both above and below. The entry of water in sufficient quantities to promote waste-package degradation and failure and subsequent radionuclide mobilization and transport has been recognized to constitute a possible failure mode for a potential Yucca Mountain repository system. Consequently, in characterizing the Yucca Mountain site to determine the suitability of the site for potential repository development, considerable effort has been expended to evaluate those features, events, and processes that could cause water to be introduced into the repository from either above or below and lead to possible repository-system failure.

In order for water to invade an unsaturated-zone repository from above, two conditions must be met. First, there must be a source of water and, second, there must be pathways present by which to convey water into and through the unsaturated zone to the repository. In general, net infiltration from rainfall and snowmelt constitutes the source of water that enters the unsaturated zone; however under present-day climatic conditions of low precipitation and high evapotranspiration, little water is available to infiltrate the unsaturated zone at Yucca Mountain. Consequently, future climatic change that would lead to increased net infiltration at Yucca Mountain emerges as an event of considerable importance to potential future waste isolation at the Yucca Mountain site. In order to address the issue of possible future climatic change, an extensive program of paleoenvironmental and paleohydrologic studies has been undertaken to assess not only the occurrence, magnitude, and duration of past climatic change in the Yucca Mountain region but also the consequences of such change on the hydrologic systems. Using past climatic change as a basis, climate modeling studies will be conducted to assess the likelihood of future climatic change at Yucca Mountain.

Increased net infiltration alone, however, need not impair the waste-isolation capability of an unsaturated-zone repository if the time for the effects of increased infiltration to reach the repository is long compared to the design lifetime of the repository system. Because the rocks exposed over much of the surface of Yucca Mountain as well as those in which the potential repository would be located are densely welded tuffs of low saturated hydraulic conductivity ($\leq 10^{-11}$ m/s), the welded-tuff rock matrix is unlikely to sustain ground-water fluxes sufficient to deliver appreciable quantities of water from land surface to the potential repository in times that are of concern. However, Yucca Mountain is a faulted, titled block of alternating welded and nonwelded tuffs of highly contrasting hydrologic properties, and the welded tuffs at Yucca Mountain tend to be highly fractured (20 to 40 fractures/m^3). Consequently, ground-water flow into and through the unsaturated zone is likely to be complexly three dimensional and may tend to be channeled into localized preferential flow pathways consisting of interconnected fracture systems, fault zones, or nonwelded tuff units of relatively high saturated hydraulic conductivity ($\sim 10^{-7}$ m/s). Evidence collected to date indicate not only that such pathways are likely to be present at Yucca Mountain but also that some of these pathways may be active under present-day climatic conditions and be capable of transmitting water from tens to hundreds of meters into the unsaturated zone. The issue to be resolved with respect to water entry from above the potential repository, therefore, entails evaluating the likelihood of future climatic change that, coupled with the presence of preferential flow pathways both above and below the repository, could lead to unacceptable releases of radioactive material to the biosphere.

The possibility of water entry from below the potential repository, in particular as a result of dynamic, tectonically or hydrothermally induced, water-table rise, has been a subject of controversy at the Yucca Mountain site. Occurrences of near-surface calcite-silica deposits in the Yucca Mountain area, consisting of veins within fault zones, cementing material in breccias, and slope-parallel deposits, have been interpreted by some to have been produced by recurrent episodes of ground water upwelling from the saturated zone beneath Yucca Mountain. An alternative interpretation, however, considers these deposits to have resulted from near-surface processes of dissolution and precipitation of calcium carbonate from meteoric water infiltrating and percolating through the soil zone. Support for the latter interpretation is provided by the widespread occurrence in desert soils of deposits of calcium carbonate as caliche and calcrete. Additional evidence for a pedogenic origin of the near-surface calcite-silica deposits at Yucca Mountain, however, derives from their geochemistry, specifically their oxygen, strontium, and uranium isotopic compositions, which virtually precludes modern ground water from the saturated zone beneath Yucca Mountain as the source water for these deposits. These geochemical data, however, are fully consistent with a near-surface, pedogenic origin for these deposits. These data, together with Ockham's razor, which enjoins one to accept the simplest hypothesis consistent with the data, support the hypothesis of near-surface origin for the calcite-silica deposits and obviate the need to devise mechanisms, such as seismic pumping or hydrothermal convection, to propel water from the saturated zone through hundreds of meters of overlying unsaturated rock to breach the surface at Yucca Mountain.

To discount upwelling ground water from the saturated zone as the source of the near-surface calcite-silica deposits, however, is not to say that the water table at Yucca Mountain has not stood higher in the past or that it will not stand higher than its present level in the future. Incomplete and somewhat indirect evidence to date, based on an analysis of water-induced mineral alteration in the tuffs beneath Yucca Mountain and limited strontium isotope data, indicates that the water table beneath Yucca Mountain has been higher in the past but is not likely to have been higher than about 60 to 100 m above its present level since the interval 11.6 to 12.8 ma when major tectonic deformation of the Yucca Mountain block occurred. This inference is supported by additional evidence that potentiometric levels within the Yucca Mountain region have undergone secular decline throughout the Quaternary Period or longer.

The most credible naturally occurring event by which water may be caused to enter a potential repository in the unsaturated zone at Yucca Mountain would seem to be future climatic change that would appreciably increase net infiltration and recharge in the Yucca Mountain area. The magnitude and duration of climatic change that would be required to introduce sufficient water into the unsaturated zone to cause a potential Yucca Mountain repository system to fail is at present unknown but probably would require appreciably increased rates of precipitation and decreased rates of evapotranspiration relative to present-day rates. The likelihood of occurrence of such a climatic event during the design life of the potential repository system is difficult to assess, not only because predictions of climatic change are inherently uncertain but also because the effects on future climates due to greenhouse-gas emissions and other human activities are largely unknown. The uncertainty attaching to predictions of future climatic change and the response of the unsaturated-zone hydrologic system to such change probably are the principal contributors to the overall uncertainty in evaluating the long-term performance of a potential repository in the unsaturated zone at Yucca Mountain in response to natural occurrences.

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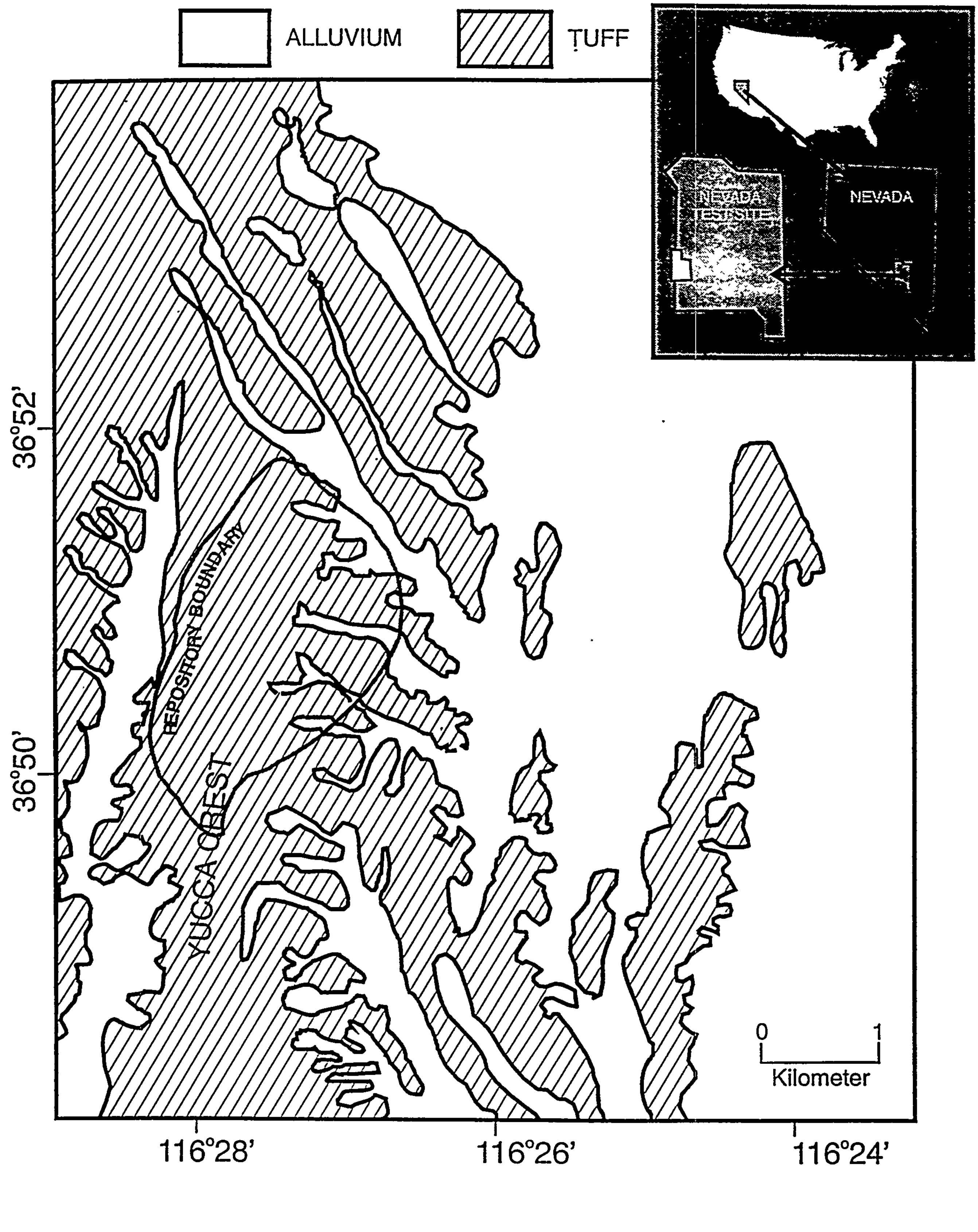

Figure 1. Map showing location of potential repository at Yucca Mountain, Nevada.