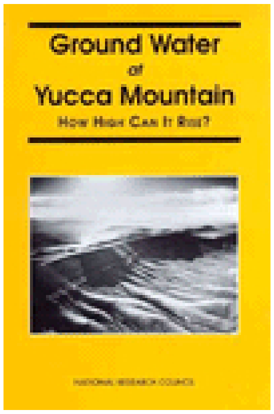

Ground Water at Yucca Mountain: How High Can It Rise?

Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain, Board on Radioactive Waste Management, National Research Council

ISBN: 0-309-54415-7, 242 pages, 6 x 9, (1992)

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Final Report of the Panel on Coupled Hydrologic/ Tectonic/Hydrothermal Systems at Yucca Mountain

Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain
Board on Radioactive Waste Management
Commission on Geosciences, Environment, and Resources
National Research Council

NATIONAL ACADEMY PRESS
Washington, D. C.1992

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Support for this study by the Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain was provided by the Office of Civilian Radioactive Waste Management, U.S. Department of Energy, under agreement DE-AC01-88RW00142.

Library of Congress Catalog Card No. 92-60573
International Standard Book Number 0-309-04748-X

S-604

Additional copies of this report are available from theNational Academy Press,2101 Constitution Avenue, Washington, DC 20418

Printed in the United States of America.

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Executive Summary

INTRODUCTION

In the ongoing national debate on nuclear power as a source of electricity, a key issue is the disposition of the high level radioactive wastes produced in the process. This waste consists primarily of spent nuclear fuel rods.

To resolve this issue, Congress designated the Department of Energy (DOE) to implement the Nuclear Waste Policy Act of 1982. DOE established the Office of Civilian Radioactive Waste Management (OCRWM) in 1983 to develop a mined geologic disposal system (MGDS) for the permanent disposal of the high level radioactive wastes from civilian nuclear power plants. To select a site for an MGDS, the DOE must study in detail the natural environment and the various natural processes to which a proposed deep geologic repository might be subject. For a site to be acceptable, these studies must demonstrate that the site could comply with regulations and guidelines established by the federal agencies to ensure the safety of the public.

Because radioactivity from spent nuclear fuel rods could most likely be released from an MGDS to the outside environment through water entering the repository and transporting the radionuclides into the ground-water system, it was considered that a repository located a considerable distance above the water table in an area with extremely low rainfall would limit that mode of release. Thus, after Yucca Mountain, in the desert of southern Nevada, had been identified as a potential site, DOE decided that if the site were found suitable, the MGDS would be located in the bedrock 300 meters above the water table.

During development of the site characterization plan (DOE, 1988), a report by a DOE staff scientist suggested that the ground water had periodically risen well above the level proposed for the MGDS onto the earth's surface in the geologically recent past and that such an event could happen again. This suggestion was based on his interpretations of field observations. The report proposed that changes in stress in the crust caused by nearby earthquakes had forced the water up to the surface, a mechanism known as "seismic pumping." Two groups of reviewers, an internal peer review group, and an External Review Panel selected by both DOE and the staff scientist did not resolve the controversy that arose.

In response to a request from the DOE, the National Academy of Sciences' National Research Council (NAS/NRC) established the Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain, Nevada, under the auspices of the Board on Radioactive Waste Management, to evaluate (1) if the water table had been raised in the geologically recent past to the level of the proposed MGDS, and (2) if it is likely that it will happen in the manner described in the DOE staff scientist's report within the 10,000-year period covered by the regulations. The report claimed that such flooding had repeatedly occurred in the past and could be expected to happen again. If that were so, and if engineered containments failed, the water could carry still-active radioactive isotopes into the biosphere, a possibility that would lead to serious questions concerning the acceptability of the site.

Evidence cited in the report of hydrothermal fluids having been driven to the surface by pressurization of ground water by earthquake or thermal processes were occurrences in the vicinity of Yucca Mountain of: (1) near-surface and sub-surface fracture fillings, or veins, composed of carbonate and silica, (2) breccias cemented by carbonate and silica, and (3) surficial, surface-parallel deposits of carbonate and silica.

To conduct the study, the Panel on Coupled Systems read the report and other pertinent literature, and interviewed or consulted with scientists involved in field and laboratory investigations of Yucca Mountain and the region for the DOE, the State of Nevada, independent scientists, and all five members of the External Review Panel. Because the thesis was based primarily on the staff scientist's interpretation of geological occurrences and relationships in the field, the panel spent several days in the field led by scientists on both sides of the controversy, visiting and studying carefully those sites that were purported to reveal evidence for upwelling ground water.

The panel regarded their task as not only evaluating the staff scientist's thesis, but also assessing the likelihood that the ground water level could rise to the height of the repository by *any* plausible geological process, or that such a rise had occurred in the past.

HAS IT HAPPENED?

The field evidence evaluated to establish whether or not deep ground water had been forced up through faults and fractures and onto the earth's surface to produce the mineralized veins and surface deposits fell into six categories: (1) the character of soil development and geomorphic features; (2) hydrologic evidence from active and ancient springs; (3) morphologic and textural evidence from chemically precipitated mineral deposits; (4) the stratigraphic/textural/mineralogic character of carbonate-cemented breccias; (5) geochemical and mineralogical considerations; and (6) the isotopic composition of the ground water and mineral deposits.

The panel's overall conclusion was that none of the evidence cited as proof of ground-water upwelling in and around Yucca Mountain could be reasonably attributed to that process. The preponderance of features ascribed to ascending water clearly (1) were related to the much older (13–10 million years old (Ma)) volcanic eruptive process that produced the rocks (ash-flow tuffs) in which the features appear, (2) contained contradictions or inconsistencies that made an upwelling ground-water origin geologically impossible or unreasonable, or (3) were classic examples of arid soil characteristics recognized world-wide.

Soils

Surface-parallel layers of calcium carbonate (calcrete) are ubiquitous in the Yucca Mountain region, as is common in arid regions around the world. Thickness of the calcrete deposits within soils correlated well with the degree of development of the various geomorphic surfaces (alluvial fan, pediment, sand ramp, etc.), i.e., the older the surface, the thicker the calcrete. Calcareous root and stem casts were often seen throughout the calcrete zone, attesting to the fact that the deposits developed within the soil, not on the surface as suggested by the proponents of the ascending ground-water thesis. These features are developed typically where rain water infiltrates the soil and deposits chemicals as it evaporates and would not be expected from upwelling of ground water.

Near-vertical veins of carbonates attributed by the proponents to deposition from upwelling ground water along faults, intersect the texturally similar surface deposits locally at Trench 14 and Busted

Butte. The slope-parallel soil carbonates on Busted Butte thin gently downslope and show no interruption in that gradient where the vertical carbonate vein, the purported source of ascending mineralized ground water, intersects them. If the fault were the source of the fluid, the surface deposits should be relatively thicker on the downslope side. The lack of any relationship between the thickness of the surface-parallel carbonates and the location of the vertical carbonate veins is compelling evidence that the latter cannot be a conduit for the hypothesized upwelling source fluids.

The panel concludes that the surface parallel carbonates formed from rainwater, and from pedogenic (soil-forming) and other surface processes.

Springs

Several features of active and ancient springs cast serious doubt on interpreting them as resulting from pressurized water from below. These include: (1) the absence of tufa, or travertine mounds, characteristic of hydrothermal springs near any of the purported past sources of ground water, (2) the occurrence of several active springs of minute discharge (0.01–0.1 liter/sec) emerging at the base of fractured ridges in the region at ambient temperatures, and (3) the isotopic compositions of these springs being similar to rain water.

Textural/Morphologic Evidence

Comparison of features of an unequivocal carbonate spring deposit in the southern Basin and Range region, at Travertine Point near Death Valley, with features in Trench 14 (excavated across the Bow Ridge fault east of Yucca Mountain) and Busted Butte shows clearly that the Yucca Mountain area veins cannot derive from upwelling CO_2-charged spring waters. The Travertine Point occurrence is characterized by a well-exposed tufa mound, coarse-grained calcite from 6 mm to 1 cm, mirror-image symmetrical banding that results from chemicals precipitating simultaneously on opposite walls of a water-filled fracture, and the absence of interlayered bands of amorphous silica. In contrast, veins in Trench 14 and other exposures in and around Yucca Mountain show no mounds, are composed of extremely fine grained calcite (less than 6 microns, or one thousandth the size of the Travertine Point calcites), have no symmetry, contain thin interlayered bands of low-temperature amorphous silica, and include soil material such as sand, clay, and volcanic ash. **These features reflect low temperature, descending and evaporating water condi**

tions, and result from surficial processes, not upwelling hydrothermal water.

Breccias

The widespread occurrences of breccias cemented by carbonate or carbonate/silica have been cited as evidence of explosive release of highly pressurized ascending fluids by proponents of this thesis. **The characteristics of the breccias show unequivocally that the breccia origins range from formation related to the Tertiary high temperature volcanic processes 13–10 Ma to low temperature mechanical erosion processes which produced the talus at the base of weathering slopes in the geologically recent past and continuing to the present. These do not constitute evidence for any one process at any one time. All of the breccia types can be best explained by processes that do not involve ascension of deep fluids.**

Isotopes

The panel's independent examination of the available stable and radiogenic isotope data show that vein carbonates in the subsurface above the present water table are generally isotopically consistent with the surface-parallel deposits. Moreover, vein carbonates from drill cores below the water table are isotopically consistent with ground water isotopic contents. **Trench 14 and Busted Butte vein carbonates have isotopic contents within the range characteristic of soil carbonates in the region, showing the veins formed from rainwater and soil-forming processes.**

CONCLUSION

The panel concludes from the geologic features observed in the field and geochemical data that there is no evidence to support the assertion that the water table has risen periodically hundreds of meters from deep within the crust. In fact, the evidence strongly supports a surface-process origin from rainwater for the vein and surface parallel carbonate and carbonate-silica deposits throughout the Yucca Mountain area.

CAN IT HAPPEN?

Although available geological and geochemical evidence indicates that the water table has not risen to the proposed repository level in the last 100,000 years, the possibility that it may do so in the future must be assessed. In considering the various mechanisms that could conceivably cause a significant rise in the water table in the Yucca Mountain area, the panel identified three possible processes that could result in a hydrologic response. The question was to determine how much of a response each of the mechanisms could generate. The three possible mechanisms were (1) an increase in rainfall, (2) a volcanic intrusion, and (3) an earthquake. In addition, the panel recognized that a steep hydraulic gradient less than 2 km north of Yucca Mountain has the potential to affect the water table of Yucca Mountain.

Increased Rainfall

An evaluation of past climate changes led the panel to conclude that, even during the maximum glacial extent, the region did not experience more than a 40 percent increase in precipitation over the present approximately 158 mm (6 inches) per year. To evaluate how an increase in rainfall will affect the water table it is necessary to estimate the amount of that rainfall that will recharge the ground-water system. This is difficult to do, especially in arid regions. A model developed by scientists associated with DOE assumed a 100 percent increase in precipitation and a 15-fold increase in recharge. The panel considers these assumptions to be overly conservative. The model calculated a 140 meter rise in the water table under those assumed conditions.

The panel did not model this problem. However, until the DOE model assumptions are tested or better constrained by more complete hydrologic data, and the techniques for estimating recharge in the region better developed, the panel considers an increase in precipitation due to a climate change a possible means of raising the water table significantly.

Volcanic Intrusion

In considering the long and complex volcanic history of the region, the possibility of a recurrence of the highly explosive volcanism of the Tertiary was dismissed because the subduction zone origin of the activity has been replaced by extensional tectonics that has resulted in the basaltic volcanism of more recent geologic time. **The progressive decline in volume of these eruptions convinces the panel that the only likely volcanic intrusion in the region during the lifetime of a proposed repository is a low-volume basaltic dike.** Theo retical considerations of elastic extensional strains suggest a near-vertical dike of 2–4 m width. Models of water table response to a dike intrusion resulted in rises of 10–15 meters, far below that necessary to pose a threat to a repository 300 meters above the present water table. Calculating the probabilities of occurrence of a dike intrusion close to Yucca Mountain results in a very small number, 10^{-8} per year. **Although there may be considerable uncertainty in the probability values, the panel considers that the small effect a basaltic dike intrusion would have on the water table and the low probability of a dike forming close to Yucca Mountain mean that volcanic intrusions can be discounted as potentially disruptive events with respect to water table stability.**

Earthquakes

The panel considered the experience of historic earthquakes and the results of different types of modeling of earthquake responses. Historically, the severest earthquakes in North America for which there is hydrologic information indicate that water table changes are on the order of tens of meters. The nature of the response differs with different types of faulting movements involved, and the reasons for the responses are not yet well understood.

Various types of modeling, using credible assumptions about the elastic properties of the earth and the aquifers, also indicate a response of the water table to be of the same magnitude as those of the historic earthquakes, that is, a rise of tens of meters. **This indicates that the seismic pumping mechanism is inadequate to raise the water table significantly.**

In addition, the probabilities of occurrence of earthquakes of significant size near enough to Yucca Mountain to affect the water table, such as up to a few kilometers away, are quite small unless a wider area, several tens of kilometers, is considered.

The panel concludes, given the experience from historic earthquakes, the small modeled response of the water table to earthquakes consistent with the historic experience, the low strain rates and low seismicity both in magnitude and frequency of occurrence of the Yucca Mountain area, that significant water table excursions to the design level of the repository are unlikely.

It is important to keep in mind, however, that all the foregoing modelling results and probability estimates involve very large uncertainties because of the limits of the information presently available. **The panel, therefore, supports continued site characterization ef**

forts to obtain the critical information necessary for more definitive assessments of the future behavior of the natural systems in the Yucca Mountain region.

It must be emphasized here, however, that these conclusions should not be interpreted as the panel's evaluation of Yucca Mountain as a repository site. The panel was not asked to, and did not, take a position on the suitability of Yucca Mountain for the MGDS. There is more work to be done, however, as there are few data to constrain the complex hydrologic system acting in the vicinity of the proposed repository. The panel supports initiation of the studies needed to develop the necessary information with which to evaluate the site.

RECOMMENDATIONS

Steep Hydraulic Gradient

Foremost of the goals of the studies to characterize the site is understanding the local hydrologic system and particularly the nature and source of the steep east-west hydrologic gradient north of the proposed repository site. This gradient is the expression of a rapid 300 m decline in the elevation of the water table starting just north of Yucca Mountain, which results in the local unsaturated condition of the proposed repository level. Too little is known about the characteristics of the geohydrologic system in general to explain the cause of this gradient. **The panel recommends a comprehensive program of drilling, scientific testing and logging and core and fluid analysis in and close to this gradient.**

Paleozoic Carbonate Aquifer

Results of regional elastic strain modeling to determine the water table response to earthquakes indicated that information on the deep carbonate aquifer is essential to more realistic modelling. The elastic and hydrologic properties of this important feature of the Yucca Mountain area are essential to predictions of water table behavior in the event of a significant earthquake.

The panel recommends that several deep holes be drilled well into this aquifer to obtain the relevant information to determine its extent, its properties, and its communication with the Tertiary aquifer. These have been identified as essential to predictions of water table behavior.

Scientific Integration/Coordination

Throughout the text, the panel has recommended studies to enhance the depth and breadth of the information essential to characterization of the area to increase confidence in the knowledge and parameters necessary to understand the complex interactive systems, hydrological, tectonic, and hydrothermal. However, during the course of the panel's study, it became clear that there was a significant lack of communication among project scientists in different disciplines, especially between those of the hydrological and solid earth sciences, and among the different scientific organizations involved in the study, such as governmental agencies and national laboratories. Even among the geologists and geophysicists there seemed to be little integration of their individual spheres of knowledge and data. **Because this important site characterization program is large and complex, strong scientific leadership must be provided to the participants and adequate attention must be paid to the continuing coordination and syntheses of scientific results. No large scale multidisciplinary study of this type known to the panel has been undertaken without a strong scientific leader coordinating and integrating the ongoing efforts of the various parts of the project.**

To that end, the panel strongly recommends that DOE appoint a scientist as site characterization science coordinator. Such a person should not be currently associated with any of the participating organizations. That scientist should have a reputation for independence and excellence, as well as the experience in managing and integrating interdisciplinary programs, and would therefore lend further credibility to these investigations and their results.

1—
Introduction

In the ongoing national debate on nuclear power as a source of electricity, a key issue is the disposition of the high level radioactive wastes produced in the process. At an earlier stage of this debate, Congress, aware of the importance of the waste issue, passed the Nuclear Waste Policy Act of 1982. This legislation required that the federal government develop a geologic repository for the permanent disposal of the high level radioactive wastes from civilian nuclear power plants. This waste consists primarily of spent nuclear fuel. Congress designated the Department of Energy (DOE) to implement the provisions of the act.

The Department of Energy established the Office of Civilian Radioactive Waste Management (OCRWM) in 1983 in response to the legislation and set about to identify potential sites. When OCRWM had selected three potential sites to study, Congress enacted the Nuclear Waste Policy Amendments Act of 1987, which directed the DOE to characterize only one of those sites, Yucca Mountain, in southern Nevada.

To characterize the site, the DOE must study in detail the natural environment and the various natural processes to which a proposed deep geologic repository might be subject. For a site to be acceptable, these studies must demonstrate that the site could comply with regulations and guidelines established by the federal agencies that will be responsible for licensing, regulating, and managing the waste facility. The regulations, which were promulgated to ensure the safety of the public, require that radiation will not be released above some established safe limit, determined by the Environmental Protection Agency (EPA), for at least 10,000 years after the repository is permanently sealed.

Earth scientists recognized early in the development of the concept of the mined geologic disposal system (MGDS) that radioactivity from spent nuclear fuel rods was most likely to be released to the outside environment through water entering the repository and transporting the radionuclides into the ground-water system. Thus, the design for a potential MGDS at Yucca Mountain, in the southern Nevada desert, calls for a location in the bedrock 200–400 m above the water table, in the unsaturated zone. The elevation of the water table there is 740 m above mean sea level (AMSL), and about 400 m below the land surface.

During development of the site characterization plan (DOE, 1988), preliminary field studies into the geology and ground-water flow system were conducted to determine the scope of the investigations needed to understand the natural systems that may be active in the region. Based on his interpretations of field observations, a DOE staff scientist suggested that the ground water had risen well above the level proposed for the MGDS more than once in the geologically recent past and that such an event could happen again, flooding the mined geologic repository. This concern developed into a report by the staff scientist (Szymanski, 1989) detailing his views of the evidence and processes that caused the postulated events. As an internal peer review group failed to be convinced by the arguments and interpretations presented in that report, and an External Review Panel selected by both DOE and the staff scientist could not agree on the validity of the hypothesis (Powers et al., 1991; Archambeau and Price, 1991), the concern remained unresolved.

In an effort to resolve these concerns, the DOE asked the National Academy of Sciences' National Research Council (NAS/NRC) to evaluate the hypothesis and assess the likelihood that the process described by the DOE staff scientist could result in raising the water table to the level selected for the MGDS.

The NAS/NRC established the Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain, Nevada, under the auspices of the Board on Radioactive Waste Management in April 1990. The panel was asked to evaluate (1) if the water table had been raised in the geologically recent past to the level of the proposed repository, or MGDS, through the action of coupled processes involving tectonic, hydrothermal, volcanic or climatic events; and (2) if it is likely that it will happen in the manner described in the DOE staff report (Szymanski, 1989) within the 10,000-year period covered by the regulations. The report claimed that such flooding had repeatedly occurred in the past and could be expected to happen again.

This hypothesis was based primarily on interpretations of geological observations at Yucca Mountain and vicinity. The report ascribed near-surface and subsurface veins composed mainly of carbonate and silica, breccias cemented by carbonate and silica, and surficial, surface-parallel deposits of carbonate and silica to emanations of hydrothermal fluids driven to the surface by tectonic and thermal pressurization of ground water by earthquake or thermal processes.

The thesis of the origin of the breccias and carbonate-silica deposits outlined in the report is controversial. Scientists involved in the project from the United States Geological Survey (USGS) and DOE, as well as independent researchers, generally believe that the near-surface carbonate-silica veins and cementation formed by deposition from surface waters filtering downward through the desert alluvium and, in some cases, reaching greater depths in steep fractures associated with faults.

The panel members have wide-ranging expertise in geology and hydrologic processes, some with special knowledge of the Basin and Range geologic province in which Yucca Mountain is located. The areas of specialization of the panel members include Quaternary geology, hydrology, geochemistry, geophysics, rock mechanics, numerical modeling of thermal/ mechanical processes and its geological applications, paleoclimatology, tectonics and earthquake risk analysis.

To conduct the study, the panel read the report (Szymanski, 1989) and other pertinent literature, and interviewed or consulted with many of the scientists involved in field and laboratory investigations of Yucca Mountain and the region, for the DOE, the State of Nevada, and independent scientists. Those interviewed included the author of the report, experts in the paleoclimatology and hydrology of the area, and all five members of the External Review Panel previously mentioned. A majority of the NAS panel members spent at least three days visiting sites considered to be critical by scientists on both sides of the controversy. The remaining panel members participated in a similar two-day trip. Five members returned for an additional three-day field trip led by J. Szymanski, author of the staff report, in April 1991, to allow the panel more complete exposure to observations and interpretations of those geologic features that formed the basis for his conclusion that the proposed repository level had been flooded repeatedly by ground water in the recent geological past.

The charge set by the panel for itself in its first meeting was the following:

> The panel will attempt to see whether there are plausible mechanisms, tectonic, thermal, or otherwise, by which the water level in the Yucca Mountain could rise to the level of the repository. We will attempt to look for evidence in the Yucca Mountain area as well as in neighboring parts of Nevada where data exist to see what previously has been the highest stand of the water level. In other words, what fluctuations have there been in the past that would lead one to believe that any of these mechanisms might actually work or might have happened before?

The charge is general in nature rather than specific to the DOE report's hypothesis. The panel, while acknowledging the importance of the stimulus provided by the author of the report, nevertheless took the position that any observations or theoretical mechanisms that might account for past or future flooding of the proposed repository level should be considered. Thus, while our report inevitably deals with details of Szymanski's interpretations, the conclusions and recommendations derive from broader considerations.

The following chapters of this report provide details of the panel's analysis of the field information and the published literature, the results of preliminary modeling studies done by panel members and others, and some direct analysis of raw data made available to the panel by field investigators of the region. Chapter 2 evaluates the evidence related to the level of the water table through time. It considers the field evidence, including that shown to panel members by proponents of the ground-water flooding hypothesis, and the geochemical and isotopic characteristics of the relevant features. Chapter 3 addresses the impact on the water table of potential climate changes by looking at evidence of past variability in rainfall and what is known of the present hydrologic regime. Chapter 4 evaluates the potential effects of an igneous intrusion near Yucca Mountain on the water level. Chapter 5 considers earthquakes as a potential driver of water from below to raise the water table. It looks at water table responses to historic earthquakes, modeling results, and the probabilities of occurrence of large earthquakes in the Yucca Mountain area. Chapter 6 summarizes the panel's conclusions and recommendations based on its experience and observations of the Yucca Mountain program and region. The panel has included some observations related to data acquisition practices and policies of the scientific program for site characterization of Yucca Mountain, and the need for coordination of scientific activities in resolving site characterization issues such as the one for which this panel was convened.

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2—

Water Levels in the Vicinity of the Proposed Repository in the Last 100,000 Years

A brief summary of the geologic history and setting will serve to put into context the panel's field observations and evaluation of the geologic and isotopic evidence used to support the hypothesis of cyclic upwelling of ground water in the Yucca Mountain region. Moreover, models assessing future behavior of the earth systems in the area, which are considered later in this report, require realistic assumptions if the results are to be credible. Therefore, consideration of the geologic setting is key to evaluating such models.

GEOLOGIC SETTING OF YUCCA MOUNTAIN AND ENVIRONS

Yucca Mountain is situated in the southwestern part of the Great Basin physiographic province. The Great Basin is coincident with the northern part of the Basin and Range physiographic province (Figure 2.1), which is characterized by numerous north-trending mountain ranges and intervening broad, flat valleys, or basins, spaced about 20–30 km apart. For the area of interest for this report, from west to east, Bare Mountain, Crater Flat, Yucca Mountain, and Jackass Flats constitute two such pairs of basins and ranges (Figure 2.2).

Yucca Mountain is located geologically within the Cordilleran mountain belt, an elongate region of active deformation on the western margin of the North American tectonic plate. While this tectonic belt is currently active, it has a long and complex geologic history (Figure 2.3). The modern surface appearance, or physiography, of the Cordilleran

Figure 2.1
Digital shaded relief map of the Cordilleran mountain belt at the latitude of California, showing positions of Yucca Mountain, the Great Basin, and the Basin and Range Province. The northern Great Basin portion of the province drains internally, while the southern portion (south of dashed line) drains into the Gulf of California.

belt is mainly the result of geologic activity over approximately the last 10 million years, but the rocks record a geologic history over the last 2 billion years. Crustal deformation that defines the Cordilleran belt proper dates back approximately 600 million years.

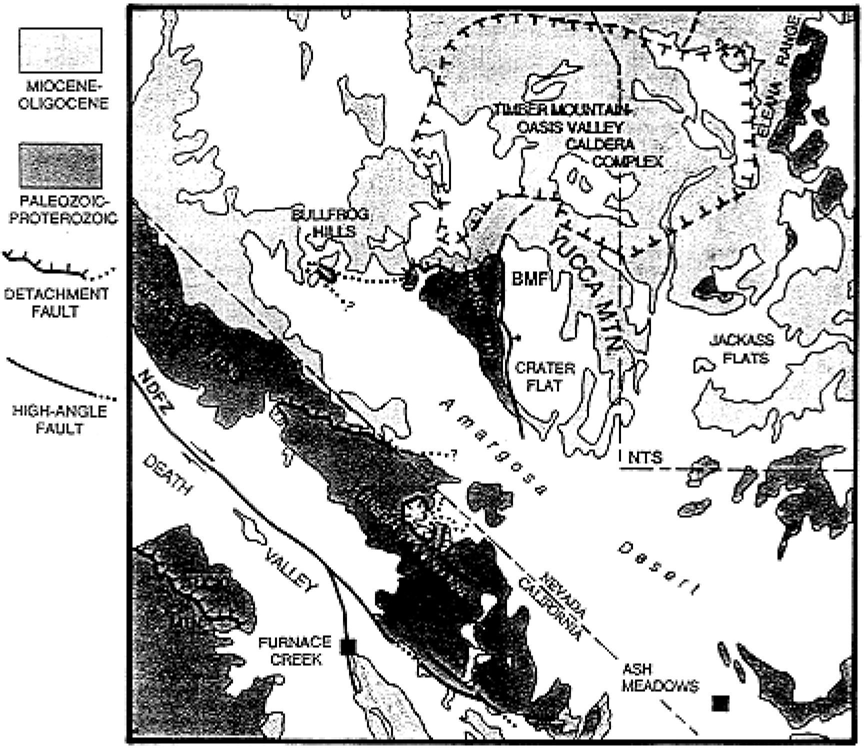

Figure 2.2
Map showing major geologic features of the Yucca Mountain area. Unpatterned areas are alluvium in modern valleys. Major active faults include the Northern Death Valley Fault zone (NDFZ) and Bare Mountain fault (BMF). Detachment faults at Tucki Mountain, in the Funeral-Grapevine Mountains, and Bullfrog Hills, and at Bare Mountain accommodated rapid, large-magnitude crustal extension over the last 15 million years, but are now mainly inactive. The Timber Mountain-Oasis Valley Caldera Complex (outlined by T's) represents the volcanic source region for tuffs that comprise most of Yucca Mountain. Furnace Creek and Ash Meadows are major hydrologic discharge areas in the southern Great Basin. NTS and associated dashed lines refer to the Nevada Test Site boundary.

The geologic evolution of the region that includes Yucca Mountain is divisible into three main episodes, each corresponding to the three major geologic eras of the past 600 million years, the Paleozoic (570–

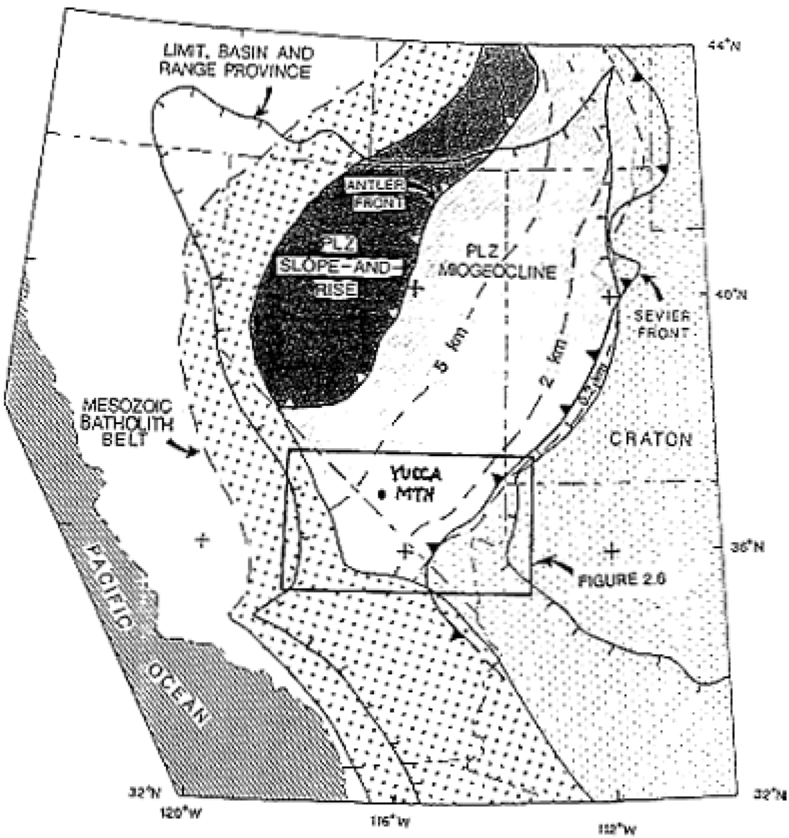

Figure 2.3
Map showing distribution of major tectonic features of the Cordilleran mountain belt. Yucca Mountain lies between an area of thin Paleozoic sediment and minor Mesozoic deformation to the east (craton) and a zone of intense igneous intrusion to the west (Mesozoic batholith belt). The intervening area (Cordilleran (PLZ) miogeocline) is characterized by a thick wedge or prism of Paleozoic sediments deposited mainly in a shallow marine sea (Figure 2.4) that was strongly shortened in Mesozoic time (Figure 2.5). The east limit of strong shortening of the miogeocline (Sevier front) coincides with the edge of thick Paleozoic sediment. Dashed contours show thicknesses of the lower, predominantly sandstone and mudstone, portion of the miogeocline. After Wernicke et al. (1988).

245 million years ago (Ma)), Mesozoic (245–65 Ma), and Cenozoic (65 Ma to the present) eras.

Paleozoic

The Paleozoic was a time of major crustal down-warping along the continental shelf and margin, which formed the miogeocline (Figure 2.4), and of sediment deposition on top of Precambrian (pre-Paleozoic) crystalline crust (formed ca. 1.7 billion years ago). In southern Nevada, shallow-marine deposits of the miogeocline, originally of sand, clay mud, and calcium carbonate (lime) precipitates, thicken northwestward from about 1 km thick in the Las Vegas area to more than 10 km thick in the Yucca Mountain region (Figure 2.4; Wright et al., 1981). The sand and clay muds of this wedge-shaped sedimentary deposit, called a clastic wedge or prism, are now predominantly quartzite, slate, and other impermeable rocks in its lower part. These rocks now constitute an aquitard, a rock unit that does not readily permit water to pass through. The carbonate, now limestone, that lies above it is an aquifer through which ground water flows easily in fractures and solution channels. Strong Mesozoic and Cenozoic tectonic events deformed these rocks and destroyed the simple wedge-shaped geometry and continuity of the original deposits. The thick Paleozoic limestone that once covered the region as a continuous layer is now a widespread but discontinuous deep regional aquifer through which large volumes of water flow in the southern Great Basin.

Mesozoic

Beginning approximately 250 Ma, the sedimentary prism was horizontally compressed into a major system of folds and west-dipping thrust faults (Figure 2.5). The total contraction of the prism was probably more than 100 km between the Las Vegas and Sierra Nevada regions (Wernicke et al., 1988). Yucca Mountain is situated in the central part of the zone of Mesozoic thrusting and crustal shortening. In the Las Vegas region, major compression persisted until approximately 90 Ma. In the westernmost part of the sedimentary wedge, molten rock of high silica, or granitic, composition was forced up into the crust, crystallizing several granitic bodies into a larger granite mass called the Sierra Nevada batholith (Figure 2.3). The Yucca Mountain area lies mainly to the east of this area of Mesozoic igneous activity. Both the shortening and igneous activity are believed to be related to subduction, or downthrusting, of the ancient Pacific plate beneath western North America (Hamilton, 1969).

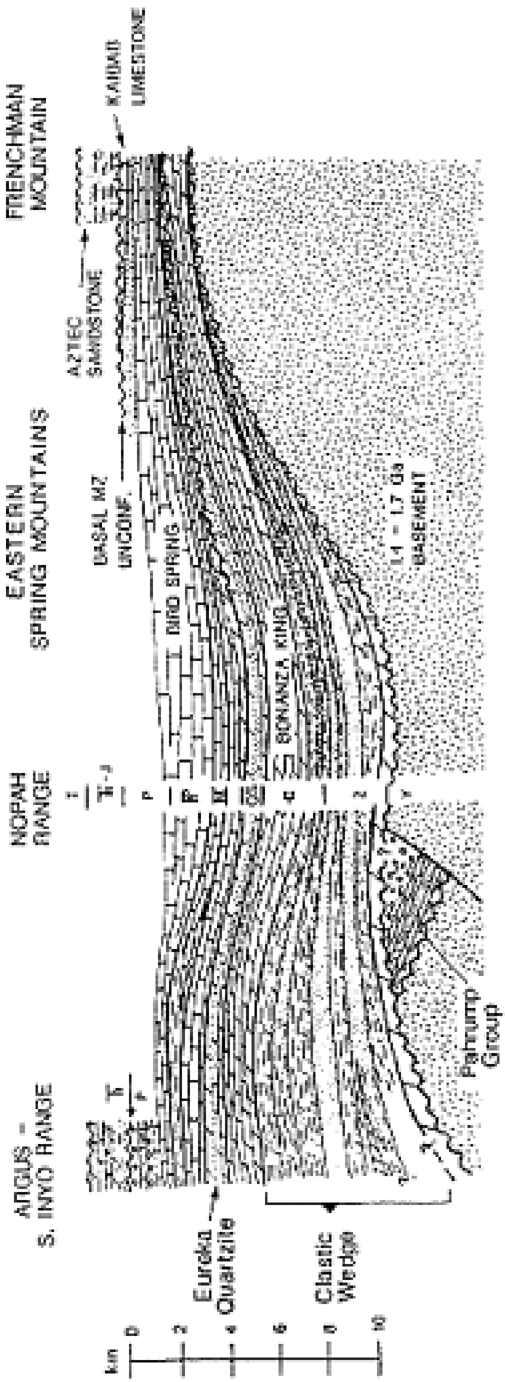

Figure 2.4
Cross-section of the miogeoclinal prism as it existed prior to Mesozoic thrust faulting. The lower sandy and muddy sediments (clastics) thicken dramatically westward. Vertical exaggeration is approximately 3:1. After Wernicke et. al. (1988).

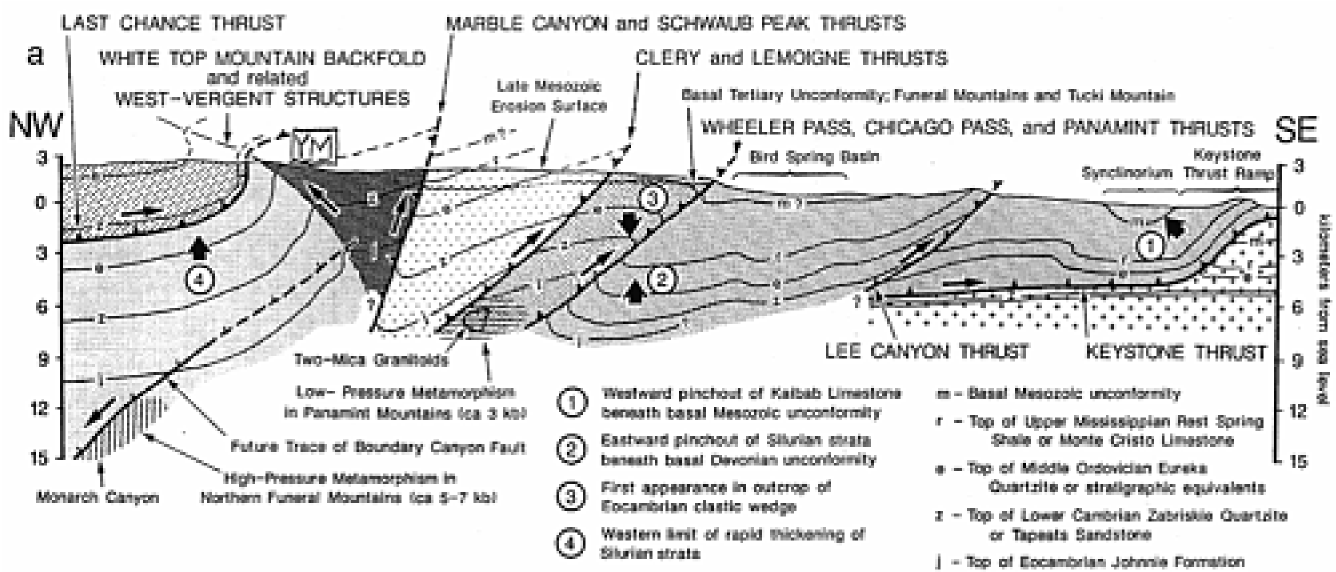

Figure 2.5
Cross-section of southern Great Basin region as it existed following Mesozoic shortening but before Cenozoic extension, showing geologic details of miogeoclinal sediments with respect to major Mesozoic thrust faults. YM shows approximate position of Paleozoic strata in the Yucca Mountain area. After Wernicke et al. (1988).

Cenozoic

A major quiet period lasting 60 million years occurred from late Mesozoic to middle Cenozoic time, from 90–30 Ma. There is no record of sedimentary deposition, or of igneous or tectonic activity during this time. Only relatively minor erosion of the thickened crust occurred. Following this hiatus, a major deformational and igneous event affected the region, and continues to the present. Although subduction of Pacific ocean crust continued into Cenozoic time and was active at the onset of renewed deformation and volcanism following the hiatus in tectonic activity, the deformation beginning about 30 Ma involved extension, or pulling apart the crust, instead of contraction. The molten rock produced by the renewed igneous activity emerged onto the earth's surface mainly as volcanoes and lava flows. This type of activity was in contrast to the deep granitic bodies that intruded the crust during the Mesozoic. Millions of years after they formed in the crust, uplift and erosion of the rocks that covered them exposed the massive granite bodies at the earth's surface, which are now called the Sierra Nevada Mountains.

Extension

Extension of the crust occurred mainly along west-dipping normal faults (roughly parallel to the older thrust faults) and associated northeast-and northwest-trending strike-slip faults (Figure 2.6). Two major north-trending belts of extension and normal faulting developed, one largely in the Las Vegas/ Lake Mead area to the east (Lake Mead extensional fault system), and another within the shortened sedimentary wedge (Death Valley extensional fault system), which includes the Yucca Mountain area. The entire Basin and Range at the latitude of Las Vegas has extended about 200–300 km across the province in two phases (Wernicke et al., 1988). Although evidence of extensional activity and related development of basins and ranges dates back to approximately 30 Ma in the southern Great Basin (Axen et al., 1991), the majority of extensional strain and volcanism in the Yucca Mountain area appears to have occurred in the last 10–20 million years (Scott, 1990; Wernicke et al., 1988). Extension appears to have been most rapid from 15–5 Ma, when the rate is thought to have been 10–30 mm per year. Extension has resulted in local severe thinning of the sedimentary crust, completely removing it in some areas. As a result the thickness of the Paleozoic limestone beneath Yucca Mountain is uncertain, but was likely very much thinned or pulled apart by extension in mid-Miocene time (15–10 Ma). Extension in the southern

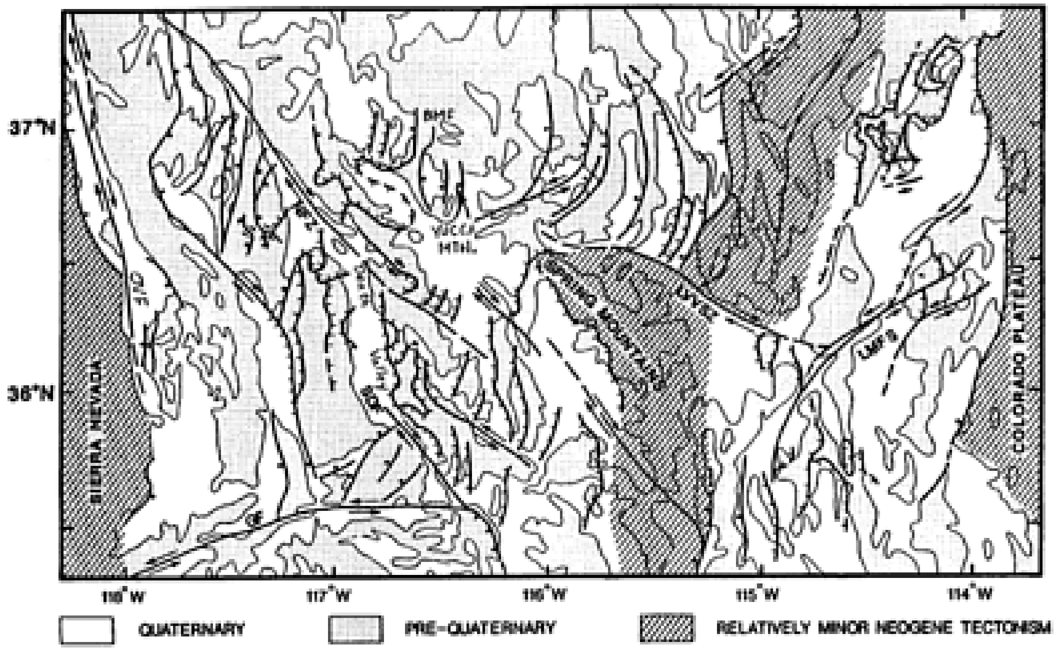

Figure 2.6
Map showing major Cenozoic strike-slip and normal faults in the Basin and Range province at the latitude of Yucca Mountain. OVF, Owens Valley fault; NFZ, SDF, northern and southern branches of the Death Valley fault zone; BMF, Bare Mountain fault zone; LVVSZ, Las Vegas Valley shear zone; LMFS, Lake Mead fault system. Two strongly extended areas of the Basin and Range, the Lake Mead and Las Vegas normal fault systems, lie east and west respectively of a medial unextended block that includes the Spring Mountains. Active strong extension is restricted to region west of Death Valley. After Wernicke et al. (1989).

Great Basin region (Figure 2.1) slowed down after 5 Ma to its present rate of approximately 5–10 mm per year.

The waning of major extensional activity migrated westward across the Death Valley region, beginning 10–15 Ma in the eastern part of the Basin and Range, but extension persists to the present day in the western part (Wright et al., 1984; Hamilton, 1988).

Volcanic Activity

Between 14 and 11.3 Ma, the Yucca Mountain area experienced large-volume, explosive volcanism resulting in extensive fallout of volcanic ash. The accumulation of massive layers of this ash resulted in the formation of rocks known as ash-flow tuffs (Frizzell and Shulters, 1990). Yucca Mountain itself is composed mainly of such tuffs, including the Crater Flat, Paintbrush, and Timber Mountain tuffs. In some places where there were thick accumulations of ash composed mainly of volcanic glass shards (fragments), the shards became welded together under the combined action of the heat retained by the particles, the weight of overlying material, and hot gases. Welded zones thus formed within ash-flow tuffs are very dense and, for the most part, impermeable, but they are also brittle and have responded to stresses by forming many fractures through which water may flow. The proposed repository at Yucca Mountain is designed to be excavated in a welded tuff, the Topopah Spring Member of the Paintbrush Tuff (Figure 2.7). The sources of the tuffs are volcanic centers of silica-rich rocks distributed throughout the region immediately to the north of Yucca Mountain (Figure 2.2). Nearby volcanic eruptions associated with these centers in the later stages of silicic activity extruded low silica/high iron lavas which cooled to form basaltic rocks (e.g., on Skull Mountain south of Jackass Flats).

It is important to note here that the high silica volcanic activity ended about 11.3 Ma, and that the low silica basalt volcanism occurred in two phases, about 10 Ma and between 3.7 and 0.13 Ma. Further discussion of the volcanic history of the Yucca Mountain vicinity appears in Chapter 4 of this report.

The age relationship between major extension and volcanism in the region is complex. While broadly synchronous, major extension largely preceded volcanic activity in some parts of the southern Great Basin and followed it in others. At Yucca Mountain, an episode of rapid extension likely occurred prior to the accumulation of the Paintbrush and Timber Mountain Tuffs, extending the previously shortened Paleozoic sedimentary wedge tenfold or more. Subsequently, the tuffs were mildly extended, resulting in a series of gently tilted domino-

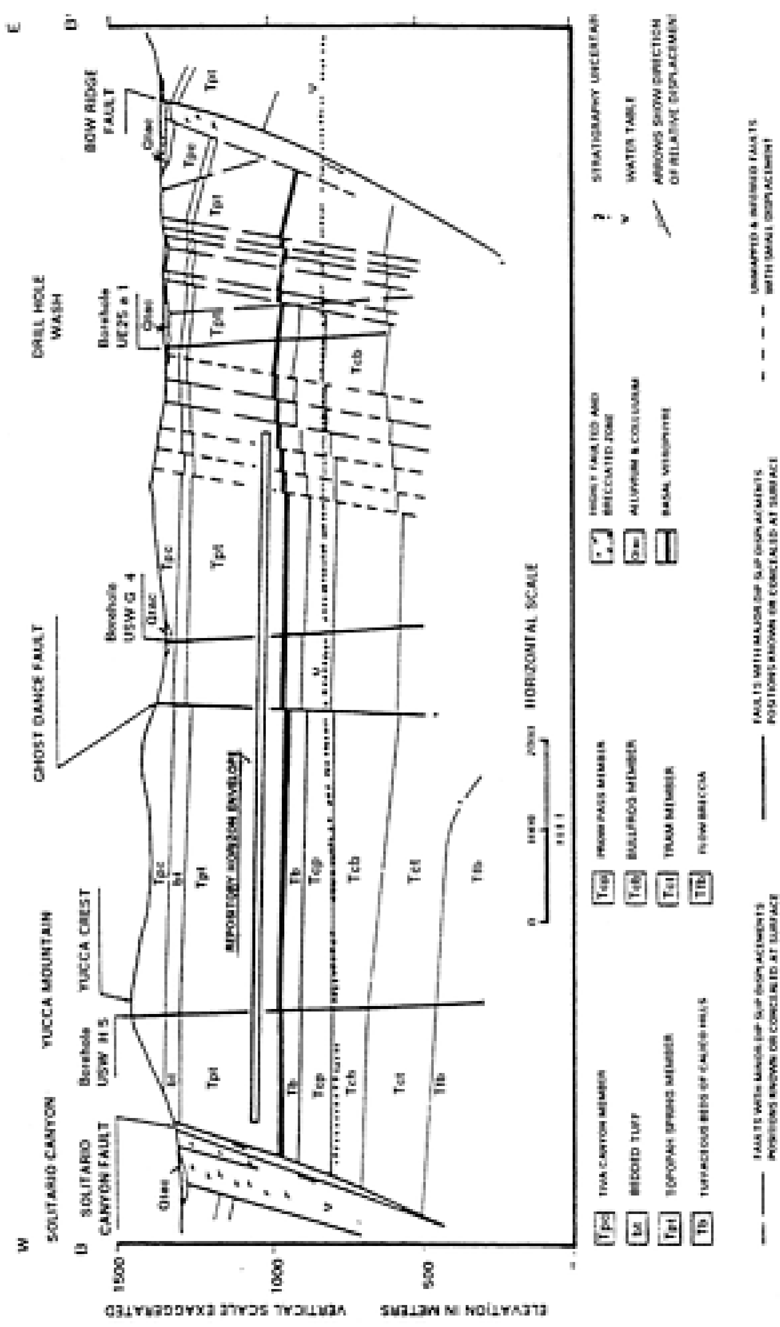

Figure 2.7
East-west cross-section through Yucca Mountain showing the tuff units and location of the proposed MGDS relative to the water table (dotted line). (From DOE Site Characterization Plan Overview, 1988).

like fault blocks (Scott, 1990). Although movement on these faults appears to have been mainly synchronous with silicic volcanism in the Miocene, at 14–11.5 Ma, a number of the faults offset Quaternary deposits (Swadley et al., 1984), indicating that extension continued to the more recent past.

Active Tectonics

While rapid extension and major silicic volcanism have ceased in the Yucca Mountain area, both continue to the west in the Death Valley/Owens Valley region, e.g., the Death Valley and Owens Valley faults, and the Long Valley Caldera. At Yucca Mountain and vicinity, Pliocene and Quaternary (5 Ma to the present) basaltic volcanic activity and slow extension appear to have continued. See Chapter 5 of this report for a detailed discussion of, and constraints on, active deformation in the Yucca Mountain region.

EPISODIC GROUND-WATER DISCHARGE THESIS

The thesis that ground water was periodically forced up from depths of hundreds of meters and discharged repeatedly on the surface of the earth near Yucca Mountain has great importance for the long-term capability of the proposed Yucca Mountain repository to isolate radioactive waste. The present level of the water table ranges from about 200–400 m below the design level of the floor of the proposed repository. The repository is designed to be about 400 m below the surface (DOE, 1988).

The chief evidence cited to support the upwelling ground-water thesis (Szymanski, 1989; and pers. comm. 1991) is the presence of surficial calcite deposits and calcite-cemented breccias related to faults in the vicinity. The calcite deposits occur (1) within the soil in layers parallel with the surface, (2) as stream-bed deposits, (3) as cement around angular fragments of tuff (breccia), or (4) as "veins" (fracture-fillings) in steep to vertical fractures in the ash-flow tuffs that make up most of the bedrock of the Yucca Mountain area. Soil, vein, and breccia deposits are exposed in several trenches excavated across faults to assess the extent of Quaternary fault movement, and in natural exposures in ridges and stream valleys near Yucca Mountain. The thesis proposes that calcium carbonate ($CaCO_3$) brought up by deep ground water was deposited in the fractures, on the ground surface, or between rock fragments broken by the force of the pressurized upflowing water to become calcite-cemented breccias.

As suggested in the introduction to this report, most investigators who have conducted detailed studies of the geology, mineralogy, and geochemistry of the fault-filling materials have concluded that these deposits resulted from surficial and pedogenic (soil-forming) processes, whereby evapotranspiration of rainwater that has infiltrated the soil and bedrock leaves behind an accumulation of calcium carbonate and silica that eventually fills the fractures (Swadley and Hoover, 1983; Taylor and Huckins, 1986; Vaniman et al., 1988; Quade and Cerling, 1990; Stuckless, 1991). Similar processes are evoked for the origin of surface-parallel and stream deposits.

The panel took into consideration the previous work done and the differing views. However, it depended heavily upon its own observations and evaluation of the evidence available to it, and its own and others' modeling, for its deliberations and findings relative to the origin of the carbonate deposits and the likelihood of ground water upwelling hundreds of meters.

The evidence bearing on whether or not the potentiometric (water table) level in the Yucca Mountain region has exceeded the level of the proposed repository at any time during the last 100 ka can be placed into six general categories: (1) soil development and geomorphological character of the region; (2) hydrologic evidence obtained from long-lived and extinct spring systems in the region; (3) morphologic/textural evidence exhibited by chemical precipitates; (4) stratigraphic/textural/mineralogic evidence exhibited by carbonate-cemented breccias; (5) geochemical/mineralogic considerations bearing on the likely conditions of deposition of chemical precipitates; and (6) isotopic evidence for the origin of waters and solutes. In addition, the relative ages of the carbonates with respect to the associated geologic or geomorphic features can provide some measure of the reasonableness of an upwelling ground water origin for these deposits.

In considering the evidence cited in support of upwelling ground water, the panel's approach was to ask a series of questions related to the above categories. Thus, in relation to the field observations, the panel asked what features or characteristics would be expected if the carbonates were derived from soil-forming processes, and what would be expected if the water were of deep crustal origin thermally and/or tectonically driven to the surface. The first question is addressed in the following section. The second is addressed subsequently in the five other categories of evidence.

SOIL DEVELOPMENT AND GEOMORPHOLOGICAL CHARACTER OF THE REGION

Characteristics of soils in various climatic regions are well known, particularly to soil scientists studying processes of soil development. The soils in semi-arid to and regions, like that of the southern Great

Basin, have common characteristics throughout the world that do not depend on a subsurface source of water; many of these regions are far from any tectonic or volcanic activity. The question is, are the soil characteristics and processes of soil carbonate development in the Yucca Mountain area similar to those of other regions with similar climate throughout the world, or is there something unique about the area in question?

Secondary carbonate can accumulate in the soil profile by a variety of pedogenic processes, as described by Machette (1985). These processes include in situ weathering of calcium carbonate from the parent materials and leaching of calcium carbonate from calcareous materials emplaced on the ground surface as airborne dust. The leached calcium carbonate is transferred in solution to a position lower in the soil profile where it precipitates and accumulates at a depth controlled by several interrelated soil properties and the degree of evapotranspiration (McFadden and Tinsley, 1985). Soils enriched in calcium carbonate are associated with semi-arid to and climates and are present throughout the southwestern United State (U.S. Soil Conservation Service, 1990; Machette, 1985). In wetter environments the carbonates remain in solution and are carried out of the soil environment.

The secondary carbonate concentrated by pedogenic processes below the soil surface horizon (A horizon) accumulates in the lower horizons (Bk and K horizons) (see Box 2.1). The A horizons are generally vesicular (i.e., they contain macroscopic spherical voids) in dry climates when associated with the accumulation of airborne dust on the surface (McFadden et al., 1986, 1987). The percentage of carbonate increases with depth in the soil and then decreases with depth still lower in the soil. The thickness of the subsurface soil horizons (e.g., B and K horizons) and the strength of individual soil properties used to describe the soil increases with increasing age of the soil. Beneath progressively older surfaces the carbonates are progressively better developed. A morphological sequence involving progressive stages of development has been established by workers in the southwestern U.S. to describe the systematic changes in the pedogenic carbonates (Gile et al., 1966; Backman and Machette, 1977; Machette, 1985). A similar sequence has also been developed to describe the progressive morphological changes in the pedogenic silica common to the Yucca Mountain area (Taylor, 1986).

The morphological stages in the case of carbonate buildup change from a few filaments and (or) thin discontinuous pebble coatings in stage I to more continuous coatings and soft nodules in stage II. Stages III and higher are represented by massive carbonate accumu

BOX 2.1 SOIL HORIZON NOMENCLATURE

A horizon[1]

This is a soil horizon that has an accumulation of humified Organic matter mixed with a mineral fraction, the mineral fraction being dominant. The horizon typically occurs at the ground surface.

This horizon is considered vesicular when it is characterized by a high volume of spherical pores, giving a sponge-like appearance. The origin of these vesicles in desert environments is often associated with eolian (wind-blown) material being added to the surface (McFadden et al., 1987).

B horizon

This term refers to those horizons which have materials illuviated (transported) into them (from the weathering of minerals higher in the soil sequence (profile) or from materials first deposited as airborne dust) or residual concentrations of materials left by leaching. B horizons, which typically occur beneath the A horizon, show little evidence of the original parent material.

Subdivisions of the B horizon are many, based upon the materials concentrated within the horizon. In arid environments these include:

Bk horizon: the "k" denoting the illuvial accumulation of carbonates.

Bt horizon: the "t" denoting a noticeable accumulation of silicate clay that either formed in place or was illuviated into the B horizon. It therefore has more clay than the overlying horizon or parent material.

Bq horizon: the "q" denoting the accumulation of secondary silica.

Bw horizon: the "w" denoting an increase in color (generally redder) or structure without noticeable accumulation of silicate clay.

K horizon

This is a subsurface horizon so impregnated with carbonate that its morphology is determined by the carbonate (Gile et al., 1965). Authigenic carbonate coats or engulfs nearly all primary grains in a continuous medium. The uppermost part of a strongly developed horizon is laminated, brecciated, and (or) pisolitic (Machette, 1986). The cemented horizon corresponds to some caliches and calcretes.

[1]An horizon in soil terminology is approximately equivalent to a zone or layer, but it lacks sharply defined upper and tower boundaries.

lations and notable cementation. Laminae, pisolites, and brecciation are apparent in the more advanced stages of development.

In the case of silica stages, stage I is represented by thin scale-like coatings on the bottoms of gravel clasts, while stage II has developed 2–4 mm pendants on the bottoms of the clasts. Stages III and IV have silica cementation, with laminae occurring in stage IV. The progression of morphological stages mirror the buildup in the percentage of carbonate and (or) silica in a sequence of progressively older soils. When used in association with increases in other soil properties (clay percent, reddening, thickness of the B horizons, etc.) and an awareness of soil-forming factors, these stages become strong indicators of soil age. When multiple soil properties reflect greater soil ages on geomorphically older surfaces, it is also strong evidence for a pedogenic origin of all properties, including the carbonates. (For excellent regional studies demonstrating these principles see Gile et al. (1966), Sowers (1985), and Machette (1985)). The progressive changes of associated soil horizons would not result from upwelling water.

All of the above features of and climate pedogenesis are present in the Yucca Mountain area. A direct correlation between the relative age of the geomorphic surface and degree of Bk or K horizon development was noted in several localities by the panel. For example, the oldest geomorphic surface observed, in Fortymile Wash (probably 1–2 Ma; Taylor (1986), M. Reheis, pers. comm., 1990) exposed a clay-rich B horizon with a K horizon 1 m thick and a silica-cemented subhorizon. Progressively younger geomorphic surfaces in Fortymile Wash have progressively less pronounced textural and calcic horizons (Taylor, 1986; M. Reheis, pers. comm., 1990). Intermediate-aged surfaces, such as the slopes of Yucca Mountain and Busted Butte, a steep-sided isolated remnant of Tiva Canyon and Topopah Spring tuffs, have calcrete horizons from a few centimeters to fractions of a meter in thickness. The youngest surfaces identified, in the localized contemporary drainages throughout the region, have weakly developed soils, characterized by thin vesicular A horizons and incipient, discontinuous thin laminae of calcrete. A notable example was observed by the panel members on the flanks of the youngest volcano in the area, Lathrop Wells cone, where the cinders are coated on their bottom side with a thin carbonate film derived from windblown silt and carbonate accumulating on the slopes of the volcano. These correlations argue for a pedogenic origin for the calcretes, because thickness of carbonate deposits from upwelling waters would have no consistent relationship to stage of soil development or age of the geomorphic surface.

An important consideration in establishing the validity of the correlation of surface age and carbonate development requires that the area not have been reset to calcrete-free conditions during any prior glacial climatic episode when rainfall was greater in the region. Paleoclimate studies of the region, discussed in some detail in Chapter 3 of this report, demonstrate that regional climatic conditions over the last 100 ka were not wet enough to reset the starting time of pedogenic carbonates formed in the oldest surfaces. The older geomorphic surfaces and related soils have been dated or assigned ages of 100 ka to 1 Ma on the basis of morphology of alluvial fans and terraces along drainage systems, the stage of development of the soils, the degree of development of desert pavement (interlocking surface stones) and rock varnish (dark coating on exposed rock surfaces), and the characteristics of buried soils. For a review of surface age control, see Taylor (1986). Thus, climatic and surface water conditions have been conducive to soil calcrete development for at least several hundred thousand years.

Other well-known pedogenic features of the surface-parallel carbonates commonly observed throughout the area around Yucca Mountain are laminar (finely layered) structure of the carbonate deposits, root casts developed by former plants that filtered the soil water, leaving behind carbonate coatings on the roots, and carbonate nodules, which are spherical or orbicular concentrations formed by the deposition of carbonate in the soil around some "seed" or "kernel" that stimulated deposition.

Because pedogenic carbonate accumulation processes and rates are dependent upon the amount of calcium ion, Ca^{2+}, and calcium carbonate ($CaCO_3$) available to the soil, it is reasonable to ask if these are present in the area. The presence of the Paleozoic limestone at depth, comprising the regional aquifer, is well established for much of the area (Dettinger, 1989) and could provide dissolved carbonate in upwelling ground water. In the Yucca Mountain region, however, considerable surface exposure of this limestone is present in the Spring Mountains, and even nearer Yucca Mountain, in Bare Mountain, on the west side of Crater Flat. Dissolution and reprecipitation of the carbonate from the limestone could occur in surface and near-surface waters. The carbonate coatings of cinders on Lathrop Wells cone, the carbonate-bearing vesicular A horizons on the volcanic ridgetops, and dust-collecting studies being carried out by scientists involved in the Yucca Mountain site characterization project (Marith Reheis, pers. comm.), attest to the presence of calcium carbonate as airborne particles, or as Ca^{2+} dissolved in rainwater. In addition, the stream-bottom carbonate deposits are laminated calcretes which suggest runoff from surface exposures of carbonates, and reprecipitation as gully-bed cementation as described by Lattman (1973) and by Bachman and Machette (1977).

Although proponents of the thesis of rising ground water assume a single source, that of upwelling deep ground water, for the secondary carbonates in the Quaternary of the Yucca Mountain region, multiple origins and ages for the carbonates are discernible. Some examples of the different sources and ages of carbonates of the region are: (1) at Travertine Point along the east flank of Death Valley, 50 km southwest of Yucca Mountain, characteristics of carbonate occurrences to be discussed later in this chapter are typical of shallow veins and spring deposits that form where CO_2-charged waters flow to the earth's surface from depths in excess of 1–2 km where the water attains high partial pressure of CO_2 greatly in excess of atmospheric pressure; (2) at a site about 14 km southwest of Yucca Mountain, known as Site 199, a spring mound provides evidence of a ground-water source that may still be active; (3) near the southern end of Yucca Mountain, carbonate-filled fractures in the Tertiary tuffs are truncated by the overlying Tiva Canyon tuff, verifying that the carbonates formed before the Tiva Canyon tuff was deposited, most likely during the cooling of the volcanic ash that became the tuffs about 13 Ma; and (4) in locations near Busted Butte, in a faulted valley at the southern end of Yucca Mountain informally known as Harper Valley, and on Old Stagecoach Road, stream-bottom carbonates are restricted to the modern topographic drainages and therefore indicate localized cementation from evapotranspiration of calcium-enriched surface waters (see, e.g., Machette, 1985).

One significant example will serve to demonstrate the contradictions that arise from the assumption of a single source for all secondary carbonate deposits in the area. The faulted tuff remnant, Busted Butte, contains numerous calcite deposits that have been cited as evidence for upwelling water. The Butte is flanked by gently sloping sand-ramp aprons. The sand ramps are built of windblown sand deposited on layers of cobbles swept down from the steep upper slopes by gravity and surface water runoff. Some sand ramps began depositing shortly before 740 ka, as determined by identification near the base of those ramps of an ash bed from a very well-dated and widespread volcanic ash, called the Bishop ash. Calcite deposits are exposed in the walls of gullies that cut into the sand ramps. The deposits are calcite-cemented cobbles and sand that spread laterally and parallel the present-day gently inclined ground surface. Some of the carbonate deposits are 0.5–1.0 m thick and, downslope, bend and merge into steep calcite deposits that fill vertical fractures in the underlying sand ramps. Similar slope-parallel deposits downslope of the vertical fracture-fillings are thinner than those above the fracture, and also appear to merge with the vertical carbonate deposits. These vertical deposits merging both upslope and downslope into slope-parallel carbonates were cited as evidence that ground water upwelling along faults precipitated the calcium carbonate in the fault and spread out on the surface to form the slope-parallel deposits. Such interpretation of the carbonate occurrences leads to two important inconsistencies: (1) the thick surface-parallel deposits upslope from the fault require that water flow uphill continuously and in greater quantity than downslope to produce the observed deposit; and (2) both gently sloping and vertical calcite deposits contain delicately calcified roots of plants wrapped around cobbles of volcanic rocks. The latter observation combined with an integrated soil profile encompassing the Bk/K horizons constitutes evidence that the surface-parallel calcite cements formed in the root zone of soil horizons, not on the ground surface.

In response to the observation by panel members of increasing carbonate thickness upslope of the fracture, proponents of the upwelling ground water origin for the carbonate deposits suggested that a fault at higher elevation than that observed was probably the source of the upwelling water. Panel members examined heads of gullies for carbonate-filled fractures or faults at higher elevations on the Butte that could have acted as upwelling ground water sources for the thicker upslope, surface-parallel calcite cements, but none were found.

To the panel's knowledge, the roots, which calcified progressively through time with the soil carbonate buildup, have not been assigned to any plant species. Although the possibility exists that they could have been wet-ground plants, it appears unlikely, given the evidence discussed above.

The foregoing observations, which form the basis of the panel's conclusions with regard to the first category of evidence, soils and geomorphology, can be summarized as follows: consistent well-established arid soil characteristics of the soil (A/Bk/K horizons) and vein carbonate, field relations indicating a correlation between age of the geomorphic surfaces and the degree of soil carbonate development, strong evidence for the presence of airborne carbonate, and the physical inconsistencies in attributing an upwelling ground water source for the slope-parallel and vein carbonate. The panel concludes from these findings that (1) the soil and vein carbonates formed from normal arid climate soil-forming processes; and (2) no field evidence observed supports the thesis of cyclical or

periodic outpouring of ground water onto the surface[1]. Although both currently active springs and ancient spring deposits occur in the area, as will be shown later in this chapter, their characteristics and ages suggest differing origins, none of which require a deep ground-water source.

HYDROLOGIC EVIDENCE FROM SPRINGS

Springs are locations where ground water emerges spontaneously onto the surface as the result of some unique circumstance of the geology of the site. There are many different circumstances that can result in a spring, and the cause of any one spring may not be immediately apparent. Warm water springs may result from deep-seated ground water rising rapidly to the surface; hot water springs often arise from near a deep volcanic source that heated the water; cold water springs suggest shallow ground water. But there may be other explanations for the variations in water temperature.

Although cold, warm, and hot springs each have unique features, they have some common attributes. Among these are chemically rich water and the buildup of a mound and/or stratiform tufas on the surface. Cold spring mounds form from the accumulation of air-borne silt. The more relevant process that is addressed here is the formation of warm or hot spring mounds. The mounds of these springs derive from the precipitates left by evaporation or loss of CO_2 from the spring water, especially in dry climates or where chemical conditions are favorable, and from the buildup of wind-blown dust trapped by dense vegetation growing on moist soils. Often the mound is composed of a porous calcium carbonate (travertine or tufa) where water flows to the surface from a relatively shallow source region (<100°–120°C). However, mounds of other chemical precipitates are known as well, such as silica (SiO_2) where water flows to the surface from a relatively hot source region (>170°C), and gypsum ($CaSO_4 \cdot 2H_2O$).

Devils Hole

Reconnaissance studies of variations in the level of the water table throughout the Quaternary in the Ash Meadows area, 40 km south-southeast (SSE) of Yucca Mountain (see Figure 3.1 in Chapter 3 of this report), found no indications of large rises in the water table

[1] In this report, the panel's conclusions and recommendations are in bold type.

(Winograd and Szabo, 1988), even though the entire region is tectonically active. Winograd and Szabo (1988) synthesized regional hydrologic, tectonic, and paleoclimatologic information, including ages of vein calcite, travertine, and other features indicative of paleo-ground water discharge. They concluded that a progressive and absolute lowering of the potentiometric surface (water table) is likely to have occurred throughout the south central Great Basin during the Quaternary.

At Ash Meadows, in an underground cavern called Devils Hole, the present water table is 16 m below the surface. Uranium-series dating of calcite deposited on the walls of this cavern by ground water shows that the elevation of the water table has not been greater than 9 m above the present water table in the last 45 ka (Winograd and Szabo, 1991). Other evidence suggests that the water table has been below the land surface at Devils Hole for hundreds of thousands of years (Winograd and Szabo, 1991). This conclusion is supported by the absence of a tufa mound or a stratiform (layered) tufa at Devils Hole.

Inasmuch as the Devils Hole area is within the same tectonic province as Yucca Mountain, the Basin and Range, and, moreover, has a rate of extension two to three times that of the Yucca Mountain area, it is reasonable to expect that if earthquakes have caused the ground water to rise hundreds of meters at Yucca Mountain, similar events would have occurred in the Devils Hole/Ash Meadows area. Yet at Devils Hole where the water table is only 16 m below the surface, and where there have no doubt been earthquakes over the hundreds of thousands of years of the cavern's existence, no evidence of episodic large and protracted upwellings of ground waters is present.

There are, indeed, small, short-lived, surging changes in the water level in Devils Hole in response to earthquakes. Instruments installed in Devils Hole continuously record water levels, but sudden upward surges greater than 0.15 m cannot be measured with this equipment because the cable extending from a float to the recorder is knocked off its pulley. However, approximate limits to the amount of upward surge of water can be determined by observing the locations of algal mat material that rises with the water and is left stranded on the rock wall when the wave recedes. A few days after the 1989 magnitude 7.1 Loma Prieta earthquake, centered about 500 km to the northwest of Devils Hole, observers in Devils Hole concluded that the upward surge of water in response to that earthquake reached a height of at least 0.6 m above the normal water level, based on the elevation of algal mat material above the water table, stuck to the rock and to the staff gage. At the time of the observations the staff gage indicated that the pool surface was back to its pre-earthquake level. Apparently there had been a very short-lived fluctuation, or upward and downward surge, in the water table with a total amplitude of at least 1.2 m (A. C. Riggs, pers. comm., 1992).

Wahmonie Spring

About 20 km east of Yucca Mountain a locale called Wahmonie Spring has been cited as evidence of recent ground-water upwelling. The Wahmonie site is a barren outcrop of white to buff gypsum-bearing ($CaSO_4 \cdot 2H_2O$) sediments interpreted by proponents of the upwelling ground water thesis as a young spring deposit 1000 years old or younger. The sulfate-rich composition of this deposit was ascribed to deep seated ground water rising along a nearby, unnamed fault. The lack of plants growing on the gypsiferous soils of the Wahmonie outcrop was cited as evidence of youthful age of this deposit.

The Age of the Wahmonie Site

In the panel's view, absence of vegetation on this outcrop is not an indication of the relative youth of the deposit. It is more likely a function of soil conditions. Although there is little in the published literature on the plant community composition of gypsiferous soils, it is widely known that gypsum substrates support few plant species and these possess adaptations to gypsum soils. The absence of plants on the Wahmonie outcrop most likely results from the lack of plant species adapted to gypsiferous soils in this part of the southern Great Basin (see, e.g., Beatley, 1976), rather than from youth of the deposit and insufficient time for plant communities to develop since its desiccation.

A more direct line of evidence relating to the age of spring deposits is material evidence of early human activity. In this desert region springs have been the locus of intense prehistoric and historic human activity. The persistent presence of Native American populations at such localities is easily noted by extensive scatters of chipped rock materials found at many presently active and extinct spring mounds in the Las Vegas Valley and the Yucca Mountain region. At the Wahmonie locality, however, no prehistoric artifacts have been found at the outcrop. Moreover, no historic Euro-American artifacts, such as tin cans or bottle glass, that would, as a matter of course, be present if there has been effluent water source present over the last century or so.

Two lines of evidence suggest that the Wahmonie deposit is of great age:

(1) The apparent total absence of elemental carbon residues of plant matter in the deposit. Late Wisconsin- and Early Holocene-age spring sediments in the Las Vegas Valley typically display two types of elemental carbon, disseminated gray to dark-gray lenses resulting from organic mats incorporated into the sediments, and charcoal resulting from the deposition of carbonized wood from the time that springs were active (see, e.g., Haynes, 1967). Neither of these is evident in the profiles of the Wahmonie deposit.
(2) Field relations suggesting that the gypsum-bearing spring deposit, on the down-dropped side of a fault, is being exhumed by headward erosion of an adjacent wash. The gypsum deposit, exposed as a relatively narrow band about 10–20 m in length and less than 3 m wide, appears to underlie a fan surface with a soil profile that panel members estimate required 10–100 ka of stability to develop. Erosion parallel with the fault and headward erosion on the fan surface have apparently removed the younger fan sediments overlying the gypsum deposit.

The weight of evidence appears to indicate that the Wahmonie outcrop is probably much greater than 11 ka in age (the widely accepted minimum age for the introduction of humans into North America). The apparent burial of the deposit and subsequent exhumation from beneath a surface judged by panel observers to be possibly as old as 100 ka strongly supports this conclusion.

Moreover, the significance of this site as evidence for deep-seated ground-water upwelling was based in part on the gypsiferous composition of the deposit on the assumption that the sulfur must have had a deep source. However, the panel noted that in the hills above this locale were abandoned mines and test pits into sulfide mineral deposits, the origin of which is very likely related to the early volcanic activity of the region more than 1 Ma. Thus, the likelihood that the sulfate-bearing surface deposit resulting from surface or near-surface runoff of meteoric (rain) water flowing through the sulfide mineral deposits is at least as credible as upwelling deep ground water, or more so, as the following discussion of Cane Spring will suggest.

Cane Spring

Cane Spring, located near the northeast end of Skull Mountain, about 20 km southeast of Yucca Mountain, was cited as a very recent upwelling, having broken through to the surface and wetted that area within the last century or two. Cane Spring is an active spring site; a large mound (ca. 40 m by 20 m) of gray to dark-gray organic-rich soils supports, among other species, cottonwood (*Populus fremontii*), willow (*Salix goodingii*), and cattails (*Typha domingensis*) rooted in perennially wet soils around an active discharge orifice with running water in evidence. The discharge of Cane Spring, however, is miniscule, on the order of 0.04±0.015 liters/sec (Lyles et al., 1990). Similar springs are symmetrically located on the southeast flank of the mountain. These springs occur near the break in slope between the steeper fractured rocky mountain and the gentler sloping fan.

The extensive buildup of organic-rich silts on this spring mound, the massive size of the trees at this locality, and the extensive development of vegetation mats attest to a long history for Cane Spring. Moreover, the occurrence around the spring of abundant prehistoric artifacts such as secondary and tertiary reduction flakes from tool-making, ground stone, and fire-cracked rocks strongly suggests that this locality has been the focus of prehistoric activities for millennia.

The source of water for this spring is uncertain. Although it lies close to a north-south fault, four factors call into question a deep-seated origin for the spring. The first factor relates to the location of several active springs like Cane Spring that occur in the area, north of Yucca Mountain. Nearly all of those currently known are located, as Cane Spring and its southeastern counterpart on Skull Mountain are, at or near the base of the rocky slopes. Secondly, the spring waters flow out at ambient temperatures, or those of the surrounding environment, not warm or hot as would be expected of water from a deep-seated origin. The third factor is the observation made by Yucca Mountain Project field investigators that Cane Spring increases in activity and flow immediately after a rainfall. The fourth factor, as discussed later in this chapter, is the oxygen and hydrogen isotope analysis of Cane Spring waters, which shows them to be similar in isotopic content to local rainwater, although enriched in both the hydrogen isotope deuterium (D) and ^{18}O in relation to ground water by evaporation (see Figure 2.8). Taken together, these factors support the conclusion that the active spring source is the infiltration of meteoric water in the adjacent mountain mass and its subsequent emergence through rock fractures at the base.

MORPHOLOGIC/TEXTURAL EVIDENCE EXHIBITED BY CHEMICAL PRECIPITATES

Where warm waters containing carbon dioxide (CO_2) gas flow upward from deep-seated reservoirs a few kilometers down in the crust and discharge at the earth's surface, steep-sided mounds, ridges, and terraces of travertine with flat to rounded tops typically form. Well-known examples of this occur at Mammoth in Yellowstone National Park (Bargar, 1978), Big Horn hot springs at Thermopolis, Wyoming (Burk, 1952), and near Bridgeport, California (Waring, 1915). The travertine in these deposits is composed of thin layers, or bands, of relatively coarse-grained (2–3 mm) calcite. Larger mineral grains are typical of higher temperature deposits.

If, as has been suggested, deep ground water has risen repeatedly and has discharged onto the surface in the Yucca Mountain area, then spring mounds should be widespread and common occurrences. However, no such surficial travertine mounds, ridges, or terraces typical of vigorous warm spring activity have been found in the immediate Yucca Mountain region. Nor have any mounds been identified of siliceous sinter, which precipitates from silica-rich water that has been in contact with very hot rock below the surface. Low-lying mounds of fine-grained calcite (calcium carbonate) may form where relatively calcium-rich waters containing CO_2 gas slowly discharge at the earth's surface and evaporate, a process that is occurring presently at Tecopa, California, near Death Valley. However, even at Tecopa, coarse-grained calcite (probably deposited from CO_2-rich water rapidly flowing over the mound) can be found interlayered with fine-grained calcite, which is usually deposited mainly by evaporation of relatively stagnant water.

At Travertine Point, on the east flank of Death Valley, carbonate veins are well exposed that extend downward beneath tufa, or travertine, mounds through coarse pebble- and cobble-bearing rock layers known as fanglomerates. Interlayered bands of amorphous or non-crystalline silica, opal, and chalcedony are absent. These carbonate veins are relatively coarse-grained (greater than 6 mm and up to 1 cm) and exhibit a marked mirror-image symmetry, expressed by textural and color variations in alternating bands of calcite that deposited simultaneously on opposing walls of water-filled open fractures. A similar grain-size distribution and symmetry is exhibited by the veins over the approximately 60 m of vertical extent of the exposure, up to just below mounds of travertine that formed on the ancient ground surface where the fluid discharged to the atmosphere. The size of the carbonate grains within the travertine mounds at the surface varies from very small to large, as can be expected in an environment where depositional conditions vary drastically and repetitively in short periods of time. Inorganic processes of deposition of calcite are likely to be dominant in close proximity to spring orifices where waters are energetically degassing, while organic processes play an increasing role further away (Chafetz and Folk, 1984). Very fine-grained accumulations of travertine form where evaporation of water occurs in surface pools.

The features described above are characteristic of deposits that form where water no hotter than about 150°C rises through fractures in the crust, i.e. very coarse-grained carbonate minerals, distinctive symmetrical banding, and no interlayered bands of amorphous silica, opal, or chalcedony. In contrast, cool surface water precipitates carbonate, silica, and other dissolved constituents by evaporation. If the evaporating water flows down the sloping wall of an open fracture not completely filled with water, there will be no symmetrical banding and minerals will be either extremely fine-grained, or, as in the case of silica precipitates, non-crystalline.

It is well known that travertine deposits become porous and much more fine-grained where water flows over the ground (or tufa mound) laterally away from spring orifices (Allen and Day, 1935; Chafetz and Folk, 1984). Also, the size of carbonate crystals deposited from discharging spring waters becomes smaller as the rate of deposition increases (Allen and Day, 1935). Archambeau and Price (1991) suggest that the very fine grain size of the calcite found in fracture fillings in the Yucca Mountain region is the result of very rapid deposition of calcite where CO_2-rich waters rapidly degas. However, at Mammoth Terrace in Yellowstone National Park, where deposition of travertine occurs at a very rapid rate from highly CO_2-charged water, individual carbonate crystals are large enough to be identified with a hand lens in the most fine-grained materials sampled from feeder veins. In contrast, the fracture-filling material in the Yucca Mountain region is so fine-grained that individual carbonate crystals cannot be identified with a hand lens.

There are even more compelling morphological reasons to conclude that the extremely fine-grained nature of the carbonate fracture-fillings at Yucca Mountain is not the result of very rapid deposition from ascending water. Rapid deposition requires rapid degassing, and this, in turn, requires a rapid rate of upflow. Where rapid rates of upflow are observed in presently active spring systems that are depositing travertine, invariably deposits of travertine rapidly build up above the ground surface. The travertine forms four types of deposits where lakes are not present: (1) waterfall or cascade; (2) sloping mound, fan, or cone; (3) terraced mound; and (4) fissure ridge (Chafetz and Folk, 1984). Certainly some of these morphologic forms would be found somewhere in the Yucca Mountain region if CO_2-charged carbonate-depositing fluids had been discharged onto the surface. In extensive examination of hot spring deposits throughout the world, a panel member and colleagues have never yet found a carbonate-depositing spring that did not produce a mound of travertine that rises above the ground surface. Nowhere, to the panel's knowledge, have carbonate deposits from outflowing spring water resulted in the morphologies and textures exhibited by the calcretes observed on the land surfaces at Yucca Mountain.

Symmetrical banding on opposing walls of the faults, resulting from simultaneous crystallization of carbonate on the walls of a fracture completely filled with upwelling water, is absent from the carbonate deposits observed in shallow trenches in the Yucca Mountain region, particularly Trench 14. The absence of symmetry implies deposition of carbonate on the fault wall down which water flowed and evaporated. The vein calcite is generally extremely fine-grained, less than 6 microns (μm), or about one thousandth (10^{-3}) the size of the calcite grains in the veins at Travertine Point, and contains thin interlayered bands of silica. The silica bands contain low temperature opal (opal CT), minor amounts of clay and other minerals, and materials commonly found in desert soils, including sand grains and volcanic ash (Vaniman et al., 1988). All of the thicker bands (up to about 2 cm) of hard "silica" from this environment that the panel examined in the field were composed of angular and rounded sand grains, material derived from soil and surface sediments, cemented by silica.

Finally, if the calcite atop Yucca Mountain formed from ascending thermal waters, dense calcite veins like those at Travertine Point should be present on the scarp slope of Yucca Mountain, but they are not. The densely welded tuffs comprising this scarp are highly fractured and would have served as ideal conduits for the hot ascending fluids.

The panel concludes, therefore, that the physical and textural evidence from the trenches in the Yucca Mountain vicinity supports a sedimentary, low-temperature origin from descending rainwater for the calcite veins, rather than one involving upwelling of thermal water from deep in the crust.

The one spring deposit exposed about 14 km southwest of Yucca Mountain, at a locale designated Site 199, is typical of marsh or seep deposits in which carbonate deposition is mainly the result of plant activity and evaporation of ground water at the earth's surface rather than the result of loss of CO_2 from upflowing water (see Box 2.2). The current persistent growth of saltgrass (*Distichlis spicata*) in the immediate area suggests that surface water is present, and may imply a "perched" water table, a reservoir of ground water maintained above the local water table because of some characteristic of the rock strata. Saltgrass occurs only in the vicinity of springs and seeps. If this is the case, the formation of the tufa found here does not require a former higher level of the regional water table.

The alternative conjecture that fracture flow of ground water at Site 199 has brought water 100 m up from the water table some

time in the past should be examined. Drilling and tests in a shallow hole of approximately 100 m could simply and conclusively discriminate between the alternate hypotheses.

BOX 2.2 CONDITIONS OF CHEMICAL PRECIPITATION FROM THERMAL WATERS

The solubility of calcium carbonate increases with decreasing temperature of the water in which it is dissolved when the partial pressure of CO_2 is constant or increasing. Therefore, where banded calcite veins have deposited underground from upwelling waters, the carbonates have precipitated as a result of the onset of calcium carbonate supersaturation caused by a decrease in partial pressure of CO_2 along the flow path. The major mechanism by which the partial pressure of CO_2 decreases during upflow is the separation of dissolved gas into bubbles that form and expand during upflow as the hydrostatic head, or water pressure, decreases For upflowing water with an initial temperature of less than 100° C, bubbles will form if the sum of the initial partial pressures of all the dissolved gases is significantly greater than 1 atm (15 pounds per square inch (psi)).

It is possible that some calcite may deposit underground from upwelling water without the partial pressure of CO_2 exceeding 1 atm. This can happen as a result of chemical reactions between the liquid and the surrounding rock that remove hydrogen ions from solution (thus raising the pH), by the alteration of initially anhydrous silicate minerals and glass to clay minerals, while at the same time increasing the concentrations of dissolved cations in the liquid, particularly calcium (Ca^{2+}) and sodium (Na^+). However, in this event relatively coarse-grained crystals of calcite are likely to form because the rate of their growth would be slow. Moreover, the rate of carbonate deposition will markedly decline or come to a stop when alteration products coat the vein walls and inhibit continued reaction of the fluid with still unaltered portions of the wall rock.

Also, where upwelling thermal waters flow through silicic tuffs, like those at Yucca Mountain, much more sodium than calcium is likely to be liberated where wait rocks are converted to clay minerals by acid attack. This is not a favorable environment for the underground deposition of calcite from upflowing and cooling water in which there is no physical separation of a CO_2-rich gas phase.

EVIDENCE EXHIBITED BY BRECCIAS

The widespread occurrence of "mosaic" breccias at Yucca Mountain and Busted Butte has been viewed as supporting evidence for upwelling of pressurized ground water (G. Frazier, pers. comm., 1990). Consisting of angular fragments of the local bedrock embedded in a matrix composed mainly of opaline silica and calcite, these rocks are interpreted to be either "explosive breccias" that formed as a result of large and fast buildups and releases of fluid pressure, or "fragmentation breccias" that formed by rapid downslope sliding of bedrock with simultaneous filling of spaces between rock fragments by minerals precipitated from upwelling deep-seated fluids (Szymanski, written communication, 1991).

As with the carbonate deposits, the panel observed a variety of breccia types originating from a variety of processes at many different times during the long and complex geologic history of this region. It is likely that there are more breccia types than the panel observed and describes here.

Levy and Naeser (in press) studied bedrock breccias along fault zones near Yucca Mountain and subdivided them into two types, primarily on the basis of rock composition: (1) crushed-tuff-matrix (CTM) breccias that contain tuff clasts (fragments) in a matrix of finely crushed tuff, with or without secondary-mineral cementation; and (2) authigenic-mineral-cemented (AMC) breccias that contain tuff clasts, large amounts of cement composed of minerals precipitated out of solutions (authigenic minerals) around the clasts, and very little fine-grained crushed-tuff matrix material. CTM breccias are composed entirely of tuff and contain no plant remains or non-tuff material, whereas AMC breccias contain abundant carbonate casts of plant roots and some exotic clasts (fragments of rocks that are different from the local welded tuffs).

On the basis of textural and mineralogic evidence, Levy and Naeser (in press) concluded that at least some, if not all, of the CTM breccia formed during cooling of the bedrock tuffs as part of the volcanic process of formation from 13–10 Ma, while the tuffs were still at least partly glassy. The panel believes that this was the case at Harper Valley, at the southern end of Yucca Mountain, where, as described earlier, Tiva Canyon caprock truncates carbonate veins in the underlying tuffs. However, AMC breccias probably formed by varying combinations of surface erosion and deposition (including contributions from eolian particles) and recent near-surface fault movement (Levy and Naeser, in press). These authors also attributed nearly ubiquitous alteration of the rock in the lower part of the Topopah Spring tuff to downward percolation of rainwater along fractures in a still-warm volcanic ash deposit.

The panel observed four types of breccias at Yucca Mountain and Busted Butte distinguished on the basis of their structure or structur al association: (1) cemented talus fragments; (2) cemented fault breccias; (3) cemented angular to slightly rounded rock fragments in irregular vertical pipe-like structures; and (4) "jigsaw" breccias consisting of fragments of tuff that have been broken and moved apart up to several millimeters, often with little or no subsequent rotation of the fragments. None of these can be attributed unequivocally to upwelling pressurized ground water; on the contrary, evidence strongly supports a surface process origin for some.

The cemented talus deposits (breccia type 1) typically are exposed in the floors and walls of steep-sided gullies, commonly along traces of faults. The talus fragments at the base of these gully walls have been cemented by carbonate. Casts of roots and twigs generally are found from the base to the top of the carbonate-cemented talus, suggesting that the carbonate cementation progressed simultaneously with accumulation of the deposit. This progressive and simultaneous development would be possible only if the carbonate has been deposited from locally derived meteoric water flowing intermittently in the stream channels for a long period of time, i.e. thousands of years. Apparently this water dissolved carbonate upslope, and redeposited it in the stream channel downslope as a result of evaporation. Contemporaneous downslope movement of talus blocks and deposition of carbonate where water evaporates can account for the apparent carbonate matrix support of many of the clasts. Carbonate deposition on the undersides of otherwise still unconsolidated talus blocks indicates that this process continues to the present. **The panel concludes that the carbonate talus breccia cement was deposited by evaporating rain water progressively and simultaneously with accumulation of the talus deposit.**

The carbonate that cements near-surface fault breccia (breccia type 2) has all of the attributes of carbonate that forms by evaporation of surface waters; it is very fine-grained (generally in the micron (μm) range), lacks concentric banding, and, as will be shown later in this chapter, is isotopically similar to pedogenic carbonates. Fission-track dating of eroded fragments of (or detrital) zircons found in carbonate that cements AMC-type fault breccia at Trench 14 and at Busted Butte gives a spread of ages showing heterogeneity of source material, with some zircon ages older and some younger than the age of the bedrock in the immediate region (Levy and Naeser, in press). However, within the analytical uncertainty, most of the ages are about 10–12 Ma, or about the same as those of the dominant volcanic rocks in the region. The ages derived for the matrix carbonates are an order of magnitude less, ranging from 40–550 ka (Swadley et al., 1984; Rosholt et al., 1985; Muhs et al., 1990). **The panel concludes that the fault breccia cement**

at Trench 14 and Busted Butte is of pedogenic or surficial origin, based on the presence of older detrital zircons, grain size and structural characteristics, and is not of hydrothermal origin.

Several examples of cemented angular to slightly rounded rock fragments in irregular vertical pipe-like structures (breccia type 3) a few centimeters to several tens of centimeters in diameter are exposed in the walls of Harper Valley at the south end of Yucca Mountain. They occur in unwelded upper parts of the Topopah Springs tuff, and in unwelded to partly welded lower parts of the overlying Tiva Canyon tuff. Panel members were unable to find any similar pipe-like breccias in the immediately overlying lowermost welded and columnar-jointed part of the Tiva Canyon tuff, even though these small breccia pipes are common in the rocks beneath it. These types of cemented breccia deposits are common in ash-flow tuffs and are generally thought to be fossil fumarole pipes that form where the strong upward discharge of steam winnows fine-grained rock fragments upward, leaving the coarser fragments behind. The steam may be derived from degassing of the hot tuff, from boiling of infiltrating rain water, or from evaporation of water trapped under the tuff at the time the tuff is deposited. Steam-rock interaction causes the rock fragments in the pipes to adhere to each other. The absence of the pipe-breccias in the Tiva Canyon tuff despite their presence in the older tuffs below supports a volcanic origin for these breccias during the formation of the lower tuffs from 13–10 Ma.

As a modern analog, silicification of rock fragments by interaction with fumarolic steam in irregular pipes occurred quickly in the tuff sheet at the Valley of Ten Thousand Smokes, Alaska, after the 1912 Katmai eruption (T. E. Keith, pers. comm., 1991).

The panel concludes that the most likely origin of these small, irregular breccia bodies was the channeling of steam and other gas that escaped during the initial cooling of the tuff, before emplacement of the Tiva Canyon welded tuff 10 Ma.

A high degree of hydrothermal alteration, oxidation, and evidence for fumarolic activity (pipe structures and fossil "frying pan" deposits that form as a result of steam bubbling through perched lenses of water) was observed by the panel in the unwelded upper part of the Topopah Springs tuff and lower part of the Tiva. Canyon tuff. These were generally absent in and above the lowermost welded zone in the Tiva Canyon tuff. The evidence is strong that the ground-water table was relatively high at the start of deposition of the Tiva Canyon tuff or that a lot of rain fell onto the still hot and highly porous basal tuff units during their accumulation between 13 and 10 Ma.

Type 4 "jigsaw" breccias were observed in a few exposures, in cluding in Harper Valley. However, one of the best exposures is at a hydrologic monitoring well, WT-7, on a low ridge west of Yucca Mountain, bordering the west side of Solitario Canyon. This exposure is interpreted by proponents of the upwelling water thesis as an "explosion breccia" in which pressurized high temperature fluids forced their way through the crust, breaking up the rocks with explosive energy (G. Frazier, written comm., 1990). In the two-dimensional view provided at the outcrop, some of the fragments appear to be entirely "floating" in the carbonate-silica matrix material. However, many breccia fragments were touching other fragments, so matrix support (or "floating") may be an illusion created by an inability to view the third dimension.

The age of the brecciation and cementation at this locality is poorly constrained, and might range from Late Miocene to Late Quaternary (Szymanski, 1989). The panel, however, believes that a Late Miocene age, contemporaneous with deposition of the ash-flow host rock, is most likely.

This view is based on two related observations: (1) thin coatings of silica (probably initially amorphous judging from the texture) were generally deposited on breccia fragments *before* the calcite deposition; and (2) some brecciation in the same general area occurred while unaltered glass was still present in the tuff (Levy and Naeser, in press). These two observations can best be explained by a genetic model that requires nearly contemporaneous deposition and brecciation. It is well known that heating of water while it is in contact with glassy tuff produces a much higher concentration of dissolved silica in solution at a given temperature than would be the case if crystalline quartz were the source of dissolved silica (Fournier, 1985a), because the glass is relatively unstable and thus releases the silica upon being heated. The source of heat in this locality would have been continuing or renewed volcanic activity that deposited additional hot ash-flow tuff on partially cooled ash-flow material from an earlier eruption. The later deposition of new hot tuff on slightly older and somewhat cooled tuff caused rapid heating of the underlying rock and of the water contained in fractures in that rock. Expansion of this water could cause the fragmentation, or brecciation, of the tuff. Such a mechanism would explain the early dissolution and deposition of silica on breccia fragments. The later deposition of the carbonate that partly cements the breccia may have occurred long after the initial fragmentation, or brecciation. Later movement along tiny fractures has resulted in deformation of some calcite matrix material at this locality.

The panel concludes that there is no need for, or good evidence

in support of, upwelling of deep hot waters to account for the brecciation or silica-carbonate cementation. Indeed, if there were a sudden upwelling of highly pressured ground water, and this, in turn, resulted in hydraulic fracturing and brecciation of near-surface rocks, the first water to reach those rocks would come from the relatively cold top of the ground-water system. Calcite would likely be the first phase to precipitate from this water, followed later by precipitation of silica as hotter water moved to a shallower level. Cool ground waters in siliceous, ash-flow tuff environments commonly contain 25–50 mg/kg dissolved silica, while well over 120 mg/kg dissolved silica would be required to precipitate amorphous silica. Thus, relatively cold ground water does not contain sufficiently high concentrations of dissolved silica to precipitate amorphous silica in the absence of extreme evaporation. Evaporation would not be expected to be an important process where fluid pressures are so high that hydraulic brecciation is occurring as a result of rapid upward propulsion of CO_2-rich fluid. On the other hand, local ground water that is rapidly heated to >150° – 200°C in contact with newly deposited glass-rich tuff is very likely to precipitate amorphous silica upon cooling.

GEOCHEMICAL AND MINERALOGICAL CONSIDERATIONS

The mineral assemblage—calcite, opal CT, and certain clay minerals—found at shallow levels along some faults exposed in trenches near Yucca Mountain is very similar to the mineral assemblage found in surficial deposits, including pedogenic calcretes and caliches, throughout southwestern Nevada (Khoury et al., 1982; Jones, 1983; Vaniman et al., 1988). This supports an origin for the fault deposits in which wind-blown dust accumulates in fractures where it becomes cemented and crusted over by carbonate and silica precipitated from infiltrating and evaporating surface water. Indeed, the total chemical, isotopic, and mineralogic character of the fracture-filling carbonates in the vicinity of Yucca Mountain is similar to carbonate-rich deposits that have been found to form worldwide in soils in the vadose (unsaturated) zone (Quade and Cerling, 1990; Cerling, pers. comm., 1991) under similar climatic conditions.

Another method of ascertaining whether the static water level in the Yucca Mountain region came close to the present land surface within the last several thousand years is to study the distribution of tuffs with zeolite mineralization. It is generally agreed that the secondary formation of zeolites resulting from the alteration of volcanic glass fragments in the tuff requires the presence of abundant water over a long period of time (Levy, 1991, and references therein). Levy studied the distribution of unaltered vitric (glassy) and zeolitized tuffs exposed at the surface and in drill holes in the Yucca Mountain region. The boundary between the altered and vitric tuffs indicated that water reached its highest levels and receded downward from 12.8–11.6 Ma, and that since that time the water level at central Yucca Mountain has probably not risen more than 60 m above its present position.

The panel concludes that the preponderance of geochemical and mineralogical evidence supports the interpretations that the static water level has been close to its present level deep below Yucca Mountain for at least the last 100 ka, and possibly as long as 10 Ma, and that the carbonate-rich fracture fillings exposed in trenches in the region are composed of wind-blown dust cemented by material deposited from evaporating water that had infiltrated unsaturated rock along open fractures.

ISOTOPIC EVIDENCE

Stable Isotopes: ^{13}C and ^{18}O

Advances in geochemical research make it possible to predict the isotopic composition of calcite precipitated from a specified ground water of known isotopic composition. Methods of isotope geochemistry can be applied to the available data on calcite deposits and ground waters of Yucca Mountain to test if these deposits are evidence for episodes of ground-water upwelling and discharge at the Earth's surface. The test consists of calculating the *predicted* isotopic content of calcite that would precipitate from an analyzed ground-water sample with a particular isotopic content. The *predicted* calcite isotopic concentration is then compared to the *measured* isotopic concentration of an actual calcite sample. If the predicted and measured isotope ratios agree, the analyzed calcite could have precipitated from the ground water. If predicted and measured compositions disagree, the calcite sample could not have precipitated from the ground-water sample. This is a direct test of the origin of the water that deposited the calcite deposit, i.e. ground water versus meteoric (rain) water.

The accuracy of the predictions may be evaluated by comparing predicted with measured compositions of calcite known to precipitate from analyzed ground-water. Consider, as a case study, the subaqueous cavern at Devils Hole, Nevada, located 40 km SSE of Yucca Mountain, in which contemporary calcite precipitation has been observed. Calcite vein deposits in the cavern date back to 566 ka. Both ground-water and calcite samples have been analyzed for oxygen, strontium, and uranium isotopes. The results of these analyses are shown in Table 2.1.[2] The Predicted column displays the ratio of the specific isotope expected to be in a calcite crystal precipitating from the Devils Hole ground water with a known isotopic composition. The Measured column shows the actual analyzed ratio of that isotope in calcite from Devils Hole. Comparison of the two columns demonstrates close agreement between predicted and measured isotopic compositions of calcite from ground water of known isotopic composition. The agreement between prediction and measurement justifies confident application of geochemical methods to deduce the origin of Yucca Mountain calcite deposits.

Table 2.1 Comparison of Predicted vs. Measured Isotopic Compositions of Calcite Precipitates at Devils Hole, Nevada

Isotopes	Predicted (±2σ)	Measured (±2σ)
*Oxygen ($\delta^{18}O_{VSMOW}$)	+13.3‰ (±0.3)	+14.0‰ (±0.3)
†Strontium ($^{87}Sr/^{86}Sr$)	0.7123 (±0.00005)	0.7123 to 0.7128
‡Uranium ($^{234}U/^{238}U$)	2.76 (±0.09)	2.70 (±0.07)

* $\delta^{18}O_{VSMOW}$ value of present day water from Winograd and Pearson (1976); measured value of contemporary calcite from Winograd et al. (1988). Predicted value calculated at 33.7°C (temperature of Devils Hole water) with fractionation factor of 26.8 (Friedman and O'Neil, 1977).
† Predicted from analyses of present-day water (Marshall et al., 1990). Measured values are from calcites 100–566 ka (Marshall et al., 1990).
‡ Predicted from water analyses of Winograd et al. (1988). Measured values are from calcites 60–566 ka (Winograd et al., 1988; Ludwig et al., 1990).

Isotopic evidence for the origin of calcite deposits at Yucca Mountain is in strong contrast to that presented for Devils Hole because the isotopic content of calcites predicted to precipitate from Yucca Mountain ground water and measured isotopic concentrations of calcites at Yucca Mountain do not agree. Table 2.2 shows the results of predicted and measured isotopic compositions for calcites at Yucca Mountain and Busted Butte. The discrepancies between predicted and measured calcite isotope compositions are too large to have been caused by chance analytical errors. **The panel concludes that the lack of agreement between predicted and measured compositions**

[2] In Table 2.1, VSMOW of $\delta^{18}O$ is Vienna Standard Mean Ocean Water, the isotope reference standard defined by the International Atomic Energy Agency, Vienna, Austria by which oxygen and hydrogen isotopic concentrations are measured.

demonstrates that the calcites of Yucca Mountain and Busted Butte could not have precipitated from analyzed modern ground waters. Available evidence on $\delta^{18}O_{VSMOW}$ and **δD_{VSMOW}** suggests that ancient ground waters were similar in composition to modern ground waters at least over the past 300 ka (Winograd et al., 1985; Szabo and Kyser, 1990). The existing data, however, are insufficient to support definitive conclusions on the isotopic compositions of paleo-ground waters.

Of the several methods available for analyzing isotopic data, an effective means of examining relationships, similarities, or differences, and trends is by plotting the data graphically. This provides a visual representation for quick comparisons of the isotopic information. The panel obtained isotopic data from several sources, both within the Yucca Mountain project and independent of it. A detailed discussion of the panel's independent analysis of the isotopic data is presented in Appendix A, which is briefly summarized here.

Differences in isotopic composition between regional ground waters, perched spring waters, and vein waters from Yucca Mountain are illustrated in Figure 2.8. The observed covariance of hydrogen and oxygen isotope abundances is controlled by the temperature at which precipitation in clouds occurs and hence by rainfall elevation. Ground water has the lowest D and ^{18}O concentration because it originates from rain and snow falling high in the Spring Mountains

Table 2.2 Comparison of Predicted vs Measured Isotopic Compositions of Calcite Precipitates at Yucca Mountain and Busted Butte, Nevada

Isotopes	Predicted	Measured
*Oxygen δ ($^{18}O_{VSMOW}$)	+12.0 to +14.4 ‰	+18.6 to +22.0‰
†Strontium ($^{87}Sr/^{86}Sr$)	0.7100 to 0.7115	0.7119 to 0.7127
‡Uranium ($^{234}U/^{238}U$)	5.0 to 6.9	<2

* $\delta^{18}O_{VSMOW}$ values of present day water from Benson and McKinley (1985); measured values of calcite (recent to 220 ka) from Whelan and Stuckless (1990) and Quade and Cerling (1990). Predicted value calculated at 33°C, representative of measured temperatures at water table, with fractionation of 26.8 (Friedman and O'Neil, 1977). Water table temperatures near Yucca Mountain range from 28°C to 39°C: for 28°C the predicted $\delta^{18}O_{VSMOW}$ of calcite is +13.0 to +15.4‰ for 39°C, $\delta^{18}O_{VSMOW}$ values are +10.7 to +13.3‰.

† Predicted $^{87}Sr/^{86}Sr$ from ground-water analyses (Marshall et al., 1990). Measured values on calcites of unknown ages (Marshall et al., 1990).

‡ Predicted $^{234}U/^{238}U$ activity ratios from ground water analyses. Measured values from calcites 30 ka to 220 ka (Muhs, pers. comm., 1990; Muhs et al., 1990).

and Pahute Mesa, among the recharge areas for the Ash Meadows-Alkali Flat/ Furnace Creek part of the Death Valley ground-water system, in which Yucca Mountain is located. The low temperatures in the high mountains influence the isotopic content of the ground water. The isotopic composition of the waters from Whiterock Spring, located 45 km NE of Yucca Mountain, indicates a lower elevation than the source of ground water but a higher elevation than Cane Spring. Waters from Cane Spring show a shift in $\delta^{18}O_{VSMOW}$ towards

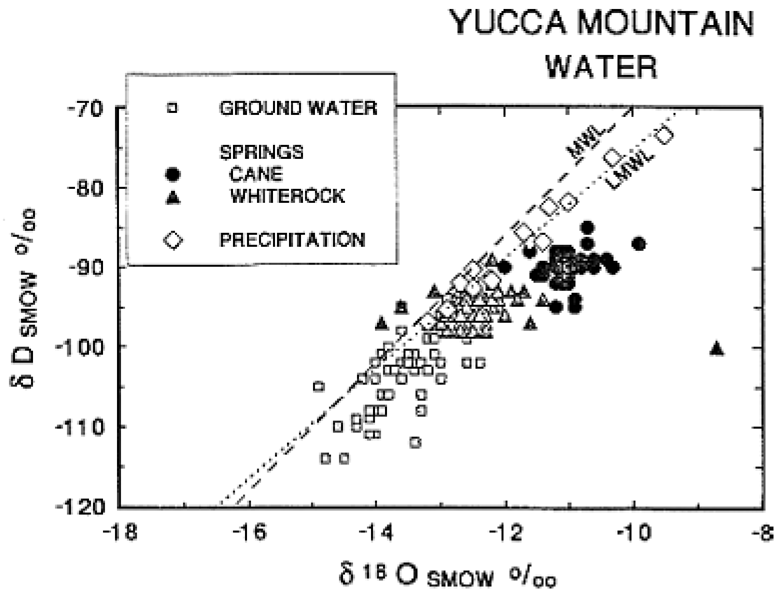

Figure 2.8
Plot of hydrogen vs. oxygen isotopic concentrations of Yucca Mountain ground waters, springs, and precipitation on the Nevada Test Site. The global meteoric water line is labeled "MWL"; the local meteoric water line is "LMWL". The ground-water samples are from the Ash Meadows and regional aquifers of the Alkali Flat/Furnace Creek subdivision of the Death Valley ground water system in which Yucca Mountain is located. Cane Spring flows from a perched water table beneath the east end of Skull Mountain, 30 km east of Yucca Mountain. Whiterock Spring is 45 km northeast of Yucca Mountain. Data and additional discussion in Claasen (1985, 1986); Benson and Klieforth (1989); Benson and McKinley (1985); Benson et al. (1983); Ingraham et al. (1990); and Lyles et al. (1990). Analytical uncertainty is ±0.2‰ for $\delta^{18}O$ and ±2.5‰ for δD. SMOW is Standard Mean Ocean Water, the standard by which oxygen and hydrogen isotopic concentrations are measured.

higher concentrations, indicating local evaporation. Samples with the highest D and ^{18}O abundances are local precipitation (especially summer samples). They reflect the low elevation and a higher average temperature than the waters of the other sources.

A significant graphical plot that brings together several categories of data (Figure 2.9) illustrates the relationship between carbon and oxygen isotopic abundances among calcite of local soils of Yucca Mountain, calcite of Trench 14 and Busted Butte, ground waters at Yucca Mountain, and calcite that would precipitate in isotopic equilibrium from these ground waters. The darker triangles represent the ^{13}C and ^{18}O abundances of the ground water in the Tertiary/Quaternary tuff aquifer of the Alkali Flat/Furnace Creek subsystem. Note that the ^{18}O abundance shows little variation, but the ^{13}C abundances vary over a range of 10‰. This is because ^{18}O content depends mainly on elevation/temperatures of precipitation in the recharge area while the amount of ^{13}C of ground water depends on the extent of exchange with atmospheric CO_2, types of vegetation, soil pH, oxygen pressure, and other localized effects. In Figure 2.9, lighter triangles represent calcites that would precipitate in carbon and oxygen isotopic equilibrium from Yucca Mountain ground water (darker triangles) assuming 25°C. Next, the measured ^{13}C and ^{18}O abundances of the calcites of Trench 14 and Busted Butte are plotted (gray circles). They clearly do not plot as calcites that precipitated from the illustrated ground water. Finally, the isotopic composition of calcite found in the local soils, plotted as diamonds, is distinct from the ground water and predicted calcite composition, but strongly overlaps the Trench 14 and Busted Butte calcite compositions. Note that if a more realistic temperature for ground water is chosen (e.g., 33°C), the $\delta^{18}O_{VSMOW}$ content predicted for calcite shifts approximately 1.0 ‰ to lower abundances, thus increasing the discrepancy between measured and predicted calcite compositions.

The panel concludes, therefore, that the calcites of Trench 14 and Busted Butte formed from the same waters and by the same surface processes as the soil carbonates, and therefore are pedogenic in origin.

Tracer Isotopes: Sr, U, and Th

Analyses of the abundances of the radiogenic isotopes of strontium, uranium, and thorium of the carbonates of Trench 14 and other Yucca Mountain localities (see Appendix A) provide similar results, i.e. the ratios or amounts of these isotopes in the calcites indicate that the calcites could not have precipitated from ascending ground waters of the Yucca Mountain region. Moreover, they show pronounced similarities to the Sr, U, and Th abundances in soil-carbonate compositions.

Subsequent to the panel's detailed analyses of stable and radiogenic isotopes, the panel received some new isotope analyses from the project scientists. The data consisted of analyzed calcites at various depths from drill cores of the area. The elevations of the samples ranged from 600 m above the water table to 1,200 m below. The samples analyzed were secondary calcite from cavities and cements in the tuffs and from vein fillings in fractures.

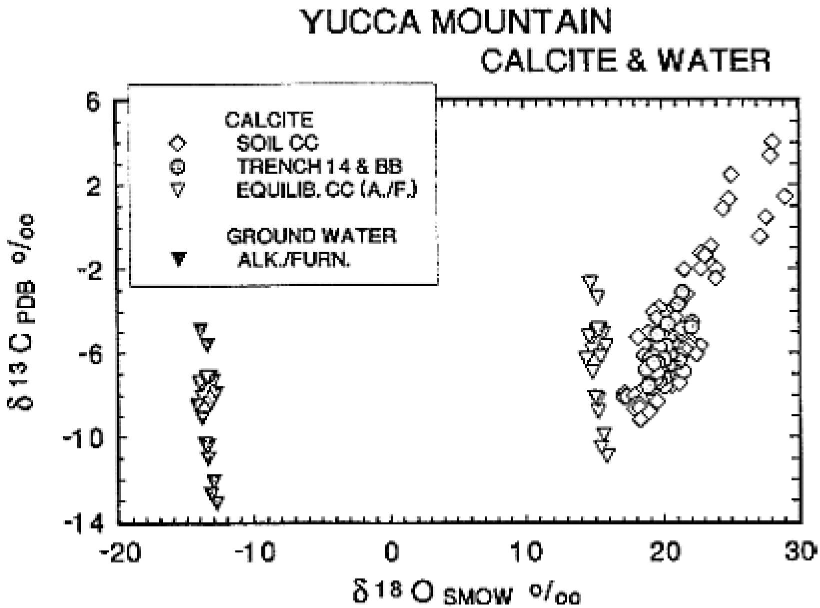

Figure 2.9
Plot of $\delta^{13}C_{PDB}$ vs $\delta^{18}O_{SMOW}$ for ground waters of Alkali Flat/Furnace Creek flow systems, and Yucca Mountain vein calcites and soil calcites. Yucca Mountain calcite data from Whelan and Stuckless (1990), Quade and Cerling (1990), and Quade et al. (1989). The values of calcite in isotopic equilibrium with analyzed ground-waters (equilib. cc) were calculated for 25°C with 1000 $\ell n\ \alpha$ ($^{18}O/^{16}O$) for $CaCO_3 = H_2O = 28.5$ and ($^{13}C/^{12}C$) for HCO_{3-} - $CaCO_3$ = -2.2 (Friedman and O'Neil, 1977). Ground-water analyses from Benson and McKinley (1985). PDB refers to the standard by which the carbon isotopic content of carbonates and water is measured.

The results showed a consistent relationship between the depth of the calcite and the content of ^{18}O and ^{13}C, with $\delta^{18}O$ decreasing and $\delta^{13}C$ increasing with greater depth. Preliminary analyses of strontium isotopic ratios showed a clear distinction in strontium isotopic composition between calcites below the water table and those above. The calcites above the water table showed a narrow range of $^{87}Sr/^{86}Sr$ composition (0.7106 to 0.7128) that overlaps the range of soil calcite and the calcite veins of Trench 14. Samples from 600 m to 1,200 m below the water table had Sr values similar to the low end of the range for waters from the Tertiary/Quaternary aquifers of the Alkali Flat/Furnace Creek ground-water subsystem.

These results lead the panel to conclude that the water table remained relatively stable over the period of time during which and since the secondary calcite was deposited.

It was reported that some inconsistent results were obtained in the ^{13}C abundances from core samples above the water table; they were in the range usually found at depths below the water table. The significance of these "outliers" is not presently clear, as nearby core samples from above the water table do not indicate a rise in the water table. The small amount of dissolved carbon in ground water and the possibility of isotopic exchange between dissolved carbon and local wall rock make variations subject to a wide range of possible causes. Moreover, the ages of the calcites have not been determined. The calcites with inconsistent ^{13}C content may have formed as a result of hydrothermal activity that occurred millions of years ago, soon after deposition of the volcanic rock as was seen at Harper Valley discussed earlier in this chapter.

CONCLUSIONS

Taking into account the expert testimony at its meetings, published information, and what was observed on the field trips and analyzed independently by panel members, the panel found no compelling evidence for the widespread discharge of deep ground water in the vicinity of Yucca Mountain that would have resulted if the regional water table had been elevated to a height sufficient to cause flow of water along the fault exposed in Trench 14 at an elevation of about 1,150 m AMSL (above mean sea level). For comparison, the estimated elevation of the present water table beneath Trench 14 is about 730m, and the design elevation of the floor of the proposed MGDS ranges from about 950 to 1,150 m (Dudley, pers. comm., 1991). **Indeed, in the panel's opinion, the morphologic, textural, mineralogic, and isotopic evidence is strong that the fault-filling**

materials formed by evaporation of descending meteoric water that only partly filled near-surface open fractures in the unsaturated zone.

Surficial calcite deposits consistently show a correlation between thicker surface-parallel calcretes occurring in better developed soil horizons and progressively older ground surfaces. The widespread occurrence of root casts within the calcretes associated with Bk or K soil horizons confirms that the calcium-rich waters concentrated in the soil zone rather than on the surface. This is characteristic of infiltrating rain water, not of ascending pressurized thermal waters. **These observations lead the panel to conclude that surface-parallel calcretes in soils originated from meteoric water by surficial soil-forming process rather than from upwelling ground water.**

In the panel's view, those breccias that appear to have formed in response to hydrothermal processes in the vicinity of Yucca Mountain and Busted Butte originated at the time of emplacement of the ash-flow tuff sequence from 13–10 Ma. They formed as a result of rapid heating of locally derived ground and rain waters. The source of energy appears to have been the heat initially contained in the tuffs, rather than the thermal and mechanical energy in the postulated hot water from a source many kilometers deep.

Younger breccias formed by a variety of processes through time, many of which show evidence of surficial water and progressive carbonate accumulation.

A variety of evidence, outlined earlier in this chapter, indicates that the water table in Devils Hole (presently 16 m below the surface) has varied less than 9 m in the past 45 ka and probably has not risen to the land surface in the past several hundred thousand years. **Considering that Devils Hole is located in the same active tectonic region, and is extending at two to three times the rate of the Yucca Mountain area, the fact that earthquakes have not resulted in even a 15 m rise in the Devils Hole water table inspires serious doubt that the seismic pumping mechanism can cause a greater than 100 m rise in the water table in the Yucca Mountain area.**

The currently active spring at Site 199 may rise from a perched water table. The isotopic composition of Cane Spring water is significantly different from that of ground water in the Alkali Flat/Furnace Creek and Ash Meadows aquifer, but similar to that of local rain water, modified by evaporation. The gypsum deposits at Wahmonie are ancient and probably formed well before the present erosion cycle. **The panel concludes that none of the springs or spring deposits in the Yucca Mountain area provide evidence of origin from ascending deep-seated ground water.**

Isotopic evidence shows that none of the surficial calcite depos

its analyzed to date could have precipitated from known ground waters. The analyzed deposits, including those at Trench 14 and Busted Butte that inspired the upwelling hypothesis, show isotopic affinities with local soils and pedogenic carbonates.

The panel concludes that to date the preponderance of evidence supports the view that the calcretes and other secondary carbonates in veins of the area formed from meteoric water and surface processes. The evidence cited here has convinced the panel that the ground-water level at the proposed Yucca Mountain repository site has not reached or exceeded the level of the proposed repository at any time during the last 100 ka.

RECOMMENDATIONS

The panel has identified some studies that may be useful. Because only a small number of the site characterization study plans are available, the panel is not aware of all the studies that are planned. If, therefore, some recommendations include studies that are already planned, these recommendations may be viewed as endorsements of the project plans.

The panel recommends that further efforts in the study of secondary calcite deposits be refocused. In the panel's opinion, it is well established that surface calcite deposits at Yucca Mountain, such as those at Trench 14 and Busted Butte, did not precipitate from ground waters sampled in deep wells.

Evidence for the isotopic concentrations of ancient ground waters is incomplete, however. **It is recommended that analyses of calcite veins intersected in drill cores be carried out for** $\boldsymbol{\delta}^{18}O_{VSMOW}$ and $\boldsymbol{\delta}^{13}C_{PDB}$, as well as of fluid inclusions. Age dating with U and Th isotopes would be an essential part of this study to reconstruct the ground-water history of the Yucca Mountain area.

Additional Characterization of Carbonate Veins in Core

The panel strongly endorses the efforts that are under way to characterize the ages and isotopic compositions of calcites in core obtained from both above and below the present water table. Along with the isotopic and age results, information should be obtained on grain sizes, chemical variations found in the carbonates (particularly Ca-Mg-Mn-Sr), and whether or not fluid inclusions are present.

Fluid Inclusion Studies

Fluid inclusions provide samples of ancient waters that were present at the time of entrapment. Information on the temperature and chemistry of the water at the time of mineral crystallization may be obtained from analysis of these inclusions. **A search should be made for suitable fluid inclusions in vein materials found in core to extract for hydrogen isotope analyses.** The isotopic composition of the corresponding oxygen in the inclusion water can be calculated from the oxygen isotopic composition of the host mineral. The panel is aware that vein materials that contain mixtures of primary and secondary fluid inclusions that formed at different times (or that contain more than one generation of secondary fluid inclusions) are not suitable for this type of analysis unless the volume percent of one type of inclusion is much greater than that of the other.

Isotopic Composition of Windblown Dust

Windblown particles that have been collected over a long period of time in dust traps in the vicinity of Yucca Mountain should be analyzed to determine if the average isotopic composition of this dust is essentially the same or significantly different from that of pedogenic carbonates and rock units exposed in the region. This study also would provide information about the possible extent to which windblown dust might influence the isotopic composition of meteoric water percolating downward through the vadose zone.

Additional Studies at Site 199

Detailed studies should be carried out to describe and document the geology, hydrology, and geochemistry of the apparent spring deposit at Site 199. Trenching and drilling of the tufa mound at this locality should be a high priority to determine if a perched water table is present, and if carbonate is currently depositing or has deposited in veins underground. This information will be valuable as an aid in further understanding the paleohydrology of the region. The hydrologic history of the region is essential, as understanding the past will bear on predicting future changes in the hydrologic system.

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3—

Might Increased Rainfall Cause Flooding of the Proposed Repository?

INTRODUCTION

Although available geological and geochemical evidence does not support the contention that the water table has risen to the proposed repository level in the past 100 ka (see Chapter 2 of this report), the possibility that it may do so in the future must be assessed, because the most likely mode for release of significant radioactivity to the outside environment is ground-water transport. It is, therefore, of utmost importance to understand the ground-water system and the various mechanisms that may cause the ground water to rise to the repository level over the next 10 ka. This assessment requires the use of mathematical models, based on known physical principles, that can simulate what might happen in the future given certain known or assumed conditions, and expert judgement to determine the input and to evaluate the results. The uncertainty in the results of these simulations depends in part on the current understanding of processes and rates that can affect the mechanisms.

One mechanism that might cause a rise in water level is increased recharge to the ground-water system as a result of an increase in precipitation. The ability of scientists to predict the response of the water table to possible increased recharge in the future must rely to a large extent on mathematical modeling. The computed rise in the water table strongly depends on (1) the assumed increase in precipitation, (2) the relationship of precipitation to recharge, and (3) the specifics of the particular mathematical (ground-water) model used in the computations for the Yucca Mountain area. These issues are addressed in this chapter.

HYDROGEOLOGICAL SETTING

Yucca Mountain lies within the Alkali Flat/Furnace Creek subdivision of the Death Valley ground-water system (see Figure 3.1). The regional ground-water system also includes the Ash Meadows and Oasis Valley subbasins. The ground-water flow within all three sub-basins is generally in a north-south direction. The principal aquifers in the Alkali Flat/Furnace Creek subdivision are in Cenozoic tuff and alluvium formations. Although a regional Paleozoic carbonate aquifer underlies a large part of southern Nevada and is thought to underlie the alluvium/tuff aquifers, only one borehole (UE-25p#1), southeast of Yucca Mountain, was drilled deep enough to encounter the carbonates (see Figure 3.2 for borehole locations). Its presence under Yucca Mountain, therefore, is still problematic.

Discharge, or outflow of groundwater, from the Alkali Flat/Furnace Creek subbasin occurs by springs near Furnace Creek Ranch in Death Valley, and by evapotranspiration, a surface process of removing water by plant activity and surface evaporation, at Franklin Lake Playa (Figure 3.3). Discharge rates in the Franklin Lake Playa are poorly known. It is also possible that part of the ground water bypasses the Franklin Lake Playa and discharges at lower elevations elsewhere. No estimates of such a discharge rate at lower elevations are available. Czarnecki (1985) assumes that the major modern recharge areas, which supply the ground water for the Furnace Creek/Alkali Flat subsystem, are the Pahute Mesa area to the north of Yucca Mountain and the Fortymile Wash area (Figure 3.3) east of Yucca Mountain. The amount of present-day recharge in other recharge areas (Jackass Flats, Crater Flat, and the Amargosa Desert (Figure 3.3)) is negligible compared to the recharge from the higher elevations of Pahute Mesa and Fortymile Wash. Carbon isotope age data imply that the water present in the deeper parts of the Alkali Flat/Furnace Creek subbasin was recharged about 10–15 ka (Dudley, 1990a). This recharge presumably occurred under conditions that were cooler and possibly wetter during the last 5 ka of Wisconsin glaciation than those prevailing now. These ground-water age data raise the interesting possibility that the Alkali Flat/Furnace Creek subbasin is still draining, and is presumably not in a steady state (see also Czarnecki, 1990). Sufficient data on ground water age in the subbasin are not yet available to describe the evolution of the ground-water system over the past 10–20 ka.

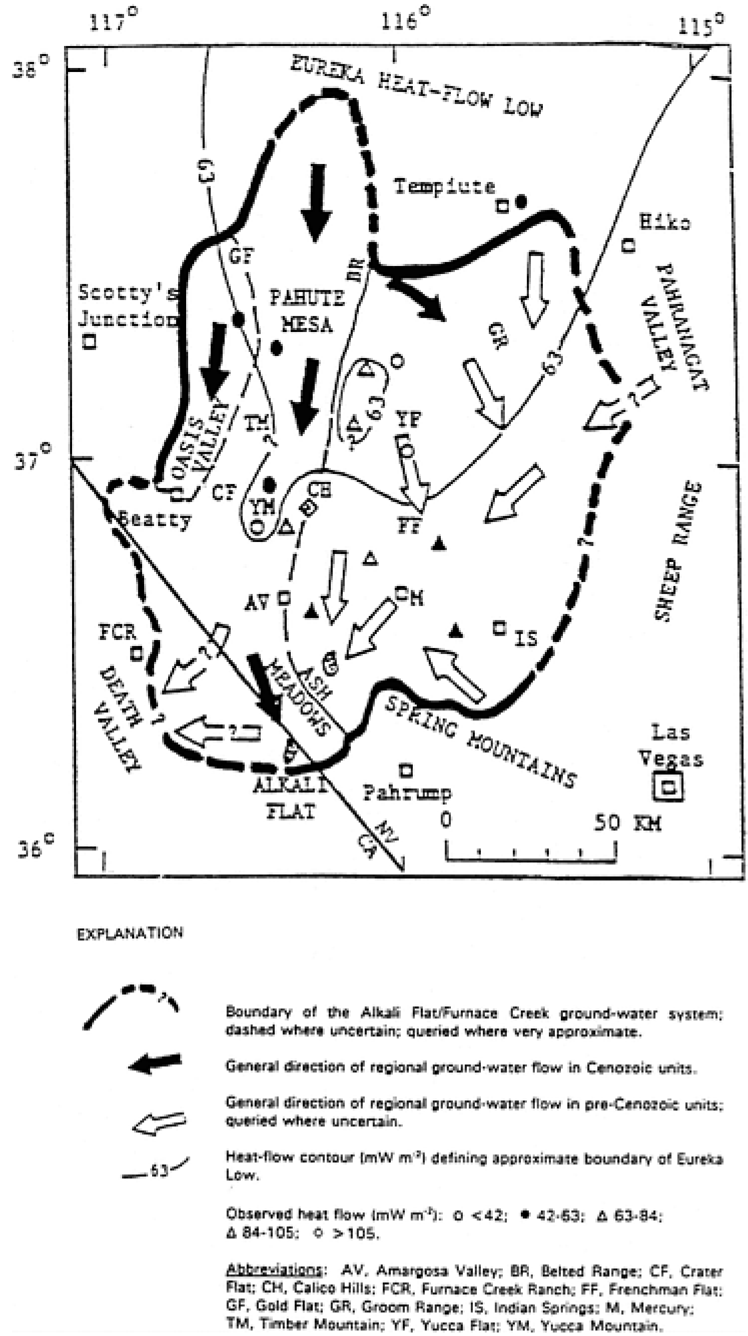

Figure 3.1
Regional ground-water systems and heat flow in the south-central Great Basin. (From Dudley, 1990a.)

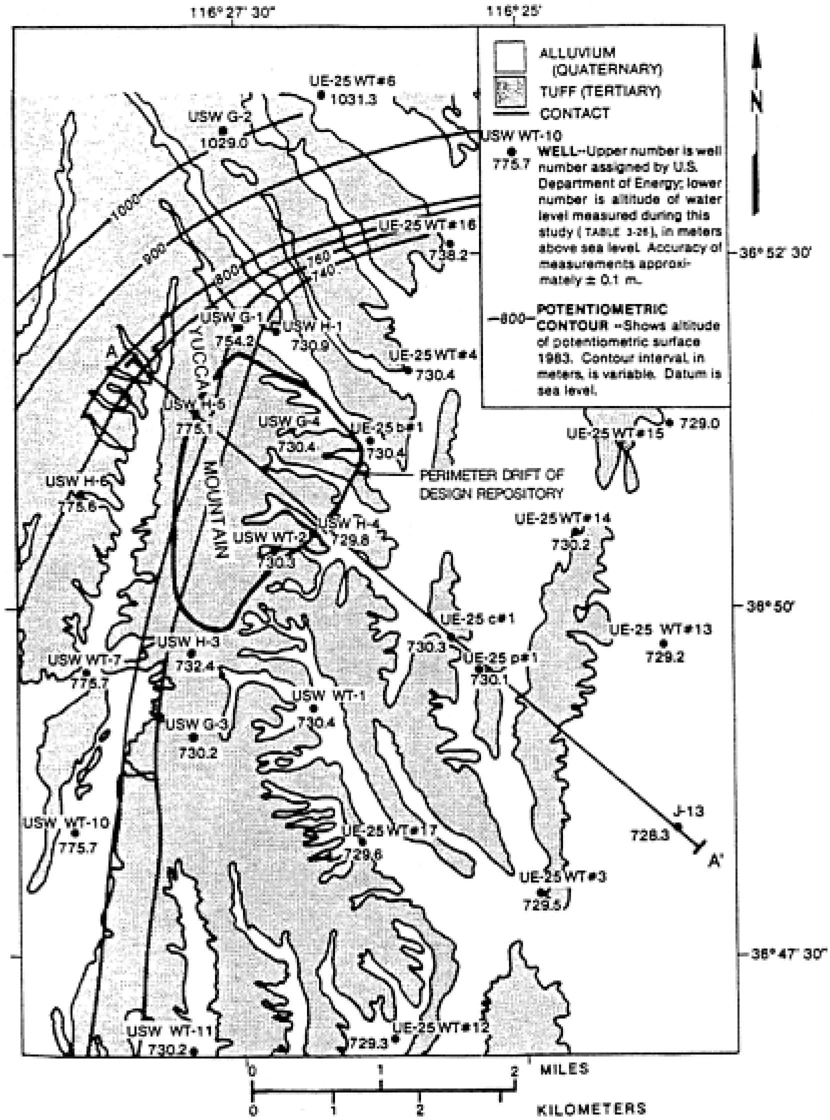

Figure 3.2
Preliminary composite potentiometric-surface (water table elevations) map of the saturated zone. Yucca Mountain. (From Dudley, 1990b.)

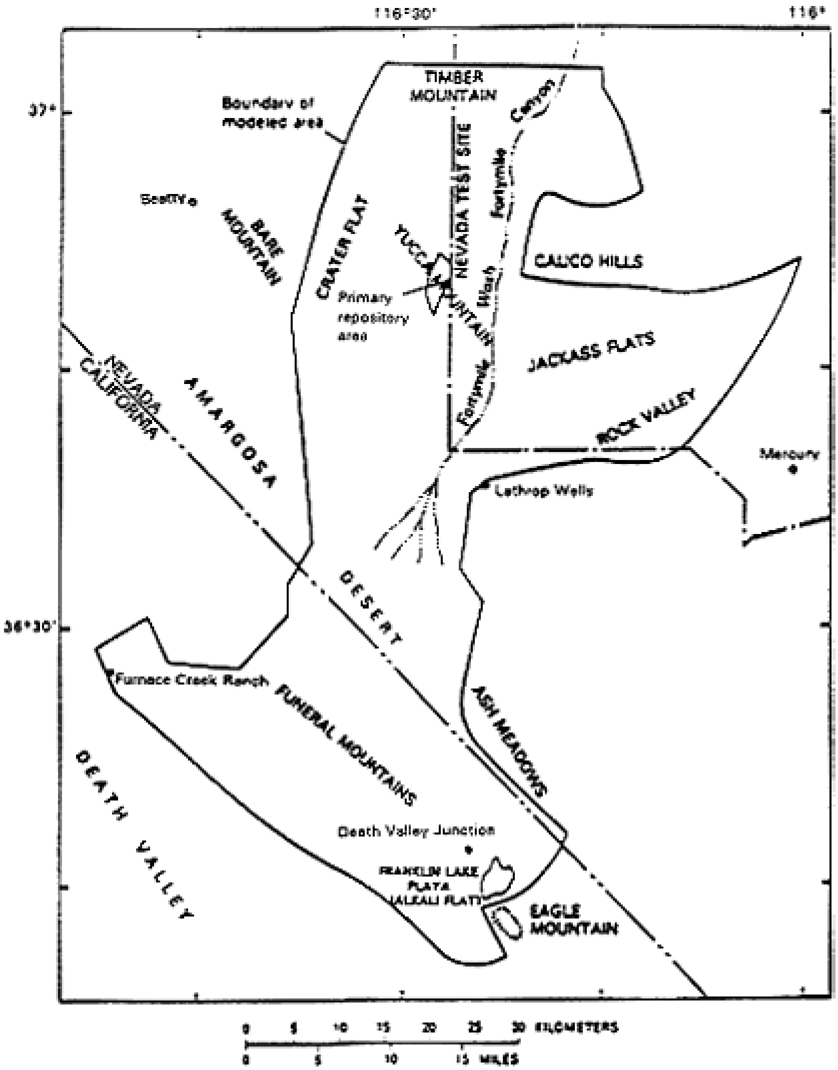

Figure 3.3
Location of subregional area modeled by Czarnecki and Waddell (1984).

The ground-water system in the Alkali Flat/Furnace Creek subdivision has been modeled by Czarnecki and Waddell (1984). These authors used a two-dimensional (areal) finite element model to simulate the *steady-state* ground-water flow occurring principally in the tuffs. The model was calibrated using available measurements of the elevation of ground-water levels. The transmissivities, or parameters describing how readily rocks will transmit ground water, and the amount of recharge in the Fortymile Wash area were adjusted until the model-calculated values of ground-water head were close to measured values.

Only a few hundred meters north of Yucca Mountain, the water table level rises northward from ~730–750 meters above mean sea level (m AMSL), measured in wells G-1 and H-1, to ~1030 m AMSL (in well G-2) over a maximum distance of approximately 2.5 km (Figure 3.2). The actual gradient may be steeper, but there are too few data at present to define it adequately. Understanding the nature and source of this steep hydraulic gradient is of fundamental importance in evaluating the long-term safety of the site for high level radioactive waste storage. In fact, it is the rapid decline of the water table level north of Yucca Mountain that allows for the "unsaturated" condition 300 m below the surface that was considered so important in the selection of the repository depth. The position of the gradient does not appear to correlate with presently known stratigraphic or structural features in the upper kilometer of the mountain (C. Fridrich, written communication, 1991).

Currently, the reasons for this large lateral increase in hydraulic head are a matter of speculation. Three conceptual models have been considered by scientists associated with the project to explain the occurrence of the steep potentiometric gradient: (1) a hydrologic dam or barrier—a narrow vertical zone (1.5 km wide) of greatly decreased transmissivity; (2) a hydrologic drain—a highly transmissive vertical zone diverting most flow from the high water table region into the lower carbonate aquifer; and (3) a low transmissivity zone north of Yucca Mountain caused by tectonically controlled stress fields. Clearly, the fundamental differences between the models involve the geometry and characteristics of the causative feature. Both the dam and the drain models require a local, east-west-trending near-vertical zone coinciding in location with the steep gradient. In the dam model this vertical zone has very low transmissivity and acts as a barrier; in contrast, the drain model requires the vertical zone to have significant vertical permeability. The third model evokes high compressive horizontal stresses north of the gradient to cause the low transmissivity. Each of these models has some supporting data and none can be eliminated with the currently available data (C. Fridrich, pers. comm.). The model of Czarnecki and Waddell (1984) treats only the dam hypothesis. The results of this model are discussed briefly further on in this chapter.

A MODEL OF GROUND-WATER FLOW AT YUCCA MOUNTAIN

The area of the steady-state ground-water model of Czarnecki and Waddell (1984) covered the region extending from Timber Mountain in the north to Alkali Flat and Franklin Lake Playa in the south (see Figure 3.3). Recharge from the Pahute Mesa area was simulated by prescribing a constant pressure boundary. Some minor fluxes were also applied to account for recharge from Jackass Flats and the Amargosa Desert, based on the earlier modeling work of Waddell (1982). However, all these fluxes amount to less than 2.5 percent of the total recharge or discharge. The recharge along Fortymile Canyon (zone 8, Figure 3.4) was obtained from the parameter estimation procedure. For the calculations the recharge in the Fortymile Wash area, estimated at 2.214×10^4 cubic meters per day (m^3/d), was assumed to account for 40.3 percent of the total recharge. Most of the rest of the recharge (about 57.3 percent) was modeled to enter the subbasin through the constant head boundary along the northernmost end of the modeled region. Discharge from the subbasin was represented as: (1) a line sink east of Furnace Creek Ranch and (2) an areal discharge out of Alkali Flat. The discharge from the Alkali Flat area is 2.214×10^4 m^3/d. It equals 64.8 percent of the total discharge from the subbasin. The remainder of the discharge was assumed to take place in the Furnace Creek Ranch area. All other boundaries were assumed to be no-flow boundaries.

Czarnecki and Waddell (1984) divided the subbasin into 13 regions (Figure 3.4); transmissivities were assumed to be uniform in each of these regions. As part of a parametric estimation procedure, the recharge in the Fortymile Wash area and the transmissivities for zones 1 through 9 were varied until a satisfactory match was obtained between the computed and measured hydraulic heads. Final transmissivity values computed by Czarnecki and Waddell are given in Table 3.1. Considering the uncertainties in head measurements, the agreement between computed and measured head values is good. Model residuals for simulated versus measured heads range from -28.6 to 21.4 meters; most are less than ±7 meters. The simulated hydraulic heads are shown in Figure 3.5.

Despite the impressive match between the measured and computed heads, the model results must be used with caution. The comput

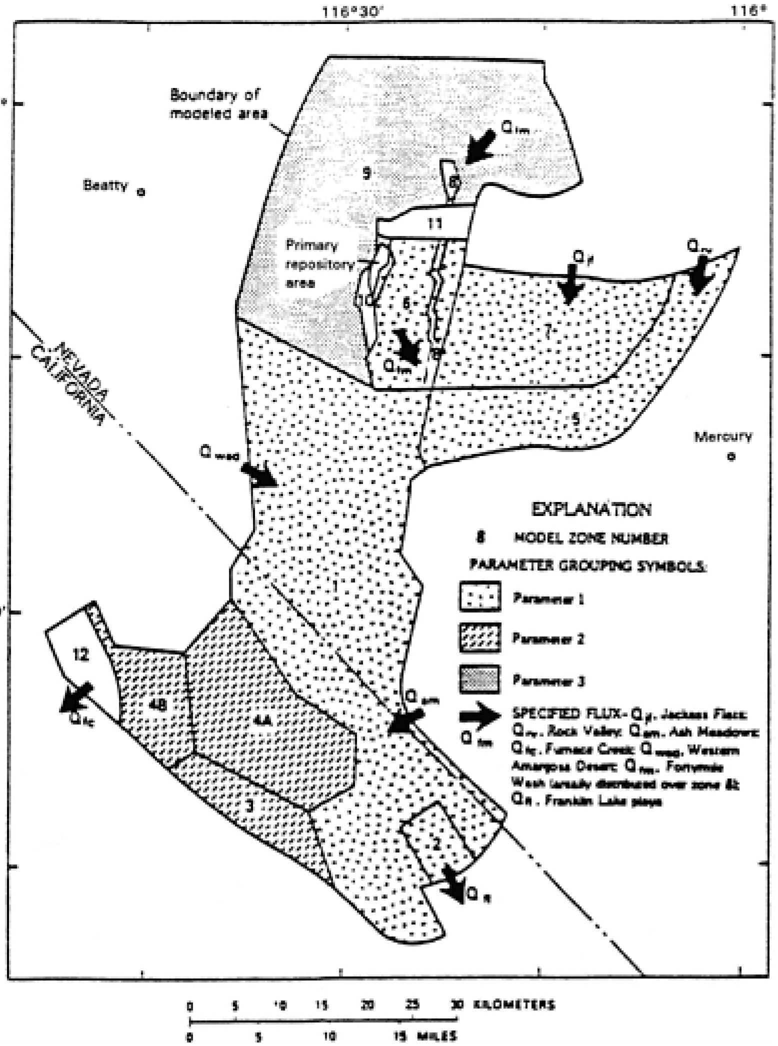

Figure 3.4
Model zone numbers, parameter groupings, and model boundary fluxes employed by Czarnecki and Waddell (1984).

ed transmissivities in zones 5, 6, 7, and 8 are extremely high. The available permeability measurements do not provide support for these high values (see Appendix B for details of the measured permeabilities of the area). An extremely small transmissivity value was assumed for zone 11 to simulate the large hydraulic gradient north of the Yucca Mountain. As indicated above, the cause of this large hydraulic gradient is not understood. The uncertainty in the amount of total discharge from and recharge to the subbasin produces a corresponding uncertainty in the computed transmissivity values. The data currently available on discharge/recharge and transmissivity distribution in the subbasin provide inadequate constraints for the model.

Table 3.1 Values of Model Transmissivities and Standard Errors. (excerpted from Czarnecki and Waddell, 1984).

[T, transmissivity, in meters squared per day; number following letter T in model variable column is zone number; dashes indicate that value was held constant]

Model Variable	Parameter Number	Value	Standard Error	Coefficient of Variation	
T1, T2	1	1.336×10^3	31.92	0.024	Alluvium
T3, T4a	2	1.282×10^2	2.421	0.019	Volcanic Rocks
T4b	2	1.197×10^2	2.260	0.019	Carbonate Rocks
T5	1	1.169×10^4	2.792×10^2	0.024	Carbonate Rocks
T6, T7, T8	1	3.340×10^3	79.79	0.024	Tuff
T9	3	95.90	0.2711	0.003	Tuff
T10	—	78.62	—	—	Tuff
T11	—	3.888	—	—	Tuff
T12	—	8.64×10^{-3}	—	—	Lakebeds

Czarnecki and Waddell (1984) used a very small transmissivity in zone 11 (see Figure 3.4) to simulate the large hydraulic gradient north of Yucca Mountain. The trend of this barrier (zone 11) is east-west, normal to the known faults in the area. Recently, Czarnecki modeled a sudden removal of this postulated permeability barrier. Such a removal of the barrier could occur due to faulting associated with an earthquake. This "dam break" causes a maximum rise of about 40 meters in the computed water-level at the repository site (J. Czarnecki, pers. comm., 1992).

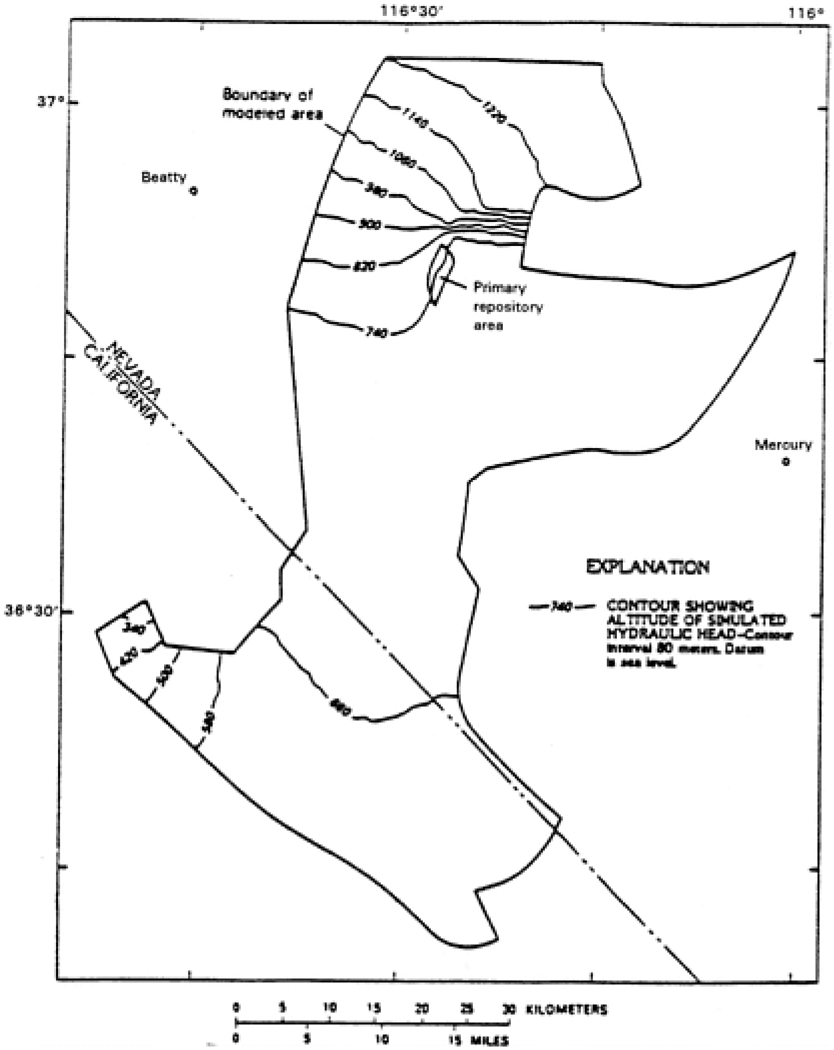

Figure 3.5
Simulated hydraulic heads. (From Czarnecki and Waddell, 1984.)

Czarnecki (1985) presented a slightly modified form of the subbasin model. The constant head boundary condition along the northernmost boundary was replaced by a constant flux boundary. The prescribed flux was the same as that computed by Czarnecki and Waddell (1984). The prescribed flow conditions along the Furnace Creek and Alkali Flat were changed to constant head conditions. Hydraulic head values in these areas were estimated from values of land surface altitudes. This model also produced satisfactory agreement with observed heads.

To the extent that the mathematical model reflects reality, it can be used to predict how ground-water levels may change in response to changes in precipitation. Before considering speculative modeling of this type, however, it is instructive to consider the paleoclimatic, paleoecological, and paleohydrological data that offer guidance on the likely magnitude of precipitation changes over the next 10,000 years.

EVIDENCE FOR PAST VARIABILITY IN RAINFALL

Evidence of former, wetter climatic conditions is widespread throughout the semi-arid southwestern United States. Among the most striking examples are the wave-cut terraces on the margins of closed valleys, evidence that these basins once supported vast lakes. In the late nineteenth century Gilbert (1890) was among the first to correlate high stands (or levels) of these lakes, and the "pluvial" (or wet) climates that they indicated, with glacial ages. The correlation between pluvial climatic episodes and glacial ages (or stades) has provided a basic time scale for major climatic fluctuations in North American deserts. Although the correlation does not hold true in other of the world's great deserts (the last pluvial climatic episode in North Africa, for example, is broadly correlated with the beginning of the present interglacial 10 ka (Ritchie et al., 1985; Spaulding, 1991a), it applies well in the western U.S. Other important issues relating to climate change in the southwestern desert regions include what constitutes a pluvial climatic regime in this region, and how much of an impact pluvial climatic episodes have in terms of increased recharge to the aquifer. These are issues of special interest because the answers to these questions affect projections concerning the magnitude of the impact of pluvial climates on the water table.

Chronological Framework

Regulations mandate that calculation of the potential for release of radionuclides from the proposed Yucca Mountain repository be per formed to assess a 10 ka period. Predicting the behavior of the water table over that period of time requires estimating the changes in climate that are likely to occur, especially the amount of precipitation. However, projecting future climatic fluctuations depends in part on the knowledge of climate changes during the late Quaternary (the last 130 ka). The historic meteorological record is, of course, too brief to encompass the major changes that take place in such a time span, as are tree-ring reconstructions of past climates.

The last glacial age, the Wisconsin, ended about 10 ka, an age agreed upon by international convention (Olausson, 1982) which is based on carbon isotope dating of organic matter found in glacial debris. The Early and Late Wisconsin were periods of maximum expansion of northern hemisphere ice sheets and maximum depression of global temperatures. The two major episodes of global climate change encompassed by the carbon isotope time scale (roughly the last 50 ka) are the Middle/Late Wisconsin transition at 23 ka, and the Late Wisconsin/Holocene transition at 10 ka. The first transition involved a change to colder environments, while the second involved a shift to a warmer and effectively drier climate accompanying worldwide deglaciation. The full glacial, or Wisconsin-maximum, witnessed the maximum extent of continental glaciers at ca. 18 ka (Spaulding, 1985; Benson and Thompson, 1987). It should be noted that at their furthest extent in North America, the ice sheets, which spread out across the continent from Labrador and Keewatin in the Canadian Shield, rarely reached south of the northern tier states. However, the continent south of the ice, including southern Nevada, experienced a colder and, in some cases, wetter (pluvial) climate.

Geographic and Paleohydrologic Framework[1]

The Yucca Mountain region lies astride the climatic and vegetation transition between the warm-temperate Mojave Desert to the south and the cold-temperate Great Basin Desert to the north (Cronquist et al., 1972; Beatley, 1975). Sparse creosote bush[2] desertscrub characteristically occupies the warm valleys of the Mojave, while relatively productive sagebrush and sagebrush-bunchgrass vegetation typifies many cooler valleys to the north. This environmental transi

[1] See Appendix C for detailed discussion of paleoclimate and evidence, which is more briefly summarized in this chapter.

[2] See Appendix C Supplement for descriptions and explanations of plant species used as indicators of moisture and temperature in paleoclimate studies.

tion from warm conditions in the south to relatively cold conditions in the north has apparently persisted through the late Quaternary.

In their study of pluvial lakes, that is, those present during former, wetter climatic intervals in Nevada (Figure 3.6), Mifflin and Wheat (1979) noted that south of 38°N latitude very few closed basins possess wave-cut terraces, it is unlikely that they supported pluvial lakes.

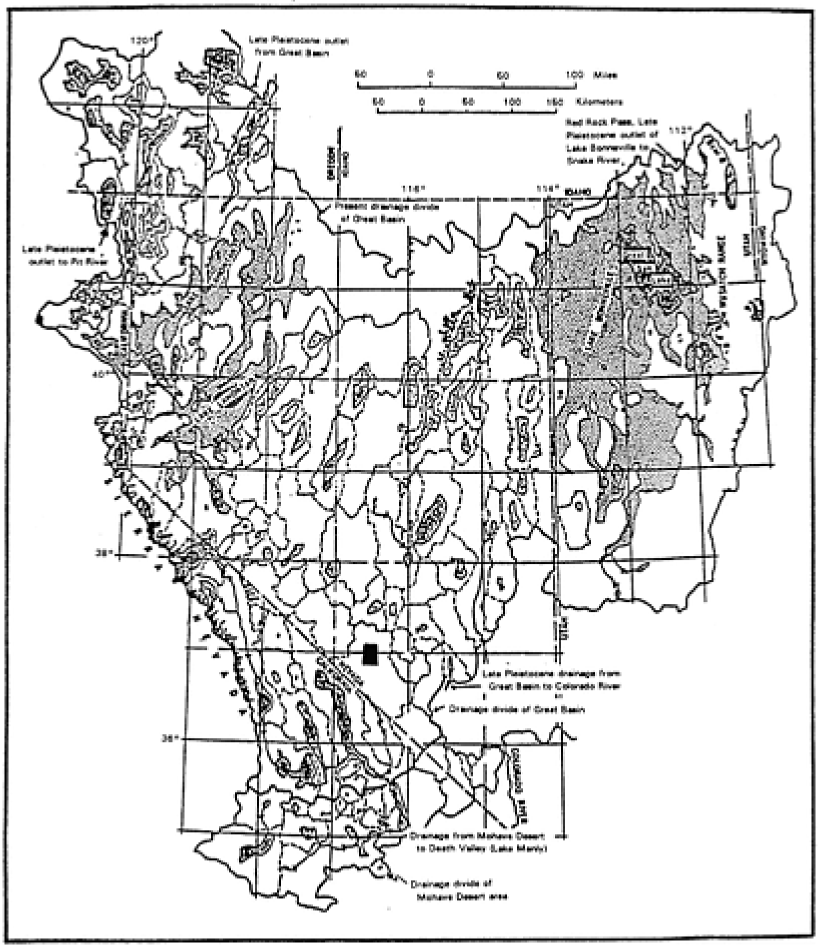

Figure 3.6
Pluvial lakes (shaded closed areas) of Quaternary age in the Great Basin. Black rectangle in southwestern Nevada is the Yucca Mountain area. Note that not all these lakes experienced maximum filling at the same time, and some may antedate the Wisconsin glacial age. (After Morrison, 1965; modifications from Mifflin and Wheat, 1979.)

The only known exception is a small basin on the northwest end of the Sheep Range, ca. 100 km east of Yucca Mountain. The widespread paleohydrologic evidence for a drier ice-age climatic regime in the vicinity of Yucca Mountain contrasts with the central and northern Great Basin record of wetter climatic conditions. Other lines of evidence that indicate that the last pluvial climatic regime in the Yucca Mountain region was actually relatively and are presented in the following discussion.

The data from two sites within the southern Great Basin are relevant to understanding the chronology of paleohydrologic changes: Searles Lake in southeastern California (Smith, 1979; Smith and Street-Perrott, 1983) and the springs of Las Vegas Valley in southern Nevada (Figure 3.7) (Haynes, 1967; Quade, 1986; Quade and Pratt, 1989). Artesian springs are end-points of a hydrologic system that differs from that of a pluvial lake. High stands of a pluvial lake largely reflect surface water runoff (Enzel et al., 1989), while spring discharge, or outflow, is affected by the amount of water entering the water table, known as aquifer recharge, chiefly from snowmelt in the high mountains. Both systems, however, should be sensitive to significant pluvial episodes. The Paleozoic carbonate aquifer of the Las Vegas Valley is a confined system, sandwiched between impermeable layers. Increased recharge in the highlands of the Spring and Sheep Ranges should increase the hydrologic gradient, which is the pressure difference between recharge and discharge areas, resulting in a rapid increase in outflow through springs at the end of that gradient. A persistent increase in rainfall should also result in increased lake levels. Thus, there is a reason for the apparent correlation of major "pluvial" episodes evident in a comparison of the record of lake-level fluctuations from Searles Lake with Las Vegas Valley spring records (Figure 3.7). It should be noted that Benson et al. (1990) have published an alternative chronology of Searles Lake to that shown in Figure 3.7. Unfortunately, they offer no guidance regarding which chronology is more reliable. In the absence of defensible arguments to the contrary, we rely on the chronology originally proposed by G. I. Smith (Smith and Street-Perrott, 1983; Benson et al., 1990).

The Paleoecological Record

Ancient packrat (*Neotoma* spp.) middens, or den deposits, provide much of the data discussed here. Descriptions of these deposits and the methods used in their analysis are offered by Betancourt et al. (1990). These middens, composed primarily of mummified plant fragments and fecal pellets encased in a matrix of crystallized packrat urine, are common in the hills of the region. The fossilized plants from a midden are assumed by most workers to have come from no more than a 30 to 50 m radius around the den, which is believed to encompass nearly all packrat foraging activities. Although normally dominated by the remains of one or two plant species, the fossil assemblages also contain a diverse array of other plants. The known climatic affinities of these plant species are then used to infer climatic

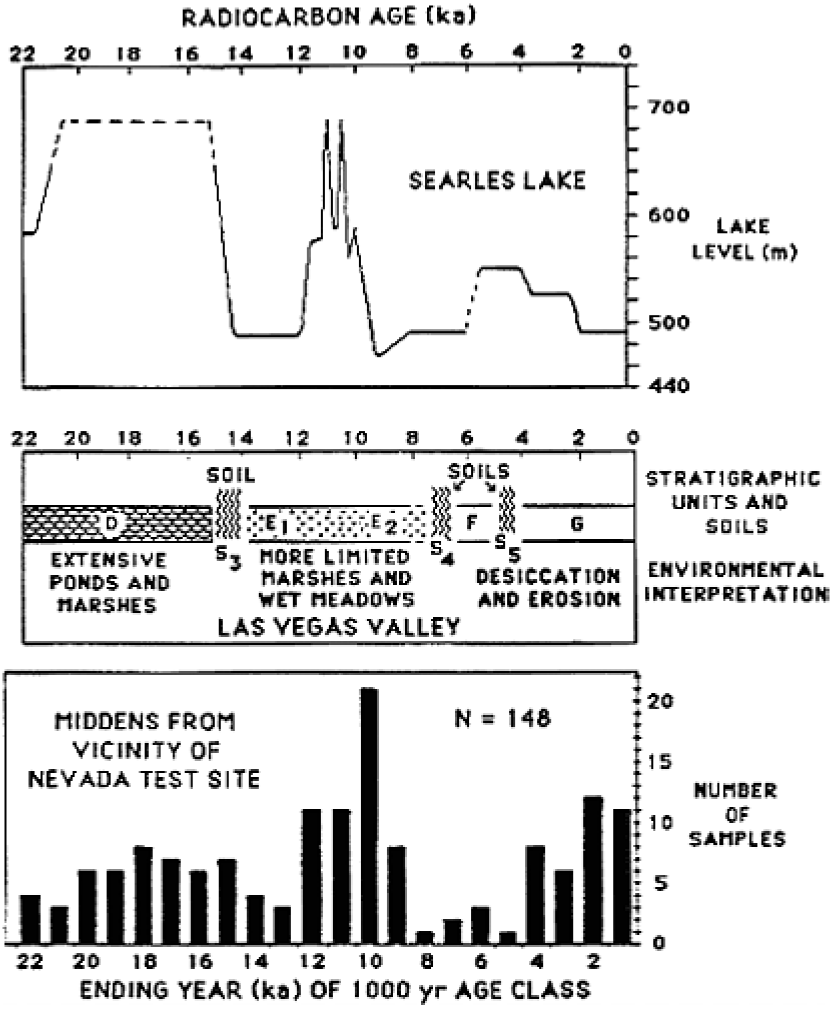

Figure 3.7
Comparison of paleohydrologic chronologies from the southern Great Basin (Smith and Street-Perrott, 1983; Quade, 1986) with the temporal distribution of packrat midden samples from the Yucca Mountain vicinity.

conditions. The time of such conditions is established by carbon isotope dating of organic material selected from the midden sample.

The paleoecological record derived from fossil pollen and plants found in carbon isotope-dated packrat middens provides direct evidence of environmental conditions during the last glacial age. Before the development of a comprehensive packrat midden record, the most detailed paleoecological evidence for the region was provided by fossil pollen studies from Tule Springs in the Las Vegas Valley. Wisconsin-age sediments there yielded abundant pine pollen, and were used to reconstruct glacial-age vegetation zonation in which pinyon-juniper woodland and pondersa pine-white fir forest extended down into the valleys some 1000 m below their current lower elevational limits (Mehringer, 1967). This reconstruction was in accord with the paleoclimatic models that were most widely accepted at that time (e.g., Leopold, 1955; Antevs, 1948): a mild and wet pluvial climatic regime with average annual precipitation perhaps double today's meager amount and a decline in average annual temperature of less than 5°C ($\Delta T_a \leq 5$°C).

More recent studies of fossil packrat middens provide more precise information on environmental change in the Yucca Mountain region. Comparison of the temporal distribution of midden samples from the vicinity of Yucca Mountain with the available paleohydrologic record (Figure 3.7) suggests that periods of increased recharge over the last ca. 22 ka can be well characterized due to a more thorough sample coverage during these times. These midden sites span ca. 2000 m of relief, from low elevations in the Amargosa Desert and Las Vegas Valley to high elevations in the Sheep Range. Fossil records from such an extensive range of elevations can be used to illustrate some principal features of the Late Quaternary environments of the region, and to demonstrate that the area was drier during the Late Quaternary than the earlier models widely accepted in the 1950's and 1960's assumed for that period of time.

The existing paleoecological record can be examined for evidence of (1) full-glacial climatic conditions, and (2) plants that require wet ground to exist (phreatophytes) regardless of when they occurred. The data relating to the full-glacial period yield insight into climate during the time when conditions were most different from those of the present. The data relating to wet-ground plants yield evidence for the extent and timing of outflowing ground water where none now exists. Contrary to earlier interpretations, the more extensive fossil record demonstrates a relatively dry glacial-age climate, and the paleobiotic evidence shows the limited former extent of perennial surface water. The evidence for these more recent interpretations is discussed in more detail in Appendix C.

During the last glacial age, juniper woodland extended to the valley bottoms, while the driest sites supported steppe shrubs such as shadscale and sagebrush. Nowhere in the Wisconsin fossil record is there evidence for the warm-desert shrubs that typify the current Mojave Desert. Above ca. 1600 m on tuffaceous substrate, and above 1800 m on calcareous rocks, there existed subalpine conifer woodland dominated by limber pine. No macrofossil evidence has been found for ponderosa pine-white fir forest during the last glacial age (Spaulding, 1985, 1990; Spaulding et al., 1983). Such forest vegetation would indicate wetter, milder conditions than those which appear to have prevailed. Rather, the widespread presence of cold-desert and dry-woodland plants indicates drier, colder conditions during the last glacial maximum. The absence of evidence for perennial water in the uplands during this time is consistent with these interpretations. Although there are extensive Wisconsin-age spring deposits in the valley bottoms of southern Nevada (Quade, 1986; Quade and Pratt, 1989), such geological evidence is generally absent from the highlands and wet-ground species appear only rarely in the southern Great Basin midden record.

To date there are but two sites that provide unequivocal records of wet-ground habitat in uplands where none now exists. Both occur in currently dry canyons that nevertheless have extensive drainage areas. Abundant seeds of the net-leaf hackberry bush (*Celtis reticulata*) from Dead Man Canyon-2 in the Sheep Range, dated by carbon isotopes at 9.6 ka, indicate the presence of perennial water at 2075 m elevation at that time. The tree is now extinct in the range (Spaulding, 1981). The second site is in Fortymile Canyon (FMC), the major drainage east of Yucca Mountain. The FMC-7 midden site lies at ca. 1250 m elevation and is a small rock shelter ca. 60 m above the canyon floor. Samples from the top and bottom strata of the FMC-7 midden yielded dates of 47.2 ± 3 ka and older than 52 ka respectively. They contained the remains of willow (*Salix* sp.), knotweed (*Polygonum lapathifolium* -type), and wild rose (*Rosa woodsii*), phreatophytes, or plants that require perennial water.

Elevation of the water table below this site is currently 1150 m AMSL. This would imply that at ca. 50 ka the water table was 100 m higher than now. However, except for the fossil flora, no evidence for ancient springs in the area has been recognized to date. Moreover, other packrat middens, within 0.5 km of this site, and at elevations slightly below and above show no evidence of wet-ground plant species. These midden sites are at elevations of 1230 m, 1240 m, 1280 m, and 1310 m, and are younger than the FMC-7 midden, with glacial age samples dating to 21.8, 18.5, 16.4, 15.9, and 12.9 ka. Lack of wet-ground species in even the full-glacial age samples (ca. 18 ka) is consistent with other evidence for a relative dry, cold climate (see next section).

PALEOCLIMATIC RECONSTRUCTIONS

Important contrasts between Middle Wisconsin, Late Wisconsin and early Holocene fossil records are that (1) wet-ground plant species appear to have been more abundant during the Middle Wisconsin and early Holocene, and (2) steppe shrubs appear to have been dominant during the Late Wisconsin. These suggest that effective moisture and temperature may have been lower during the Late Wisconsin, and particularly during the full glacial when the coldest temperatures prevailed. This makes sense on meteorological grounds; low temperatures can lead to decreased precipitation, because the ability of the atmosphere to evaporate and transport water is strongly affected by air temperature.

Full-Glacial Climates

Paleoecological data indicating a substantial reduction in winter temperature ($-\Delta T_w$) in the Yucca Mountain region during the Late Wisconsin have been discussed by Spaulding (1985). The absence of warm-desert plants from even the lowest altitude and most and sites is consistent with a $-\Delta T_w$ of at least 6°C. The prevalence of steppe shrubs and drought-adapted conifers suggests similarities between the full-glacial fossil records from this area and the modern vegetation and climate of the northern Great Basin.

Most paleoclimatic reconstructions call for lowering full-glacial summer temperatures ($-\Delta T_s$) in excess of $-\Delta T_w$ (Spaulding et al., 1983). Values of $-\Delta T_s$ derived from the lower elevations at which key plant types have been found in the Yucca Mountain region range from 6.4° to 9°C. The decline in average annual temperature ($-\Delta T_a$) in the area during the Late Wisconsin is estimated to have been ca. 7°C (Spaulding, 1985). These reconstructions accord well with the distribution of relict features indicating permanently frozen ground on Great Basin mountain ranges (Dohrenwend, 1984).

Moisture-loving mountain trees such as ponderosa pine and white fir were expected in the fossil record when the model of a mild, moist glacial-age climate was thought to apply (see, e.g., Mehringer, 1967). Subsequent research showed that these plant species were actually rare (white fir) or apparently absent (ponderosa pine) from the fossil record of the southern Great Basin (Spaulding, 1990). An estimated increase in average annual precipitation (P_a) of 40 percent is all that is required to account for the paleobiotic record in this region (Spaulding, 1985), rather than the 100 percent increase inferred from less extensive data sets. With the fossil record dominated by drought- and cold-tolerant species it is difficult to see how the increase could have been greater.

General analogs and model simulations of the full-glacial climate in this part of the Southwest suggest even less summer precipitation than today's meager amounts (at present ≤ 25 percent of the annual total in southern Nevada, which is approximately 158 mm (6 inches) per year (DOE, 1988). Thus, a substantial increase in winter precipitation is necessary to account for the apparent increase in full glacial Pa. This strong winter-seasonality of precipitation is analogous to present conditions in the central and northern Great Basin. Appendix C discusses the changes in atmospheric circulation that could have forced increased winter precipitation.

The Terminal Wisconsin-Early Holocene

The southern Great Basin paleohydrologic record indicates that there was a general decline in effective moisture between ca. 17 ka and 13 ka (Figure 3.7). This is consistent with model simulations of late-glacial climate change, which indicate the northward retraction of the westerly jet stream between 18 ka and 12 ka, largely due to the retreat of the North American ice sheets (COHMAP, 1988). The result in the Yucca Mountain area should have been a decline in the frequency and intensity of winter precipitation events. The later (14–13 ka) high stand of pluvial Lake Lahontan to the north (Benson and Thompson, 1987) may have been caused by increased precipitation associated with the repositioning of the prevailing westerlies at this more northerly latitude.

Despite evidence for the northward retreat of the westerly jet stream, effective moisture continued to exceed that of the present until the close of the early Holocene in southern Nevada (Spaulding, 1985; Van Devender et al., 1987). The Searles Lake and the Las Vegas Valley records even suggest episodes of increased effective moisture between ca. 12 and 9 ka (Figure 3.7). At most sites there was near-complete turnover in plant community composition between 13 ka and 11 ka. This involved the reduction or elimination of steppe shrubs and low-elevation conifer populations. Increases in summer seasonality of precipitation and warmer winter temperatures may account for these changes. Increased summer precipitation is indicated by the frequency of grasses and succulents (agave, Yucca, cacti) in low-

Table 3.2 Packrat Midden Records of Hydrophilic Species from the Nevada Test Site and Vicinity.

Area & Site	N. lat.	W. long.	Elev. (m)	Sample	Species	Source	14-C date (ka)
Amargosa Desert							
Skeleton Hills-1	36° 32'	116° 20'	910	Sk-1B (2)	Celtis reticulata seed	long distance	9.2 ± 0.14
Skeleton Hills-2	36° 38'	116° 17'	940	SK-2(2)	muskrat tooth	long distance	8.17 ± 0.1
Sheep Range							
Willow Wash-4	36° 28'	115° 15'	1585	WW-4B	Populus sp. twig	local (?)	9.82 ± 0.11
Flaherty Shelter	36° 30'	115° 14'	1650	Unit 3/125cm	Celtis reticulata seed	long distance	*
Deadman-2	36° 37'	115° 16'	2075	Dm-2	Celtis reticulata seeds	local	9.56 ± 0.18
North Yucca Mountain							
Fortymile Canyon-7	36° 57'	116° 22'	1250	FMC-7 (1)	Salix sp., Rosa woodsii Polygonum lapathifolium-type	local	47.2 ± 3.0
	36° 57'	116° 22'	1250	FMC-7 (3)	several phreatophytes	local	>52
Sandy Valley							
Sandy Valley-2	35° 53'	115° 42'	935	SaV-2 (3)3	Celtis reticulata seed	long distance	9.4 ± 0.09

*Sample from bioturbated cave sediment, 75 cm below a radiocarbon date of 6.95 ± 0.32 ka (A-1297).

elevation fossil records between ca. 12 ka. and 8 ka (Spaulding, 1990). However, because conditions were changing rapidly, it is premature to offer specific climatic reconstructions for the terminal Wisconsin and early Holocene. Early Holocene records of wet-ground plant species (Table 3.2) do suggest that recharge was still sufficient to support expanded springs and water courses, despite the development of increasingly arid-climate vegetation on upland slopes. The contrasting lack of wet-ground plants from full-glacial middens is suggestive, but may be simply due to sample distribution (Figure 3.7).

Climates of the Last 8,000 Years

Essentially modern vegetation and climatic conditions were established in the Southwest between 7.8 ka and 7 ka. Within the last seven millennia it appears unlikely that ΔT_a exceeded 1.5°C or that P_a varied more than 20 percent from current long-term averages. However, there were marked variations within these limits. Much of the first half of the middle Holocene (from ca. 7.5 ka to 5.5 ka) appears to have been effectively more and than the present (Hall, 1985; Spaulding, 1991). And much of the late Holocene (after 3.5 ka) appears to have been characterized by levels of effective moisture equal to or slightly exceeding those of the present (Cole and Webb, 1985; Spaulding, 1990).

MODEL CALCULATIONS OF POTENTIAL RISE IN THE GROUND-WATER TABLE DUE TO INCREASED PRECIPITATION

Czarnecki (1985) applied the two-dimensional model for ground-water flow at Yucca Mountain to estimate the magnitude of water level changes that might occur in response to a change to a pluvial climate. He used the empirical approach of Eakin et al. (1951) (see Czarnecki (1985) for a detailed discussion) to estimate the increase in ground-water recharge that would occur under an assumed 100 percent increase in modern-day precipitation. He calculated that the consequent increase in recharge would exceed current amounts by more than an order of magnitude (13.7 times greater than at present, rounded upward to 15 times present recharge). It is important to note in this context that the 100 percent value for an increase in precipitation is a speculative figure proposed by Spaulding et al. (1984) to account for poorly constrained evidence of "monsoonal pluvial" climatic conditions between 12 ka and 8 ka (Spaulding and Graumlich, 1986; Spaulding 1991a). Detailed analyses, as discussed earlier in this report, indicate that a ca. 40 percent increase above current average annual precipitation, coupled with a decline in average annual temperature of more than 6°C, accounts for conditions during the last glacial maximum. Despite the present uncertainties about the climatic conditions obtaining during the terminal Wisconsin and early Holocene, it is very likely that the 100 percent increase in precipitation assumed by Czarnecki is overly conservative.

The computed rise in the water table beneath the proposed repository area, based on the assumed 100 percent increase in precipitation is about 130 m (Figure 3.8). Interestingly, a modeled increase in precipitation acting in concert with the "dam break" of the steep hydraulic gradient does not cause a larger rise in computed ground-water level than that caused by climate change alone. The predicted rise in ground-water level is extremely sensitive to the recharge in the Fortymile Wash area. To the extent that the modern recharge (and its 15-fold increase due to a 100 percent increase in precipitation) in the Fortymile Wash area is poorly constrained, the computed rise in water level must be regarded as speculative. The magnitude of the calculated rise in water level would place the water level some 70 m below the proposed MGDS and suggests that further investigation of this scenario is required. The modeled effect of a 15-fold increase in recharge is a substantial increase in spring discharge north of the steep hydraulic gradient immediately north of the Yucca Mountain (Czarnecki, 1985). This area of spring discharge includes the middle reaches of Fortymile Canyon, where as previously mentioned, there is one Middle-Wisconsin (>47 ka) record of wet-ground plant species at the Fortymile Canyon-7 site. It is significant that no such records have been recovered from middens in the same area that date to the last glacial maximum. This supports the inference that, during the Late Wisconsin, precipitation and recharge amounts were well below the maximum values incorporated into Czarnecki's model (Czarnecki, 1985, 1990).

Estimates of ground-water recharge must be viewed with caution. Ground-water recharge, which is the movement of surface water to the water table through the unsaturated zone, cannot be measured directly. Recharge rates are controlled by the amount of rainfall, by plant and soil factors that govern evapotranspiration, and by geologic characteristics that determine the rate of movement of water to the water table. In semi-arid and arid regions, according to a National Research Council (NRC) ground-water study on recharge, evapotranspiration is nearly equal to precipitation, so that little or no water is available for recharge to the ground-water system except after very large rainfall events, which are infrequent in such climates (NRC,

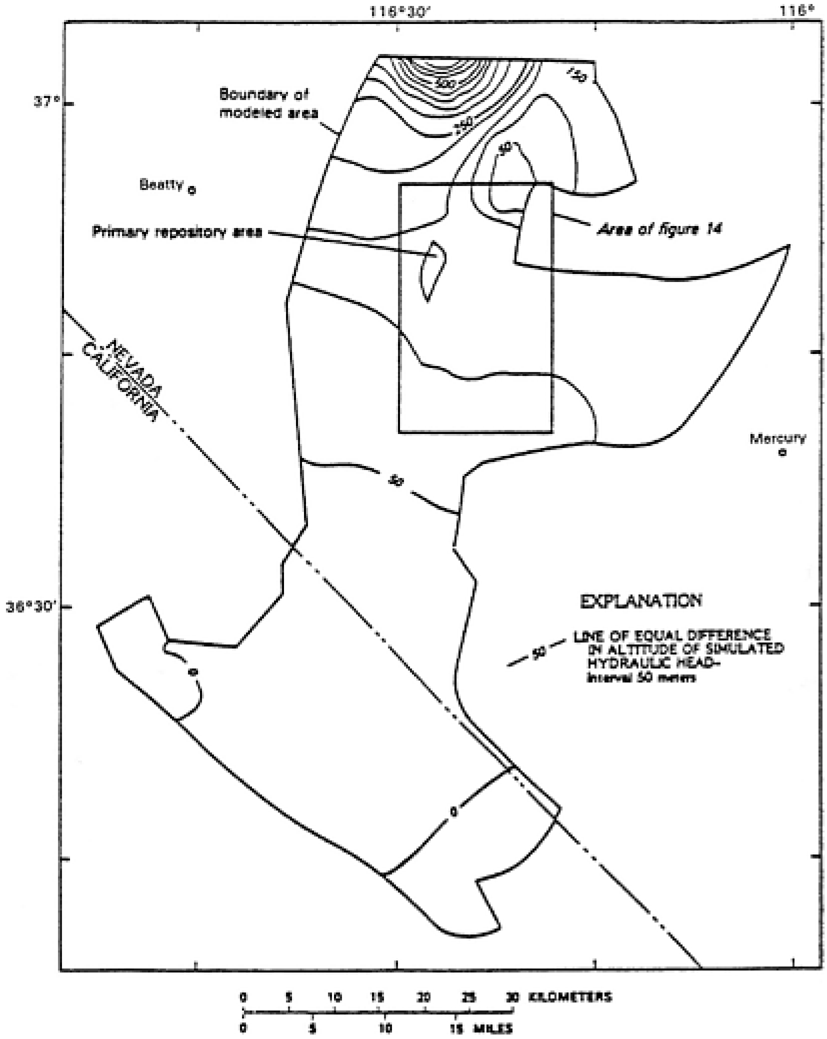

Figure 3.8
Differences in simulated hydraulic head between baseline simulation representing present-day conditions and the simulation involving a postulated 100 percent increase in precipitation. (From Czarnecki, 1985.)

1990). While there are several methods for estimating recharge, the NRC study cautions that different methods result in different estimates even for the same locale and time period, and concludes that recharge estimation is difficult and characterized by large uncertainties. Moreover, it suggests that reliable estimates of recharge in dry climates may be beyond present-day technology (NRC, 1990). For this reason, hydrologic models that describe water table responses to changing climatic conditions using simplified recharge assumptions must be used with caution because of the large uncertainty associated with those assumptions.

While these caveats are true, the method suggested by Eakin et al. (1951, P. 14–16)—often referred to as the Maxey/Eakin Method—has been widely utilized in Nevada for more than 40 years. The method is purely empirical but has been shown to provide reasonable estimates of recharge. However, the use of this method to predict recharge under climatic conditions that are quite different from the present is speculative.

Thus, to the extent that an increase in the number of discharge points (indirectly measurable with the fossil record) indicates an increase in recharge, the sparse fossil record of wet-ground species allows a qualitative observation that recharge increase during the last glacial maximum was moderate (Table 3.2).

Czarnecki's model of increased recharge predicts discharge in the central Amargosa Desert west of Ash Meadows in an area that is currently dry. Sediments in this area indicate the existence of a past discharge area (J. Czarnecki, written comm., 1992).

CONCLUSIONS

Much more information is needed on discharge, recharge and transmissivity to characterize the ground-water flow system. **The panel concludes that identifying the cause of the steep hydrologic gradient north of Yucca Mountain, where the potentiometric surface descends sharply about 300 m southward, is the top priority in predicting future behavior of the Yucca Mountain flow system in general, and the water table in the vicinity of the proposed repository, in particular.**

There is virtually no evidence in the glacial-age fossil record for an increase in average annual precipitation exceeding 40 percent of modern amounts. The nature of full-glacial plant species assemblages can be attributed to a relatively cold and dry climatic regime with increased average annual precipitation approximately 40 percent above that of the present, coupled with mean annual temperatures approxi mately 7°C below those of the present. The only local record of perennial water where none exists now, other than the Fortymile Canyon-7 site, comes from Dead Man Canyon in the Sheep Range. The general dearth of fossils of wet-ground plant species in the Late Quaternary fossil record and their absence during the full glacial, suggest that an and to semi-arid climate and low recharge conditions have prevailed over the last ca. 50,000 years. **The panel concludes that pluvial climates in this region were much drier than that which would be inferred from the standard application of the word "pluvial." Therefore, models of climate variability that call for 100 percent increase in precipitation are probably overly conservative.** More refinements in the data and techniques for estimating recharge, together with the use of model scenarios that reflect more closely established paleoclimatic conditions, are necessary to obtain realistic models of the response of the water table to increases in precipitation.

Nevertheless, according to the only model to date, an increase in precipitation due to a climate change has the potential to cause a rise of the water table on the order of 100 m. **Until more complete hydrologic data of the area are obtained to constrain the model assumptions, the panel must regard climate change as a possible means of raising the water table significantly in the Yucca Mountain area.**

The one known record of local wet-ground vegetation in Fortymile Canyon, which is dated to the Middle Wisconsin, is consistent with modeled responses of ground-water to increased recharge north of the steep hydraulic gradient north of Yucca Mountain (Czarnecki, 1985). This record deserves further consideration, in part because it lies ca. 60 m above the present floor of Fortymile Canyon, and 100 m above the present water table. It points to the need for additional investigations of paleohydrologic conditions in the vicinity. However, it does not necessarily constitute evidence for a radical change in the elevation of the water table in the vicinity of the Yucca Mountain, south of the break in elevation of the potentiometric surface. As previously mentioned younger, full-glacial middens from the same area, within 0.5 km of that site, provide no evidence of wet-ground vegetation at elevations somewhat below and above the site at which the wet-ground evidence was found.

RECOMMENDATIONS

Because of the importance of understanding the steep hydrologic gradient, the panel recommends that a series of wells be drilled in the region of the gradient north of Yucca Mountain. These wells should be drilled both within and outside the gradient, and should be deep enough to penetrate the pre-Tertiary carbonates underlying the tuffs. Hydraulic head and permeability measurements from both pumping and interference tests in these holes should lead to at least a qualitative improvement in understanding the hydrological regime in this important area, as well as the cause of the steep gradient.

These wells would also provide data on the elastic properties of the Paleozoic rocks underlying the site, data that are much needed to understand the potential for rises in the water table due to seismic activity (see Chapter 5 of this report). The wells should be designed in close coordination with those responsible for geochemical studies (including isotopic. studies) because, as outlined in Chapter 2, an understanding of hydrogeological processes at Yucca Mountain will depend heavily on inferences based on geochemical signals.

There is a need for a better characterization of the long-term variability of the hydrologic regime in the Yucca Mountain area. Additional chronological data are needed from isotopic analyses of ground waters, as well as of spring deposits and dry lake sediments. **The panel recommends that samples of water present at various depths in the Alkali Flat/Franklin Lake subbasin be dated and further analyzed for the isotopic concentrations.** If these studies confirm that the last recharge episode actually dates to 10–15 ka, then important inferences may be drawn regarding the coupling of climatic change and recharge events, for instance, that the full glacial was not wet enough to recharge the hydrologic system in the Yucca Mountain region. Furthermore the ground water history can be deduced from the isotopic content of the water.

The results of mathematical modeling are also strongly conditioned by available hydraulic data (Appendix B). The panel has several specific recommendations on the collection and interpretation of hydraulic data, which should lead to improvements in the ability to estimate potential changes in water level, are listed below.

- **Existing well data (drilling, stratigraphy, repeat temperature surveys, pumping tests) should be re-examined to determine if the major permeable horizons are associated with specific formations and/or formation interfaces.**
- Permeability studies of the "slug test" variety in some Yucca Mountain area wells produced an anomalous fall-off response in the graphic representation of fluid behavior. This has been interpreted to indicate the state of the minimum horizontal stress in the crust (Szymanski, 1989). **The panel recommends that the anomalous response in the slug tests be reanalyzed to determine the cause of the observed behavior.** (See Appendix B for a fuller discussion).

- **The panel considers it worthwhile to attempt to remeasure hydraulic potential in isolated sections of existing boreholes.** A knowledge of the three-dimensional hydraulic head distribution is essential for developing a detailed three-dimensional model of fluid flow in the Yucca Mountain area.
- One of the major sources of uncertainty in the present understanding of the hydrologic regime is the recharge in the Fortymile Canyon area, and the rate of evapotranspiration in the Franklin Lake Playa area. **The panel therefore recommends that efforts be made to characterize more fully the recharge and discharge rates for the ground-water system in the vicinity of Yucca Mountain.**
- Independent determination of permeability is necessary to constrain and guide computer modeling studies. Since much of the permeability is believed to be fracture controlled, laboratory measurements of permeability on small rock samples may not be representative of flow conditions in situ. Well tests in this case are invaluable. **The panel recommends, therefore, a carefully designed set of pressure interference tests between wells to delineate the permeability structure in the Yucca Mountain area.**

The hydrologic models of the Yucca Mountain area have been restricted to the Tertiary tuff aquifer, which may be an oversimplification of the ground-water system. **The panel recommends that a multi-layered model be constructed which includes both the shallow Tertiary aquifer and the Paleozoic carbonate rocks with currently available data. The data should also be used in a sensitivity analysis to test the coupling between the tuff aquifer and the Paleozoic carbonates.** Current hydrologic information from the single hole penetrating the carbonate aquifer in the Yucca Mountain area is insufficient to characterize such a model. Additional drill hole data and tests in the carbonate aquifer are critically needed. Such a model should also be useful in assessing the "drain" concept as an explanation for the steep hydraulic gradient north of Yucca Mountain. **Moreover, the panel recommends that geochemical data, as well as hydraulic data, be used to assess the validity of the modeling. The panel strongly urges that the use of geochemical interpretations become an integral part of the hydrogeological modeling at Yucca Mountain.**

The panel recommends that, as sufficient data become available, more definite three-dimensional modeling studies be carried out for both the transient and steady states. A transient three-dimensional model can provide new insights into the evolution of the ground-water system over the past 10–20 ka. Such modeling of the transient state is routinely used in geothermal reservoir engineering to model the natural state.

As discussed earlier in this Chapter, an understanding of the relationship between recharge and precipitation is still evolving. It is essential to consider methods to reduce uncertainty in estimates of ground water recharge under different climatic conditions. **In particular, the panel recommends undertaking an assessment of the reliability of empirical methods and newly developing considerations in estimating recharge under present arid, as well as much wetter and cooler, conditions to evaluate the potential effects of climate change on the water table.**

The panel recommends that the assumptions and results of Czarnecki's (1991) model of increased rainfall and recharge be critically reviewed considering paleoclimate reconstructions, the potential for increased precipitation, and methods of calculating recharge in and regions. To reduce the present uncertainty level, it will be necessary to obtain additional hydrologic, paleoecologic, and recharge data to provide constraints on future modeling efforts.

To resolve the apparent contradiction between what appears to be increased discharge (as a consequence of increased high-elevation recharge at Fortymile Wash) and evidence in the Yucca Mountain area for increased aridity in existing fossil records, **the panel recommends a continued search for evidence of perennially moist conditions in currently dry water courses in the area, and for high-elevation (>2000 m) fossil records contemporaneous with a possible latest Wisconsin-early Holocene pluvial episode. The panel also recommends establishment of a data base relating species' ranges to measured climatic parameters, and its application to the macrofossil record.** This would provide a great deal of new information on climatic stability of the Yucca Mountain vicinity, and would allow more sophisticated climatic interpretations of the fossil data. The known climatic affinities of plant species within a given fossil assemblage could be used for quantitative derivation of paleoclimatic parameters, if standardized data existed.

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Can an Igneous Intrusion Raise the Water Table to the Proposed Repository Level?

SUMMARY OF TERTIARY VOLCANIC HISTORY OF THE REGION

The late Tertiary geologic history of southwestern Nevada has been dominated by volcanism and the consequent deposition of volcanic flows and tuffaceous rocks. Yucca Mountain, like most surrounding ranges, is composed dominantly of a series of well-studied, Miocene ash-flow tuff units and silicic volcanic rocks. The tuffs erupted between 17 and 7 Ma from multiple caldera complexes located throughout the region (Christiansen et al., 1977; Byers et al., 1976). The uppermost unit of these widespread eruptive tuff deposits exposed on Yucca Mountain is the Tiva Canyon member of the Timber Mountain caldera complex, dated at about 12.5 Ma.

Concurrent with the silicic episode, large-volume olivine basalt lava flows erupted between 11 and 8 Ma near and within some of the silicic centers in the Yucca Mountain region (Crowe et al., 1983a and 1986). In roughly the same time period (6–10 Ma), other basalt and basaltic andesite flows erupted that appear unrelated to the silicic centers (the "older rift basalts" of Crowe et al. (1986)). These basaltic flows probably mark the beginning of "modern" basin and range extension in this region of southern Nevada. Modern basin and range extension refers to the stress and faulting regime, still active today, which is responsible for the formation of the modern range and basin blocks. It is generally dated between 10 and 7 Ma throughout the northern Basin and Range region (see, e.g., Stewart, 1978; Zoback and Thompson, 1978; Zoback et al., 1981).

The next and last-recorded volcanism in the Yucca Mountain region involved flows and cinder cones of young basalt that erupted in Crater Flat, which borders Yucca Mountain on the west, between 3.7 and 0.13 Ma (the "younger rift basalts" of Crowe et al. (1986)). The alignment of cones suggests they were fed from dikes as is commonly the case elsewhere (see, e.g., Nakamura, 1977). These younger basalts interfinger with and are overlain by unconsolidated to semi-consolidated clastic (fragmental) material deposited in a variety of environments in response to extensional normal faulting.

STYLE AND SIZE OF A LIKELY INTRUSION IN THE YUCCA MOUNTAIN REGION

We concur with the conclusion reached by previous researchers (Crowe et al., 1983b; DOE, 1988) that the possibility of future large silicic caldera-forming eruptions can be dismissed from consideration in the Yucca Mountain area. The Miocene caldera complexes formed because of their location in a continental intra-arc setting close to, and overlying, an active east-directed subduction zone along the western continental margin. The subsequent evolution of the San Andreas transform fault system (see, e.g., Atwater, 1970) replaced the subduction zone along much of the western margin and changed the tectonic regime in Nevada. The current southernmost boundary of active subduction below western North America is the Mendocino triple junction at approximately 40°N, more than 300 km north of the latitude of Yucca Mountain. The present day volcano-tectonic regime throughout the northern Basin and Range province, which includes most of Nevada and the western half of Utah, is extensional, characterized by low-volume basaltic eruptions, such as those in Crater Flat (see, e.g., Christiansen and Lipman, 1972).

The age of the basaltic volcanism in Crater Flat remains the subject of considerable debate. Isotopic ages between 3.8 and 0.3 Ma have been obtained from the cinder cone centers in Crater Flat by Turrin and Champion, (1991). However, Wells et al. (1990) have argued that a nearby basaltic center, the Lathrop Wells cone located about 20 km south of Yucca Mountain, may be as young as 20 ka based on geomorphic and pedogenic characteristics as well as on the scatter of isotopic ages. Wells et al. (1990) further suggest that this center contains at least three discrete and temporally separate eruptive events that may have occurred over time spans of 1–10 ka, based on mapping of stratigraphic relations of tephra (volcanic debris) units here and elsewhere in the Basin and Range (Crowe et al., 1989). In contrast, $^{40}Ar/^{39}Ar$ age dating of two separate flow units in the Lath rop Wells volcanic center yields arithmetic mean of ages of 183 ±21 and 144 ±35 ka (Turrin et al., 1991). On the basis of this dating and as yet unpublished K/Ar dates, Turrin et al. (1991) conclude that there were two eruptive events at Lathrop Wells, dated at 136 ±8 ka and 141 ±9 ka. They speculate that the time interval between flows may be less than 100 years because field mapping and paleomagnetic data indicate remanent magnetization directions only a few degrees apart for the two flow units. Differences in remanent magnetization directions can be accounted for by secular (temporal) variation of the earth's magnetic field, the rates of which have been calibrated in other volcanic fields at approximately 4° per 100 years. Thus, they interpreted the nearly identical remanent directions in the two Lathrop Wells flow units to imply a short duration (<100 years) of eruptive activity. However, this interpretation of the paleomagnetic data is controversial. Because both remanent directions are very similar to the time-averaged geomagnetic field in the study area, these directions could represent equally well eruptions separated by 100 years, 10 ka, 100 ka, or 1 Ma.

The geologic record thus indicates that the only likely style of intrusion in the Yucca Mountain region in the lifetime of the repository is a low-volume basaltic dike intrusion. To place constraints on the size and geometry of such intrusions we can look at the occurrence and distribution of other Quaternary basaltic dikes, flows, and cinder cones throughout the northern Basin and Range province. Most of this young basaltic activity occurs within the modern basins, with many of the eruptive centers occurring along basin margins, particularly localized near range-bounding faults (Smith et al., 1990). In virtually all cases, including the basaltic centers in Crater Flat, the alignment of cinder cones, fissures, and other eruptive centers trends N to NNE. This is the direction of the regional maximum horizontal principal stress throughout the Quaternary, as established by earthquake focal mechanisms and fault striation studies (Zoback, 1989). The N to NNE trend thus appears to coincide with a principal stress plane, as expected theoretically (Nakamura, 1977; Nakamura et al., 1978). There is little or no shear stress across these planes. Models in which basaltic volcanism is localized along (or controlled by) major crustal shear zones have little or no corroborating analogs, either theoretically or in field examples.

Some basalt intrusion has occurred within what are now modern range blocks. A dike exposed along the Solitario Canyon normal fault where it cuts into the Yucca Mountain range block NW of the proposed respository site has been dated at 10 Ma (C. Fridrich, pers. comm., 1991). This dike is probably part of the the "older rift basalt" sequence that erupted in the early phases of modern basin and range extension. Models that fit ground magnetic highs located further to the south adjacent to Solitario Canyon include a vertical zone of increased magnetization which could be interpreted as a basaltic dike (Bath and Jahren, 1985); however, there is no surface expression of such a dike in this region. Bath and Jahren (1985) did report a personal communication from R. B. Scott, USGS, that weathered basalt fragments had been found at a lower elevation and about 0.8 km south of the magnetic anomaly. However, despite excellent and abundant outcrops (especially scarp slopes of ridges) and core from five continuously-cored drill holes, no dikes younger than 10 Ma have been found within the Yucca Mountain block. (See also R.F. Marvin, written comm., 1980 in Carr et al. (1986)). However, the drill holes were vertical as are most of the dikes.

Dikes produced during the most recent episode of basaltic volcanism near Yucca Mountain are typically 2 m or less in width (Bruce Crowe, pers. comm. in Carrigan et al., 1990). The maximum width of the 10 Ma dike exposed along the Solitario Canyon fault mentioned above was also 2 m (Chris Fridrich, pers. comm., 1991). Theoretical consideration of elastic strains in surrounding rock in response to normal stresses caused by dike widening constrains dike dimensions (Davis, 1983). A brittle crust 10–15 km thick should limit dike width in the upper crust to 2–4 m (Carrigan et al., 1990). Thus, theoretical considerations, as well as structural and geologic evidence from the Yucca Mountain region and the surrounding Basin and Range province, suggest a likely geometry for basaltic dike intrusion in the upper crust in the vicinity of the repository to be a 2–4 m wide (or less) near-vertical zone of intrusion of magma initially at about 1200°C.

A recent analysis of seismicity in regions of young volcanism cited the Crater Flat area as one example of a number of young basaltic centers characterized by a paucity of background seismicity and low rates of recent normal faulting (Parsons and Thompson, 1991). Parsons and Thompson suggest that ongoing regional extensional strain accumulation is released in these areas primarily by expansion of the crust due to dike intrusion, rather than by normal faulting. Thus, the present-day lack of seismicity down to very small magnitude ranges ($M \approx 0$) in the vicinity of Yucca Mountain (Gomberg, 1991) may be an indication of either active dike intrusion at depth or the fact that the regional strain accumulation was largely relieved by the Quaternary basaltic volcanic events. Possible evidence for molten rock below Crater Flat is discussed later in this chapter.

Estimating the accumulated extensional strain since the last basaltic episode (20 ka or 140 ka), using an average Quaternary extension al rate of 0.01 mm/yr (based on estimates of Quaternary offset of faults in the Yucca Mountain region, (Scott, 1990), results in an accumulated extension on the order of 0.2 m (for a 20 ka event) or 1.4 m (for a 140 ka event). This strain could be relieved either by extensional faulting or by dike intrusion. A 1.4 m dike width is consistent with the other estimates of basaltic dike widths in the Yucca Mountain region as discussed above. It should be noted, however, that not all dike intrusions accommodating regional strain necessarily reach the surface or the near-surface. Dikes tend to propagate subhorizontally in the seismogenic (brittle, elastic) crust in the depth range of about 2–10 km (Halls and Fahrig, 1987; Rubin and Pollard, 1987).

MODELS OF WATER TABLE RISE ACCOMPANYING DIKE INTRUSION

Two independent types of models of water level changes associated with dike intrusion have been investigated for Yucca Mountain. Both models assume intrusion along a vertical zone beneath the repository with the top of the intrusion located 250–500 m below the water table. Kuiper (1991) computed the potential water table rise due to the increased temperature effect of the intrusion using both scoping calculations and a two-phase (steam and water) flow model. In an alternate approach, Carrigan et al. (1990) focused solely on the elastic strain effect of a dike intrusion that results in a region of dilation just above the level of dike intrusion and a region of contractional strain centered just below the dike top. Pore-water pressure enhancement was computed from the volumetric strain, and the excess pore-water pressure was used to drive the flow.

The computed response of the water table for these two very different models was less than 25 m for the thermal model of Kuiper and generally 4–6 m for the poro-elastic model of Carrigan et al. Kuiper assumed a 10 km long, 100 m wide vertical disk-shaped zone of temperature rise (related to dike intrusion) with a 1-hour period of temperature increase of 300°C, and included the effects of subsequent cooling. His maximum increase in water table level of less than 25 m was strongly dependent on both the assumed width and the magnitude of the temperature increase related to the zone of intrusion. Thin basaltic dikes intrude into the near surface at approximately 1200°C and cool rapidly. Unfortunately discussion of Kuiper's model was available only in an abstract in which the exact intrusion dimensions assumed to produce the 100 m wide zone of a 300°C temperature increase were not given.

Carrigan et al. (1990) investigated the effect on the water table of intrusion of both a 2 m and a 4 m wide dike beneath the repository. Using uniform permeability values, they found a maximum rise of the water table of 4 m for a 2 m wide dike (6 m for the 4 m wide dike) over a 1 km wide region centered on the dike, occurring 8.6 days after the intrusion. For an assumed vertical permeability that was everywhere 10 times greater than the horizontal permeability, they found a peak of 6.5 m in less than one day for the 2 m dike. They also examined the effect of a tenfold to a thousand-fold increase in the vertical permeability (10^1 to 10^4) of a local 100 m wide zone centered on the dike, such as might result from cracking induced by the intrusion. Sharp peaks in the water table rise were predicted for the large vertical permeability enhancement. The maximum water table rise of 12 m for the 2 m wide dike (14 m for the 4 m dike) was associated with a 10^3 increase in vertical permeability. Further increases in vertical permeability resulted in no further increase in the water table level, suggesting that any further rise was limited by the volume of ground water available to be channeled into the zone of enhanced permeability.

POSSIBLE DEEP (LOWER CRUSTAL) MAGMA CHAMBERS IN THE YUCCA MOUNTAIN REGION

Analysis of far-traveled earthquake waves (P-waves) passing nearly vertically through the crust and upper mantle beneath Yucca Mountain and surrounding regions (Evans and Smith, 1992) shows no evidence of a low velocity feature that would suggest a volume of molten rock (or magma chamber) beneath Yucca Mountain. The minimum size of a feature identifiable in that study is 4 km across. However, a volume of slightly lower velocity material extending upward from the Moho (the boundary between the earth's crust and mantle) to within 12 km of the surface was found directly to the west, beneath Crater Flat. The seismic P-wave velocity in this anomalous volume beneath Crater Flat is about three percent lower than material beneath Yucca Mountain in the same depth range. The standard errors of this type of velocity analysis are about 0.4–0.5 percent; the minimum believable velocity change is therefore on the order of 1 percent.

The three percent lower velocity anomaly identified under Crater Flat is considerably smaller in magnitude than velocity anomalies associated with known large-scale high silica magma chambers, such as Long Valley, where velocity decreases of six to eight percent are typically found (Iyer, 1988). **The possibility that molten rock is present beneath Crater Flat deserves further study.**

To establish the presence (or absence) of molten rock currently beneath Crater Flat, a broader and higher resolution analysis would be required. Seismic reflection profiling techniques tuned for identifying the presence of "fluids" should also be included. Such a study would need to include the determination of the velocity of shear (S) waves, which are much more sensitive to the presence of fluids or melts, in addition to P-waves, as well as attenuation studies, which investigate the rate of change of the amplitude of the waves, and can detect the presence of fluids or melts.

PROBABILISTIC ASSESSMENT OF THE LIKELIHOOD OF A BASALTIC DIKE INTRUSION

Several assessments of the probability of a basaltic dike intrusion at Yucca Mountain are available. All rely on dividing the probability assessment into two steps: (1) P_1, the probability of basaltic activity in the general region of the proposed repository, including Lathrop Wells and Crater Flat (called the Crater Flat Volcanic Zone by Crowe), and (2) P_2, the conditional probability that, given volcanic activity in the area, the assumed basaltic dike would be close enough to affect the proposed repository. The total probability of volcanic activity affecting Yucca Mountain is calculated as the product of the two.

Crowe and his co-workers (1983, 1986, 1991) have estimated P_1 to be on the order of 10^{-6} per year, based on four clusters of events in 3.7 Ma. If the seven identified events in the region are used, the rate is twice this. If volcanic activity in the region is mature and will wane in the future, as suggested by Crowe (1991), the assumption of a stationary rate of occurrence is conservative for future occurrences.

The calculation of P_2 depends on the geometry of the proposed repository with respect to the volcanic field, and on the spatial characteristics governing the location of vents and dikes (the size and ratio of length to width of the volcanic field). The trend of the major axis of vents or feeders of contemporaneous eruptive centers within a volcanic field can be estimated from paleovolcanic events; this trend is NNE for the two main eruptive centers in the Crater Flat Volcanic Zone. The trend of dikes is generally perpendicular to the direction of least principal horizontal stress, which is WNW-ESE in the region. Sheridan (1990) developed an illustrative calculational model of these effects and estimated P_2 at about 8×10^{-3}. Crowe (1991) estimated P_2 at about 10^{-2}.

Combining these two probabilities (P_1 and P_2) leads to a total probability of about 10^{-8} per year for the occurrence of a basaltic dike that would affect the proposed repository at Yucca Mountain. This is the thresh old probability for consideration of events that might affect a waste repository in EPA regulations, and is indeed a small number.

Some researchers (e.g., Smith et al., 1990; Trapp, 1989) use other areas within which to define probabilities of occurrence, based either on geometrical areas (Smith et al.) with some consideration of the present regional stress regime or on interpretation of aeromagnetic data (Trapp). Any associated calculations that assume that future volcanic vents are unrelated in space to existing vents have less credibility, in the panel's view. Furthermore, where probabilities are assessed only qualitatively (Smith et al., 1990), comparison to quantitative calculations is not possible. **While the uncertainty may be several orders of magnitude in the probability values described here, the panel concludes that the probability of volcanic intrusion into the proposed repository is low.**

CONCLUSIONS

Geologic observations indicate that the form of intrusion most likely to affect the repository is a near-vertical dike of basaltic composition, with a width of 2–4 m. Modeling of the pore-elastic effects of such a dike intruded directly beneath the repository (and with a top less than 1 km below the bottom of the repository) results in maximum water table rises of less than 10 m in both an isotropic case, in which rock properties are the same in all directions, and in a case where the vertical permeability is 10 times the horizontal permeability. Concentrating the water rise in a 100 m wide vertical highly permeable zone directly above the dike resulted in a maximum rise of 12–14 m when vertical permeabilities were enhanced 10^3–10^4 within the vertical zone. **Thus, the panel concludes that the elastic effect of dike intrusion would result in raising the water table no more than a few tens of meters.**

Models of the thermal effects on water table rise are highly dependent on the total amount of heat energy released as a result of the intrusion. The modeled 100 m wide zone of 300°C temperature increase produced a water table rise of less than 25 m; however, the number and exact configuration of dikes within this zone was not specified. For a single dike of 2–4 m width, the modeled 300°C temperature rise over a width of 100 m is clearly an overestimate of the heat energy. As an upper bound, considering energy equivalence, the maximum amount of energy available in a 4 m wide dike intruded at an effective temperature of 1400°C (which includes effects of the latent heat of crystallization) is approximately equivalent to a temperature rise of about 60°C, not 300°C, over a 100 m wide zone. **In the opinion of the panel, therefore, a 25 m rise in water table is clearly a conservative upper bound estimate for the expected form of intrusion in the Yucca Mountain region.**

It is the panel's view that the low probability of a dike forming close enough to affect the proposed repository, combined with the small effect that a basaltic dike intrusion at Yucca Mountain would have on the water table, means that the threat of volcanic effects is sufficiently low that volcanic intrusions can be discounted as potentially disruptive events.

RECOMMENDATIONS

Unfortunately, modeling of the coupled thermal and pore-elastic problem of the effects of dike intrusion on the water table has not been addressed. While the thermal effects may dominate, the panel notes that this modeling could establish the maximum water table excursion due to dike intrusion.

The study plan for the characterization of volcanic features calls for drilling core holes to investigate aeromagnetic anomalies that may represent either buried volcanic centers or intrusive rocks (probably basaltic in composition). No mention is made of studying the core to determine the extent, if any, of hydrothermal activity (temperature variations in adjacent rocks, fluid inclusion studies, hydrothermal alteration products) that may have been induced by intrusion or extrusion of a body of volcanic rock. **The panel recommends this type of investigation be added to the work plan.**

Further teleseismic studies for better definition of the low velocity zone beneath Crater Flat should be carried out. A combination of P- and S-wave velocity and attenuation studies should constrain both the nature and source (e.g., possible fraction of melt if present) of this velocity anomaly. Although the panel does not consider it likely that either a larger volume or a different style of igneous intrusion will be found that is inconsistent with the recent geologic record, it would be prudent to follow up with an evaluation of this anomaly to ascertain its significance.

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Could a Nearby Earthquake Cause Flooding of the Proposed Repository?

INTRODUCTION

Contemporary Crustal Motions

Understanding contemporary crustal motions in the Yucca Mountain area is fundamental to estimating recurrence rates and magnitudes of earthquakes that might be expected, and hence to the problem of assessing tectonically induced hydrologic effects on Yucca Mountain. Theoretical models to date, as discussed later in this chapter, suggest that both interseismic (between earthquakes) and coseismic (during earthquakes) strain are unlikely to cause flooding of the repository for a broad range of crustal strain rates. Nonetheless, the contemporary strain field is one of the few parameters in most models of tectonically induced water table fluctuations that can be measured, and both the number and size of potential excursions of the water table from its present level induced by earthquakes over the next 10 ka are dependent in part on contemporary crustal motions. The lower the contemporary displacements, the lower the chances of tectonically induced flooding, and vice versa.

As was suggested in Chapter 2, both rapid and slow tectonic extension has affected the Yucca Mountain area over the last 20 Ma. Here it is important to distinguish between rapid extension and slow extension rates in the region. The Great Basin in general is currently extending slowly and fairly diffusely, at a total rate of 5–10 mm/yr. However, at various times in the past, rapid extension (10–30 mm/

yr) developed locally in narrow domains embedded in various places in the province. Slow extension appears to be associated with the formation of the modern basins and ranges in the northern Great Basin, and largely post-dates the early rapid extension. The Death Valley extensional fault system is the youngest of these rapid-extension domains. Much of the basin-range topography in the region is a reflection of rapid extension over the last 10 Ma (especially south of Yucca Mountain in the Death Valley region), but slow extension faults that post-date rapid extension appear to control much of the topography in the Yucca Mountain area (e.g., the Bare Mountain fault). While relatively rapid extension may still be active in the Death Valley/Owens Valley region, the Yucca Mountain area has not experienced rapid extension in the last 10 million years. Thus while rapid rates may have approached 30 mm/yr in mid-Miocene time (15–10 Ma), the average extension rate across the entire basin and range since then is probably on the order of 10 mm/yr, currently concentrated in areas to the west of Yucca Mountain (see, e.g., Eddington et al., 1987; Wernicke et al., 1988).

Several independent means of determining contemporary motions have been employed, emphasizing varying scales of deformation. Calculations of contemporary plate motions for the last 2 Ma combined with the movement history on the San Andreas fault indicated a discrepancy between the inferred net plate motion between the North American and Pacific plates and the measured slip on the fault. Reconciling the difference in movement estimates requires including WNW extension across the Basin and Range of about 8–11 mm/yr (Minster and Jordan, 1987). This rate is corroborated by very long baseline interferometry (VLBI), a technique that measures distances on the earth's surface by the use of radio waves, and can measure small changes in those distances over time. The changes in distance measured suggest contemporary extension of not more than 12 mm/yr in the region east of the San Andreas fault (Minster and Jordan, 1987).

Seismic analysis, although covering only a brief segment of the recent past, suggests similar values. Adding up the fault slip and averaging it into an extension rate across the southern Great Basin yields approximately 3.5 mm/yr total. This calculation excludes the 1872 Owens Valley earthquake which had a magnitude of approximately 8 ($M \approx 8$) on the western edge of the basin. The rate increases to 29.2 mm/yr if that event is included (Eddington et al., 1987). The northern Basin and Range yields values on the order of 8–10 mm/yr. These values are in broad agreement with local geodetic studies (e.g. Savage, 1983) and estimates from slip rates on Quaternary faults (summarized in Eddington et al., 1987).

There are few data on the nature and rate of contemporary motions in the Yucca Mountain area because of the low seismicity there. On the basis of a summary of geologic information related to Quaternary vertical offsets on faults on Yucca Mountain, Scott (1990) estimated the present extension rate to be less than 0.01 mm/yr. There is, however, considerable uncertainty associated with that estimate.

Elevation surveys in Nevada along a line from Tonopah to Las Vegas that crosses the southern part of Crater Flat and Yucca Mountain suggest 25.5 ±3.5 cm. of subsidence of Crater Flat relative to Bare Mountain and Yucca Mountain over the last 75 years, based on three surveys from 1910 to 1984 (Gilmore and Carr, unpublished data). These data indicate a subsidence rate of over 3 mm/yr. Such subsidence could occur as a result of slip on dipping normal faults and hence would require extension rates at least two orders of magnitude greater than the accumulated slip rates on Quaternary faults on Yucca Mountain estimated by Scott (1990). The greater rate, 3 mm/yr, is consistent with the rate determined for the southern Great Basin excluding the Owens Valley event. Unfortunately, no detailed geodetic information across Yucca Mountain has been published that could be the basis for evaluating the difference in rates.

Additional uncertainty about the total strain of the region results from unknown relative contributions of strike-slip and normal dip-slip movement on faults of the region. The 0.01 mm/yr Quaternary extension rate reported by Scott (1990) was based only on the easily observable vertical components of fault offset in alluvium. Often small lateral offsets on young faults are much more difficult to detect and measure. Contemporary analysis of fault motion from seismic data (focal mechanisms) of small to moderate earthquakes in the southern Nevada region indicate the dominance of strike-slip motion (Harmsen and Rogers, 1986). This dominantly strike-slip mode of deformation is observed in focal mechanisms in a 100–150 km wide zone along the Northern Basin and Range-Sierra Nevada border zone (Zoback, 1989). Large historic earthquakes with surface rupture in this zone all show primarily strike-slip offsets (Beanland and Clark, 1992; Bellier and Zoback, 1991; dePolo et al., 1987; Saunders and Slemmons, 1979).

Thus, the focal mechanisms in the southern Nevada area and regional relations all suggest that a future large magnitude earthquake in the Yucca Mountain area would be strike-slip, not dominantly dip-slip as has been assumed in the past. Consideration must be given to potential strike-slip fault zones such as a possible fault up Yucca Wash. Furthermore, extension rates calculated from vertical fault offsets may be poor indicators of the total contemporary strain in the Yucca Mountain region.

Recommendation

Another means of measuring changes in crustal dimensions is the Global Positioning System (GPS). The advent of GPS satellites in the last five years provides the capacity to measure crustal positions accurately to within approximately 3 mm for 10 km baselines, without need for line-of-sight procedures between stations (Hager et al., 1991). In addition, GPS yields vector motions (changes in lengths and angles) between points, rather than simply angles or absolute distances, and does so with easily deployable receivers. Thus GPS offers the potential to constrain the contemporary displacements in the Yucca Mountain area. With this rapidly developing technology, it is expected that in the near future GPS surveys will be able to distinguish baselines extending at <0.3 mm/yr or greater. Although the impact of this information on increased understanding of the hydrologic conditions around Yucca Mountain is uncertain, knowledge of the rate of crustal strain is clearly important to nearly any seismic risk assessment related to the proposed repository site. **In the panel's view, this information used as an accessory to, or confirmatory of, more standard information on rates of crustal deformation, can provide additional confidence in the prediction of future tectonic behavior and the probabilities of seismic events in the area.**

The panel recommends that a combined GPS and leveling program be carried out across the Yucca Mountain region. GPS is more accurate for horizontal motions than vertical, but with relatively short baselines and atmospheric corrections it is also capable of precision at the millimeter scale in the vertical. Leveling surveys and local GPS surveys across Quaternary faults have been initiated by the USGS (G. Perasso, pers. comm., 1991), but longer baseline studies that offer valuable information for evaluating risk should also be included.

HYDROLOGIC RESPONSES TO EARTHQUAKES

Assessing how ground water in a specific locale will respond to a nearby earthquake involves several diverse considerations, including the hydrologic character of the region, the type of crustal rocks and their response to stresses, the tectonics of the region and likely type of faulting, historical seismicity (to evaluate the possibilities), and the probability that earthquakes of a particular size will occur. These considerations involve knowledge of a variety of disciplines and the application of several techniques. Besides hydrology and seismology, geology is needed to define the location, geometry, and potential of seismic sources; geophysics is required to identify the elastic properties of materials at depth; and historical seismicity must be considered to provide the experiences of past earthquake history; mathematics, especially the statistical/probabilistic subdiscipline, and modeling, or computations of likely behavior and responses, are necessary for evaluating the possible response of a system to earthquake wave disturbances, whether it is natural, like the hydrologic system, or engineered (see, e.g., Reiter, 1990). The likelihood (or probability) of the occurrence of an earthquake of a given size in a specific location is an important part of that evaluation.

Thus, in evaluating the range of possible responses of the water table to an earthquake that could reasonably be expected to occur in the Yucca Mountain vicinity, the panel has considered some examples from the historical record of water table responses to significant recent earthquakes; some modeling results, with the data and assumptions used in the calculations; and the probabilities of significant earthquakes occurring in the area.

There are two distinct responses of the ground-water system to an earthquake: (1) the dynamic response accompanying the passage of earthquake waves that follow the earth's surface, and (2) the response that accompanies the resulting permanent change (volume strain) in the rocks of the crust after the earthquake waves have passed through.

The dynamic water-well response is usually associated with dynamic changes in rock volume that accompany the type of surface wave called the Rayleigh wave. This response can occur at great distances from the earthquake epicenter. For example, the water level in a well in Florida fluctuated approximately 10 meters in response to the Alaskan earthquake of 1964 (Waller, 1968a). This dynamic response of ground water is a short-lived phenomenon known as a transient, and therefore is not relevant to the long-term behavior of the crust in the vicinity of a proposed repository.

The response of the ground-water system to the permanent post-earthquake changes in both strain and permeability of the rocks is of concern because either or both types of change may produce long-term changes in the level of the water table. The observed long-term responses appear to be related to either of two phenomena: (1) a change in pore fluid pressure resulting from the dilatation produced by the permanent volume strain, or (2) an increase in permeability produced by the dynamic ground motion. The two phenomena may be difficult to distinguish from one another.

HISTORICAL EVIDENCE

The hydrologic changes associated with moderate and large earthquakes have been known for some time (Carnegie Institution, 1908; La Rocque, 1941). As suggested above, many of the observed phenomena are associated with the dynamic response (Eaton and Takasaki, 1959; Cooper et al., 1965; Liu et al., 1989). As examples, post-seismic changes in both spring flow and stream flow were documented in response to: (1) the 1952 Arvin-Tehachapi earthquake—M=7.1 (Briggs and Troxel, 1955), (2) the 1959 Hebgen Lake earthquake—M=7.3 (Stermitz, 1964), (3) the 1968 Matsushiro earthquake swarm (Nur, 1974), (4) the 1983 Borah Peak—M=7.0 (Whitehead et al., 1985; Wood et al., 1985; Wood, 1991), and (5) the 1989 Loma Prieta earthquake—M=7.0 (Rojstaczer and Wolf, 1991, 1992). The stream flow was observed to increase following the earthquake in all of these instances. Post-seismic changes in ground-water levels have also been observed in (1) a series of Los Angeles basin earthquakes from 1933 to 1940 (La Rocque, 1941), (2) the Dixie Valley-Fairview Peak, Nevada earthquakes of 1954 (Bell and Katzer, 1987), (3) the Arvin-Tehachapi earthquake (Davis et al., 1955), (4) the Good Friday earthquake in Alaska, 1964—M=8.6 (Waller, 1968a; Waller, 1968b), (5) the Borah Peak earthquake (Wood et al., 1986; Wood, 1991), and (6) the Loma Prieta earthquake (Rojstaczer and Wolf, 1991, 1992). This is not a comprehensive list of previous observations in this area.

Several mechanisms have been postulated to explain the observed long term changes. As suggested above, the mechanisms fall into two classes: (1) a change in pore pressure associated with volume strain produced by the earthquake, and (2) an increase in permeability caused by dynamic ground motion. The best documented of hydrologic responses are for the Alaskan Good Friday earthquake; the Loma Prieta earthquake; and the Borah Peak earthquake.

In some instances it is difficult to distinguish between the hydrologic effects produced by volume strain and those produced by an increase in permeability. If the steep gradient north of Yucca Mountain (discussed in Chapter 3 of this report) is the result of a permeability barrier, dynamic shaking could increase the permeability of the barrier. The results of a study modeling this scenario, also described in Chapter 3, suggest a modest rise of the water table, about 40 meters, beneath Yucca Mountain.

Loma Prieta, California

The Loma Prieta earthquake (M=7.0) of 1989, which was in the San Francisco area, caused a tenfold or more increase in the amount of water flowing in streams of the nearby Santa Cruz Mountains. The most dramatic increases were measured in a 30–40 km2 area north of the end of the ruptured part of the fault that caused the earthquake. This phenomenon was well documented by a number of stream gages in the area that measured the increase in stream flow (Rojstaczer and Wolf, 1991, 1992). The best explanation of these observations appears to be that the ground motion, which was amplified along Skyline Ridge as the surface wave passed through, increased the permeability of the shallow aquifers. The increase in permeability caused the water table to drop as the ground water drained downward through the rocks and discharged to the streams. Numerous water wells at higher elevations along Skyline Ridge dried up, suggesting that the mechanism described was the likely cause. As yet, no analysis of the magnitude of the increase in permeability has been made. This hydrologic response to the Loma Prieta earthquake is the best documented example of this phenomenon. The increases in streamflow persisted for 6 to 12 months.

Anchorage, Alaska

Wells in the Anchorage area near the epicenter of the Good Friday, 1964 earthquake (M=8.6) had changes in water levels that are clearly associated with that event (Waller, 1968a; Waller, 1968b). This earthquake is the largest in North America in historic time. It involved thrust faulting (denoting compressed crustal rocks) along a 1000 km section of the Alaskan subduction zone. As in the Loma Prieta event, in most cases the ground-water levels declined by amounts ranging up to approximately 5 meters. Most of the observed lowered water levels were in quite shallow wells.

Borah Peak, Idaho

The hydrologic responses associated with the Borah Peak earthquake of 1983 (M=7.0) are well documented (Wood et al., 1985; Wood, 1991). The Borah Peak earthquake involved movement on a normal fault (denoting extended crustal rocks) along the western front of the Lost River Mountain Range in Idaho. Many springs in the area in creased their flow. The baseflow, or ground-water discharge, to local streams also increased. The stream flow effects resemble those for Loma Prieta, but smaller; in the Borah Peak area stream flow increased by a factor of only two or three. Unlike Loma Prieta, however, there was a 5–35 m increase in water levels in the vicinity of the epicenter attributed to an increase in ground-water pressure (Wood et al., 1985; Wood, 1991); in one area of cavernous carbonate aquifers, unconfined fountaining of jets of ground water to 5 m in the air occurred for several minutes, about 2 km west of the fault trace.

The largest observed effect of increased water pressure resulting from the Borah Peak event occurred in the Clayton Silver Mine, about 50 km west of the epicenter, where the seepage into the mine following the earthquake could not be controlled, as it had been before the earthquake, by the 930 gallons per minute (gpm) pump previously installed to keep the mine dry. Due to post-earthquake changes, an increase in ground-water flow caused the water level in the mine to rise approximately 60 m in a matter of 10 days. Two weeks later a 2000 gpm pump was installed and the water was lowered back to the mining level. Increased flow into the mine could have resulted from either an increase in permeability or a rise in pore pressure. The data are insufficient to determine which was the cause.

The mechanisms responsible for the hydrologic changes resulting from the Borah Peak earthquake are not easy to interpret. Wood (1991) observed that the major increase in hydraulic head (elevation to which water rises because of ground-water pressure) occurred on the down-dropped fault block. This suggested to him that a compressive volume strain within the block caused the rise in water level.

RECOMMENDATION

The information included here by no means reflects an exhaustive search of the water level changes associated with earthquakes. **The panel recommends that DOE conduct a detailed literature search to determine the hydrologic effects of other historic earthquakes, local and worldwide, to evaluate the potential for significantly large water table rises by the coupling of the seismic and hydrologic systems.** Such information as earthquake magnitudes, type of faulting, rupture length of the fault, depth to the pre-earthquake water table, and details of the hydrologic system and its response should be obtained for comparisons and analysis of possible natural analogs to Yucca Mountain.

EARTHQUAKE MODELS

Introduction

Two approaches have been used to evaluate the impacts of a nearby earthquake on the water table. One models the strain in the traditional way, using dislocation theory, which examines the effect of the fault movement associated with an earthquake on the surrounding rocks. The difficulty with the dislocation model is that it does not yield a regional change in the state of stress. The mathematical procedure integrating the change in stress across the fault, in effect, balances the resultant extension on one side of the fault following an earthquake caused by movement on that fault with the compression on the other side of the fault. The change in stress thus sums to zero. This suggests that the increase in pore-water pressure on the compressed side of the fault will dissipate as the water is driven towards the opened pores on the extended side of the fault and equalize. A rise in the water level is thus unlikely.

The second approach is to model the change in the regional stress caused by a normal-fault earthquake in a region of extension, where the earth's crust is pulling apart, such as the Basin and Range. In that case the earthquake has the effect of removing the horizontal tension. Release of the horizontal tension is roughly equivalent to increasing the horizontal compressive stress. This then compresses the rocks at depth, squeezing out ground water, which now can only move upward. This mechanism could raise the water table.

Both modeling approaches (the dislocation and the regional stress change), have been used to analyze the effects of an earthquake on the water table level. Carrigan and King (1991) used the dislocation model and focused on a relatively shallow depth, approximately 1 km below the surface. A subsequent analysis (Carrigan et al., 1991) included depths to 8 km and high-magnitude earthquakes. Cook and Kemeny (1991) used the regional stress change model. Bredehoeft analyzed the problem (unpublished, Appendix D) using a three-dimensional dislocation analysis similar to that of Carrigan and King (1991). The panel also did an analysis using the regional stress change model.

Dislocation Models

Dislocation model analyses suggest that a small disturbance of the water table, generally a rise of less than 10 m would result from a M=6.5–6.8 normal fault earthquake (Carrigan et al., 1991; Bredehoeft,

Appendix D). Looked at in the larger context, zones of extension on one side of the fault are balanced by nearby zones of compression across the fault. Unless the fault is exceptionally impermeable, local ground water flow will quickly flow across it to equalize initial changes in pore-water pressure. Thus, the ground water tends to move horizontally, inhibiting vertical excursions (Carrigan et al., 1991). One has to invoke an improbable permeability distribution with this model to produce a large water table rise.

Regional Stress Change Models

Cook and Kemeny (1991), and the panel did very similar analyses for the regional change in stress in the deep crustal rocks that accompanies a nearby earthquake. Both analyses assumed a 100 bar (=100 atmospheres=1500 psi) drop in the shear stress that accompanies an earthquake. Both used a simple poro-elastic analysis based primarily on the elastic properties of the rocks in question. Cook and Kemeny (1991) obtained the porosity, rock density, and elastic constants used in their model from seismic refraction data. The panel used rock properties derived from the tidal and barometric analysis of Yucca Mountain water wells (Galloway and Rojstaczer, 1988).

Parameter values for the model used for analysis by the panel were obtained from Galloway and Rojstaczer (1988). These values indicated that the Paleozoic carbonate is extremely stiff, with very low porosity. In a very stiff rock a significant part of the strain is taken up by the solids in the rock, rather than by the pore space. However, the parameter values for the Paleozoic carbonate are based on a single drill core from that unit, and therefore may not be reliable.

In evaluating the effect of stress on pore pressure, the ratio of the change in mean stress to change in pore pressure (known as *Skempton's B coefficient*) can be derived if one knows certain elastic properties of the whole rock and of the individual minerals that make up the rock. These properties are known as the rock bulk modulus (incompressibility), K, and the bulk modulus of the minerals (solids) that make up the rock, K_s. The assumptions and parameters used to compute the changes in pore pressure are outlined in Box 5.1.

To illustrate the effect on the water table of the difference in compressibility between the mineral grains and the whole rock, the panel made calculations for rocks with the same properties as the lower tuffs (Galloway and Rojstaczer, 1988), a rock type with elastic properties that seem typical of crustal rocks. For the lower tuff Galloway and Rojstaczer's parameters suggest K/K_s is 0.66, which yields a rise of 22 meters.

BOX 5.1 ASSUMPTIONS FOR DETERMINING CHANGES IN WATER LEVEL

The calculations that yielded the results in Table 5.1 are based on the following assumed parameters:

(1) a solid with a grain compressibility, $1/K_s$, of 2.2×10^{-12} cm^2/dyne;
(2) a Poisson ratio of 0.25;
(3) a 100 bar drop in the shear stress;
(4) a seismogenic srustal thickness of 10 kilometers;
(5) an unsaturated porosity at the wate table of 0.01; and
(6) a rock porosity for the saturated crustal rocks of 0.15.

The results depend upon the ratio of the mineral grain compressibility ($1/K_s$) to whole rock compressibility ($1K$), or K/K_s

Table 5.1 indicates that as the rock becomes much more compressible than the individual grains (the K/K_s ratio decreases), much of the volume strain is taken up in the pore space causing the spaces to close and the water to be squeezed upward. The table shows that the results can approach a water level rise of 100 m or more only if the compressibilities of the whole rock is considerably greater than that of the individual minerals. As the compressibilities of the rock and the grains approach each other (a ratio closer to 1.0), the volume strain is distributed in both the solids and the pores, and the amount of the water level rise diminishes. Although direct data are not available, the general tendency of bulk rock compressibility is to decrease with depth, so that pore strain at or below 3–4 km or so should be quite low (K/K_s = 0.7–0.9). This suggests that the water table rise will be less than 40 meters (see Table 5.1).

Table 5.1 also indicates that knowledge of the properties of the carbonate rocks at depth at Yucca Mountain is essential to predicting water table behavior in response to changes in the regional crustal stresses produced by earthquakes. **The panel recommends that more data on the elastic and hydrologic properties of the deep carbonate aquifer be obtained so that credible models can be developed.**

Cook and Kemeny (1991) calculated a water table rise of approximately 10 m. Their calculation is based upon the assumption of seven percent unsaturated porosity. The panel calculated a potential rise of approximately 20 m, using a one percent unsaturated porosity and a K/K_s equal to 0.66. Had Cook and Kemeny used one percent unsaturated porosity their calculated rise would have been approximately 70 m. Their value is this high because the parameters they used resulted in a K/K_s close to 0.3 which the panel considers unlikely at the depths of the carbonate aquifer. In addition, one percent unsaturated porosity is probably a conservative assumption.

Table 5.1 Effects of Ratio of Mineral Compressibility to Rock Compressibility on Rise in Water Table Level Resulting from a Seismic Event

K/K_s	**Water Table Rise**
0.1	330 meters
0.3	150 meters
0.5	78 meters
0.7	36 meters
0.85	16 meters

The analyses of both the panel and Cook and Kemeny indicate that the calculated water table rise in the regional stress change model is especially sensitive to: (1) the amount of the stress change, (2) the compressibility of the whole rock versus the compressibility of the individual minerals that make up the rock, and (3) the moisture content above the water table.

The water table rise associated with a regional drop in shear stress, which accompanies an earthquake, is a transient imposed on the system. It is equivalent to adding an instantaneous slug of recharge to the water table over a large area. This will gradually dissipate. The panel did not attempt to analyze the life of this transient.

Sources of Information on In Situ Physical Properties

A summary of the information on in situ physical properties of the rocks applicable to earthquake modeling in the Yucca Mountain region suggests how inadequate the available data is.

Information on the characteristic stress drop following a seismic event in the Basin and Range, which is on the order of 100 bars, was determined by analysis of earthquakes (Kanamori and Anderson, 1978; Scholz et al., 1986). The data on the compressibility of the deep carbonate rocks beneath Yucca Mountain is based on analyses from a single well (Galloway and Rojstaczer, 1988) and on the seismic refraction data used by Cook and Kemeny (1991). These data suggest stiff rock of low permeability at depth.

Approximately 100 unsaturated samples of cores from above the water table at Yucca Mountain have been analyzed for porosity and saturation (Montazer and Wilson, 1984). The results show wide scatter. The deeper tuff units, closer to the water table, indicate two or four percent unsaturated porosity; some of the unwelded tuff is nearly saturated.

This sums up most of the data that are available for developing poro-elastic models to predict the behavior of the crust and the resulting hydrologic responses. This severe limitation of the data base produces large uncertainties in any analytical results.

CONCLUSIONS BASED ON RESULTS OF MODELING TO DATE

The models suggest that regardless of which approach is taken, only a modest rise in the water table of less than 50 m is likely to occur as the result of a nearby earthquake. **Although the models are based on very limited data, the panel concludes that stress/strain changes resulting from an earthquake are inadequate to cause more than a few tens of meters rise in the water table based on the convergence of the results by a variety of models and assumptions, especially if the deep carbonate aquifer is as incompressible as the limited data suggest.**

A Possible Alternate Modeling Approach: Discontinuum Analysis of Ground-Water Motion

Another approach to prediction of seismically induced ground-water motion is based on explicit recognition of the discontinuous state of a seismically active rock mass. Cundall and Strack (1979) introduce the essential concepts for analysis of the discontinuum mechanics of a saturated rock mass. In principle, the geometry of a rock mass can be described in terms of the spatial arrangement of the set of faults, joints and other fractures distributed through the rock body. Each feature is a potential pathway for fluid movement under the hydrostatic potential field (pressurized water) that may be generated by change in the stress distribution in the rock. The volume of fluid mobilized by an incremental change in the normal stress is deter mined by the storativity of the fracture aperture, i.e. the degree to which open fractures can store ground water, under the prevailing state of stress. Furthermore, each fracture is a potential conduit for fluid flow because it can open if properly orientated relative to the prevailing normal stress.

An obvious question concerning fractures in an otherwise low-porosity rock mass is whether the specific fluid storage capacity (storativity) of fractures at depth can provide sufficient fluid which, on subsequent displacement, can have a substantial effect on the water table in the near-subsurface. The states of stress in the shallower part of the crust are typically low, resulting in open fractures, and consequent high storativity.

It is well known that the hydraulic conductivity of fractures in rock is highly sensitive to change in fracture aperture, and therefore to change in the state of effective normal stress on the fracture. In principle, if a sufficient volume of water were mobilized by an earthquake, a network of fractures could provide a highly conductive channel to transfer water from domains of high pressure at depth to higher elevations in the host rock. Such a mechanism is implied in the hypothesis of seismic pumping (Sibson et al., 1975). The hypothesis suggests that an analysis based on discontinuous deformation of the rock mass may lead to a better understanding of the hydrologic response by focusing on the flow of fluid through fissures, or open fractures.

The Distinct Element Method is a comparatively well developed technique for discontinuous analysis of fractured rock masses. The principles of the method were presented initially by Cundall (1971). A rock mass is considered an assembly of rock blocks generated by the system of fractures transgressing the medium. The individual blocks may be considered to be continuous and elastic and to interact with their neighbors through a deformable joint contact. The description of the deformation behavior of the contact can account for the mechanical behavior of both the solid rock and the fluid in response to changes in the stress field.

Several examples demonstrate the application of discontinuum analysis of coupled solid deformation and fluid flow in a jointed, saturated rock mass (Pine and Bachelor, 1984; Lemos, 1988). These studies illustrate the utility of the Distinct Element Method for analysis of coupled rock deformation and ground-water flow. In particular, it is possible to account for the storativity of joints, joint and rock mass dilation during shear displacement, the stress dependence of joint and rock mass permeability, and the effect of the time history of motion on rock displacements.

These factors suggest that scoping studies with the Distinct Element method would contribute substantially to establishing possible modes of rock and ground-water response to seismic events at Yucca Mountain. The studies should be based on cross-section models of the Yucca Mountain setting, representing the general features rather than the details of the structural geology and hydrogeology. The model may be used to determine changes in ground-water conditions for stress changes within the range of values that may occur during a major seismic event. Furthermore, the model may be exercised to determine the site and seismic conditions that could induce substantial upward flow of ground water. It may then be possible to determine if physically reasonable conditions consistent with an hypothesis of seismically-driven flooding of the repository horizon would develop at the site.

RECOMMENDATION

The panel recommends that additional modeling be done to aid in the understanding and prediction of the likely behavior of the water table at Yucca Mountain in response to earthquakes. However, the models must be better constrained by data. Additional data are needed on the hydrologic and elastic properties of the deeper carbonate rocks and the chemical and isotopic composition of fluids in the saturated zone below the water table that underlies the proposed repository site.

As the panel's independent analysis indicates, data are needed on rock compressibility, porosity, and permeability of the deep aquifer. Several deep core holes should be drilled well into the Paleozoic carbonates to obtain this information.

Moreover, the dependence of the results on the unsaturated porosity of the vadose (unsaturated) zone requires that more knowledge of the properties, character and history of the unsaturated zone be obtained.

The panel is confident that this information will reduce the large uncertainty presently associated with all coupled processes models of the Yucca Mountain area.

EARTHQUAKE PROBABILITY

All of the modeled seismic/hydrologic effects are conditional upon the occurrence of an earthquake that releases extensional stress, causing dilatational changes in crustal rocks. A separate but important question is the likelihood of such earthquakes occurring in the vicinity of the repository. The panel has applied a preliminary eval uation of earthquake probabilities to Yucca Mountain (see Appendix E), using estimated slip rates for identified and suspected active normal or normal-oblique faults in the region (Figure 5.1 and Table 5.2).

Slip rates for the late Quaternary determined from field measurements on most of these faults are not available. One exception is the Windy Wash fault, for which a vertical offset of 40 cm on a 270 ka gravel is documented (Whitney et al, 1984), yielding a vertical slip rate of 0.0015 mm/yr. Movement on this fault is probably oblique, given its orientation with respect to the regional principal stresses. Assuming equal amounts of vertical and strike-slip movement, the total current slip rate on this fault is estimated as 0.0021 mm/yr.

In order to make estimates of slip rate on other faults and faulted zones close to Yucca Mountain, the panel has made several assumptions about the responses of these faults to the tectonic processes currently active in the area:

1. On average, all faults and faulted zones have a slip rate equal to that observed on the Windy Wash fault.
2. The current slip rate is proportional to the total displacement observed on the Topopah Spring member of the Paintbrush Tuff, as represented by Scott and Bonk (1984). (This unit is approximately 13 million years old and is not a reliable indicator of the current slip rate, but is used to estimate relative rates of current deformation.)
3. All moderate earthquakes (magnitude 5 to 7) that might affect crustal stress conditions and the water table near Yucca Mountain will occur on one of the identified faults or faulted zones.

The most critical of these assumptions is the first; it says that the slip rate on the Windy Wash fault is typical of slip rates on other faults in the region. The resulting estimated slip rates are in fact comparable to those estimated by other investigators, as is noted below.

The maximum magnitudes allowed on the ten faults in Table 5.2 range from 6.5 to 7, depending on the hypothesis considered in the next section. These values may be conservative in that the length of faulting mapped on Figure 5.1 may not support such large events. On the other hand, there is no conclusive evidence that these faults do not extend farther north or south, nor is there evidence that they are not structurally connected with other mapped faults to the north or south.

Table 5.2 shows, for each fault and faulted zone, the length of the fault, the offset of the Topopah Spring unit, and the slip rate estimated as described above. For this table, and for computations, the Ghost Dance and Abandoned Wash faults have been assumed to be one continuous fault. By way of comparison, Coppersmith and Youngs

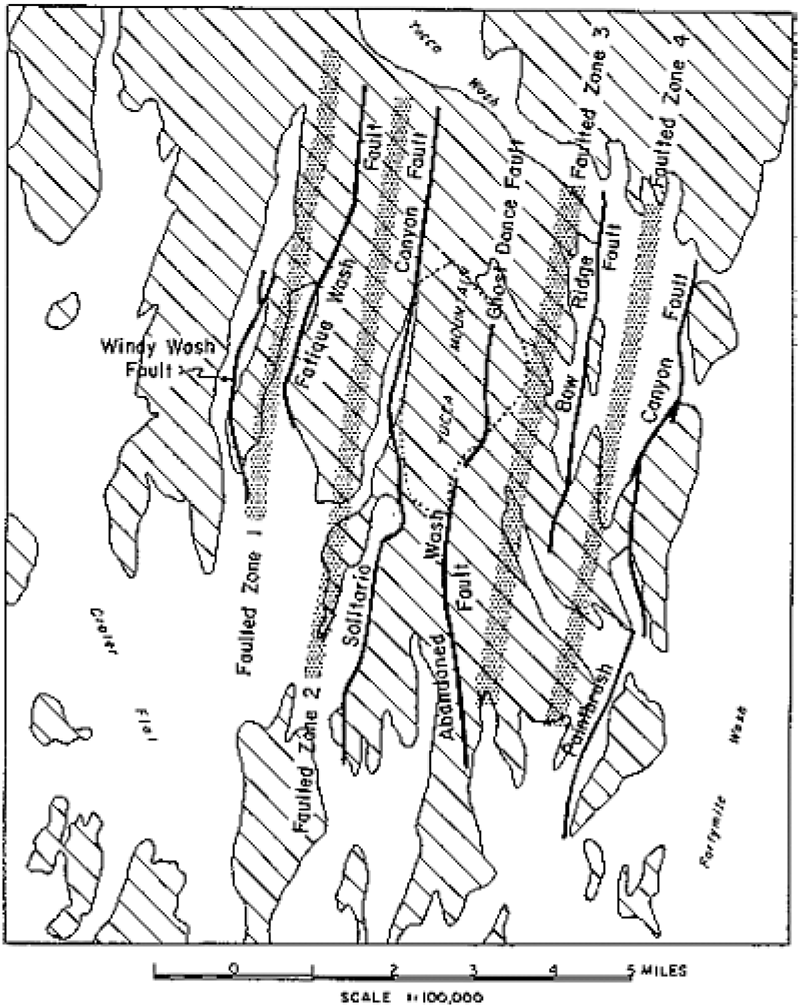

Figure 5.1
Active faults and faulted zones in the vicinity of Yucca Mountain. The proposed repository boundary is shown as a dotted line; rock units in the area are shown hatched.

(1990) estimated slip rates between 0.002 and 0.006 mm/yr for the six named faults, and a total slip rate of 0.0275 mm/yr. All tectonic activity was ascribed to the named faults by Coppersmith and Youngs, with other movement being secondary faulting subsequent to the main rupture. The total rate of 0.0275 mm/yr is of the same order as the total of 0.0212 mm/yr shown in Table 5.2. Again, the purpose here is to make reasonable estimates of slip rates that are not low or high by an order of magnitude. If alternative slip rates are preferred, their effects on the probabilities reported here would be proportional, at least at the lower probability levels. That is, if slip rates were doubled, the lowest probabilities reported in Box 5.2 would approximately double. It should be noted that in Chapter 4 of this report, a slip rate of 0.01 mm/yr was used to calculate effects of a basaltic dike intrusion. The panel does not consider this inconsistent because it is within the range of uncertainty in the estimates of slip rates.

In calculating current slip rates it is reasonable to consider that the offset of 270 ka geologic units is most relevant, and that only earthquakes in the immediate vicinity of Yucca Mountain (within several km) will affect ground-water levels for long time periods. Under these assumptions, the probability of an earthquake is 3 to 15 percent over 10 ka (see Box 5.2). The validity of alternative assumptions cannot be completely ruled out, however, and these might lead to

Table 5.2 Faults and Parameters Used In Analyses of Slip Rates

Fault	Length, km	Offset of Topopah Spring Unit m*	Slip rate,** mm/yr
Windy Wash	4.6	400	0.0021
Faulted Zone 1	10.0	70	0.00090
Fatigue Wash	7.1	60	0.00077
Faulted Zone 2	10.0	225	0.0029
Solitario Canyon	13.7	205	0.0027
Ghost Dance-Abandoned Wash	9.2	50	0.00064
Faulted Zone 3	10.0	338	0.0043
Bow Ridge	7.4	196	0.0025
Faulted Zone 4	10.0	130	0.0017
Paintbrush Canyon	12.0	206	0.0027
		Total	0.0212

*Taken from Scott and Bonk (1984) for all faults except Windy Wash, which was taken from Carr (1984).

**Estimated over the last 270 ka, based on slip rate for Windy Wash fault.

probabilities approaching 100 percent if a much larger area is included for the occurrence of an earthquake.

BOX 5.2 CONSIDERATIONS IN CALCULATING EARTHQUAKE PROBABILITIES

Important questions relevant to the calculation of earthquake probabilities within the Yucca Mountain area are:

- How close to the proposed repository must an earthquake be to affect the water table at the proposed repository?
- What are reasonable estimates of slip rates for faults in the area? Should we estimate them from observed offsets of 13 Ma geologic units, or from offsets of younger units?
- What fraction of the total fault slip is contributed by seismic events?

These issues and their effects on earthquake probability calculations are discussed in Appendix E. Assuming all slip on faults occurs seismically, the results can be summarized as follows:

	Occurrence Within Several km of Prop. Repos	Occurence Within Several 10's of km of Prop. Repos
Rates estimated over last 270 ka	3%–15%	10%–100%
Rates estimated over last 13 Ma	30%–100%	≈100%

It should be noted that apparent slip rates over the past 13 Ma are an order of magnitude larger than those described above. This can be concluded from two independent interpretations. First, the vertical offsets of the Topopah Spring Member shown on Table 5.2 total 1880 m; dividing this by the 13 Ma age of this unit gives a total vertical slip rate for the faults in Figure 5.1 of about 0.15 mm/yr. Assuming oblique slip with equal components of horizontal and vertical movement gives a total slip rate of 0.21 mm/yr.

A second, independent estimate of total slip rate can be obtained from paleomagnetic declination data in the region. These data (from Rosenbaum et al., 1991) indicate that the southern portion of Yucca Mountain has rotated 20° to 30° clockwise about a vertical axis since the emplacement of the 13 Ma Tiva Canyon tuff. Assuming that this rotation was accommodated by block rotations and strike-slip on faults between the blocks and assuming some average distance between the active faults, one can estimate the long-term average fault slip rate. For rotations of 20° and 30°, and faults spaced 5 km apart, average strike-slip rates (left-lateral) are in the range of 0.25 to 0.35 mm/yr. Assuming equal components of normal and strike-slip movement would yield a total slip rate of 0.35 to 0.49 mm/yr over a 5 km width.

If these high slip rates apply to the present and are assumed to be entirely seismic, it would imply that three to five earthquakes with a total oblique slip of 1 m could occur over the 5 km faulted zone within 10 ka. However, as previously discussed, the rate of extension of the region has undergone a documented decrease over the last 5–10 Ma, especially in the Yucca Mountain area, suggesting that the more recent slower rate of extension is a more relevant measure to apply to average slip rates.

An additional complication is that fault movement may be primarily strike-slip, as discussed earlier in this chapter, in which the north-trending faults (Figure 5.1) respond to WNW-ESE extension. If this is so, vertical offsets are not reliable as indicators of current total slip rates, and rates of activity may be higher than those discussed here. We have no data with which to estimate the possible rates of strike-slip faulting suggested by the focal mechanisms of small magnitude earthquakes in the Yucca Mountain area.

All of this points to the large uncertainties in estimating fault slip rate, given current information. These uncertainties undoubtedly can be reduced with further site-specific fault investigations. For perspective on rates of earthquake occurrence, the panel used the slip rates estimated over the past 270 ka (as shown in Table 5.2), with the understanding that further fault-specific site investigations are likely to improve or refine those estimates.

CONCLUSIONS

A range of uncertainties necessarily accompany any current assessment of the effects of earthquakes on the water table in the Yucca Mountain area, because of the absence of sufficient data to constrain the models, to determine slip rates, and to predict earthquake magnitudes.

There are uncertainties in the changes in the water table that could be induced by earthquakes. Based on modeling by the panel and others of which we are aware, and the historical record, these changes likely are small; but larger changes cannot be ruled out, given current uncertainties on rock properties at the site. Additional investigations are required to resolve these uncertainties, especially those regarding properties of the Paleozoic carbonate aquifer.

Furthermore, the likelihood of an earthquake close enough to induce significant stress changes in the vicinity of the proposed repository depends strongly on how large an area might be affected by earthquake-induced stress changes. If changes are limited to several kilometers around a fault, the probability of such an event occurring at the proposed repository is several percent in 10 ka (with large uncertainties). If changes occur over distances of several tens of km, then the probability is nearly unity that a moderate earthquake will occur within that distance of the proposed repository over 10 ka, even using the low slip rates derived from offsets of young gravels on the Windy Wash fault. All of these conclusions have significant uncertainty as a result of the uncertainties in fault slip rates.

Therefore, while there are uncertainties in current interpretations because specific site data are not available, the panel concludes that there is nevertheless sufficient confidence in the aseismicity of the site and in the inability of earthquakes to generate large water table changes at the site, based on the historical evidence and modeling results, to warrant further characterization of the site to determine its suitability for a MGDS. That is, while current uncertainties exist, the panel supports further characterization to resolve those uncertainties and to assess the safety potential of Yucca Mountain as the high level radioactive waste repository.

RECOMMENDATIONS

The panel is aware that fault studies are in the site characterization plan. Considering the large uncertainties in fault slip rates, lengths of faults, and ages of offsets, the panel strongly endorses studies to obtain the data necessary to reduce the uncertainties in the probability estimates.

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Summary of Conclusions and Recommendations

The charge by the National Research Council to the Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain was to evaluate an earth science issue, the potential effects on the water table of various natural processes in the Yucca Mountain area. The questions addressed by the panel dealt with the potential for ground water to rise more than 200 meters to the level of the proposed repository below Yucca Mountain: "Has it happened? and Can it happen?" The panel was not asked to, and did not, evaluate the suitability of Yucca Mountain as the location for a high level radioactive waste repository. Nevertheless, although the panel does not take a position regarding Yucca Mountain as a repository site, it recognizes the importance of the responsibility given to the Department of Energy by Congress. The decision concerning the long-term viability of any site being evaluated for a mined geological disposal system (MGDS) must be based on exacting, thorough, and well-coordinated and integrated scientific investigations, if the results are to lead to an understanding of the complex natural systems. It is this understanding that is necessary for prediction of the future behavior of those systems with some acceptable level of confidence. Moreover, predicting for a ten-thousand-year time period, with an exactitude unprecedented in human endeavors, will require a large number of data and substantial understanding of the interactions of those systems. Even with extensive data, predictions will depend heavily on expert judgment. The more that is known and understood about those systems and their interactions, the greater will be the confidence with which those judgments will be made.

This chapter summarizes what the panel considers its most important conclusions and recommendations that appear throughout the text. It does not cover every finding and recommendation in the report. On the other hand, some of the considerations and recommendations presented here are not directly related to the charge and are therefore not discussed in the body of the report, but bear on the scientific needs of the site characterization program identified by the panel. They may not be included in the present site characterization plan or be given what, in the panel's judgement, is the appropriate degree of attention.

It should be noted that the charge to the panel included an evaluation of the particular concepts described in the report by Szymanski (1989). Those concepts involved seismic pumping as the primary mechanism for driving the deep ground water to the surface in a cyclic progression of crustal stress changes. The panel evaluated the geologic evidence presented for this process and found both the evidence and the seismic pumping model inadequate to support the consequences attributed to them. As the panel was concluding its studies, the "minority" members of the 5-member external review panel selected by DOE and Szymanski to review his report informed the NAS panel that both the interpretation of some of the evidence and the model itself had changed: that Szymanski no longer believed that seismic pumping alone could drive the water up as high as he had stated in his report, and that he now had a *new* concept involving a thermally driven hydrotectonic cycle. This information was presented at the NAS panel's last meeting. Although there was no time left for the NAS panel to give consideration to a new thesis, nor was there a written document that could be evaluated, the cyclical concept as presented to the NAS panel appeared to have little validity, given that the panel is convinced that the geologic evidence refutes the assertion that ground water has risen repeatedly 100 meters or more in the recent geologic past. Because an essential part of the "cycle" has not yet happened, there is no basis for postulating a cyclical process whatever the proposed mechanisms involved.

The panel took two approaches in its examination of the potential for flooding of the proposed repository at Yucca Mountain by a rise in the ground-water level for a prolonged period. These were (1) to see if there was geological evidence for any large water-table excursions throughout the late Quaternary (last ca. 120 ka), and (2) to examine the results from model calculations that coupled hydrologic responses to tectonic, volcanic, and climatic changes. Given the known geologic and tectonic history of the area, these appeared to the panel to be the processes most likely to be able to affect the water table. Inasmuch as the only deposits associated with hydrothermal processes in close proximity to Yucca Mountain were formed more than 10 Ma during formation of the tuffs, and the only Quaternary evidence for warm springs observed by the panel was more than 55 km from Yucca Mountain, at Travertine Point (from the earliest Quaternary (2 Ma–700 Ka)), the panel discounted hydrothermal systems as a potential mechanism for raising the water table level in the Yucca Mountain area.

HAS IT HAPPENED?

Field Evidence

The panel spent several days in the field on separate occasions with proponents of the hypothesis that upwelling ground water caused the surface-parallel soil carbonates and the calcite-silica vein deposits in Trench 14 and elsewhere in the Yucca Mountain area, and with others claiming a surface soil-development, or pedogenic, origin for those deposits. On the basis of the panel members' knowledge, experience, and judgment, which were brought to bear on their observations of field geologic features, none of the evidence cited as proof of ground-water upwelling in and around Yucca Mountain could be reasonably attributed to that process. A few occurrences were equivocal, and some indeterminate, on the basis of field observation alone, but the preponderance of features (1) were clearly related to the much older (13–10 Ma) volcanic eruptive process that produced the tuffs in which the features appear, (2) contained contradictions or inconsistencies that made an upwelling ground-water origin geologically impossible or unreasonable, or (3) were classic pedogenic features recognized worldwide. Some examples follow.

Soils

The stages of morphological development of the carbonate accumulation within soils correlated well with the relative age of the various geomorphic surfaces (alluvial fan, pediment, sand ramp, etc.) throughout the area examined, as would be expected if the carbonate developed through progressive pedogenic processes. No such correlation would be expected if the carbonates developed from spring or ground-water upwelling.

On Busted Butte, the slope-parallel surficial carbonate deposits were attributed by proponents of the ascending water thesis to upwelling of ground water along a vertical, vein-filled fault or fracture zone. At the surface, however, the thickness of the surficial deposits decreases everywhere downslope. The downslope gradient of thickness of the carbonate deposit is uninterrupted where a pronounced vertical fault, one presumed source of the carbonate-bearing fluids, intersects the surface. Had this carbonate-filled vertical fracture zone been the source, the deposits downslope would have been thicker than the deposits immediately upslope. Moreover, the panel could find no evidence upslope for other vertical faults that could have served as sources for ground water upwelling that might have led to the continuous, uninterrupted thinning of the surficial carbonates downslope. The exposures on Busted Butte, where steep gullies cut clearly through the single vertical, vein-filled fault, would have clearly exposed such faults that might have provided conduits to permit such a continuous downslope thickness. Moreover, the presence of abundant root casts in the carbonate horizon is a clear indication that the carbonate formed in the soil zone rather than on the surface. **The panel concludes that meteoric water and progressive pedogenic processes produced the surface-parallel carbonate deposits. The hypothesized cyclic upwelling of ground water along faults demonstrably does not account for their presence at Busted Butte.**

Modern and Paleo-Springs

The abundant carbonate veins in the Yucca Mountain area, if they are the conduits of ascending subsurface waters during specific events of the past, should be capped by abundant tufa, or travertine, mounds. The absence of these surface deposits above purported extinct spring openings argues against ascending water. The excellent mound and feeder veins exposed at Travertine Point near the entrance to Death Valley have several features that confirm their hydrothermal origin, features that differ in all aspects from those of the Yucca Mountain area, as described in Chapter 2 of this report and briefly reiterated below. The one mound present in the Yucca Mountain area at Site 199, about 14 km SW of Yucca Mountain, appears to be the site of a still active seep, possibly of a perched water table, rather than the result of some tectonically driven upwelling in the past.

The modern springs present in the Yucca Mountain area and to the north of it all occur at the base of fractured ridges. The discharge of these springs is very small, in the range of 0.01 to 0.1 liters/sec. At least one of these springs, Cane Spring, has been observed on more than one occasion to become more active after a rainfall, with the water emerging at surface water temperatures.

Finally, the isotopic content of the water is similar to the local rainwater, differing only in having somewhat higher concentrations because of evaporation, and is unlike that of the local ground water. **These observations lead the panel to conclude that the spring derives primarily in part from rainwater infiltrating through fractures and emerging at the base through the adjacent fractured mountain mass, not from warm water ascending from great depth.**

Textural/Morphologic Evidence

Several features at Travertine Point are characteristic of deposits from ascending thermal waters: a tufa mound, carbonate veins with coarse-grained calcite (greater than 6 mm up to 1 cm), mirror-image symmetrical banding, and the absence of interlayered bands of amorphous silica, chalcedony or quartz. In contrast, the veins in Trench 14 and other exposures in and around Yucca Mountain show no mounds, are composed of extremely fine-grained calcite (less than 6 microns, or one thousandth the size of the Travertine Point calcites), have no symmetry, and contain thin interlayered bands of low-temperature, amorphous silica, and other materials, such as clay and volcanic ash, commonly found in desert soils. **The panel concludes from these features that the trench veins formed under low temperature, descending and evaporating meteoric water conditions, which implies an origin by surficial processes.**

Breccias

The widespread occurrences of breccias cemented by carbonate or carbonate-silica, which are considered evidence of explosive release of highly pressurized ascending fluids by proponents of this thesis, formed by a variety of processes at different times during the geologic history of the region. The origins of the breccias range from formation during the Tertiary high temperature volcanic processes 13–10 Ma to the low temperature mechanical erosion processes that produced the talus at the base of weathering slopes, most likely through the late Quaternary and probably into the Holocene. These breccias, therefore, could not, in the panel's view, constitute evidence for any one process at any one time. However, none of the breccias require formation as a result of upwelling of highly pressurized fluids from great depth. **Indeed, the panel concludes that all of the breccias appear to be best explained by processes that do not involve ascension of deep seated fluids.**

Those that were not clearly part of the volcanic process, e.g. talus breccias and fault breccias, had characteristics consistent with a pedogenic origin for the carbonate cements that bind the rock fragments. Carbonate root and twig casts throughout the thickness of the talus breccias suggest progressive development of the carbonate cement simultaneously with accumulation of the talus deposit. **Such features are possible only if they resulted from surface processes involving the evaporation of local rain water intermittently flowing downslope carrying dissolved carbonate from the upper slopes.** Thin carbonate deposits on the underside of still-uncemented talus blocks of tuff or basalt indicate the process is still continuing.

The fault breccia cements observed by the panel were extremely fine-grained, lacked concentric banding around the fragments, in some cases incorporated detrital minerals of anomalously old ages, clay or volcanic ash derived from the soil, and had isotopic compositions similar to soil carbonates. These characteristics are typical of carbonates formed by pedogenic processes.

The panel concludes that the cements of these fault breccia were deposited by precipitation from evaporating meteoric water as part of the soil-forming processes.

Isotopes

The panel's independent examination of stable and radiogenic isotope data shows that the Trench 14 and Busted Butte vein carbonates formed from the same water and processes as the soils, and that they could not have formed from the present-day ground water of the area. Their carbon ($^{13}C/^{12}C$) and oxygen ($^{18}O/^{16}O$) isotopic content overlap the range of values for modern soil carbonates, but differ significantly from the calculated isotopic content of carbonates in isotopic equilibrium with (or derived from) ground water of the isotopic composition measured for the Tertiary/Quaternary aquifer beneath Yucca Mountain. Available data suggest that the isotopic content of ground waters has not changed greatly over the past 300 ka. Additional study is needed, however, of the stable isotope content and isotopic ages of calcite as well as of their fluid inclusions in order to reach reliable conclusions regarding the isotopic content of paleo-ground waters. Moreover, data obtained by the DOE project investigators showed a correlation between depth and the carbon and oxygen isotopic content; $\delta^{18}O$ decreases and $\delta^{13}C$ increases with greater depth.

Similar results were obtained from the radiogenic isotopes: calcites above the water table showed strontium isotopic ratios that fell within the range of soil calcite and veins, while samples from below the water table had values within the range for waters from the tuff aquifer. Although some data obtained by the Yucca Mountain project scientists after the panel's analysis showed some inconsistencies in the isotopic composition of some carbonates above the water table in a core from one well, the fact that no other such inconsistencies were found in other wells in the vicinity suggest that it does not indicate a rise in the water table. Further studies are needed to understand the origins and processes involved.

Nonetheless, the isotopic evidence now available indicates that no prolonged excursion of the water table above its present level has occurred in the last ca. 100 ka.

Paleobiological Evidence

Field evidence from fossils obtained by a panel member and associates several years ago in a study unrelated to that of the panel indicated an absence of perennial spring discharge, or wetlands, in the last 50 ka in the vicinity of Yucca Mountain area, with one significant exception. Wet-ground plant species dated at about 50 ka were found at one site in the middle reaches of now dry Fortymile Canyon, the major drainage east of Yucca Mountain, 60 m above the canyon floor. This need not be interpreted as the result of a significant rise in the water table, because no other nearby fossil sites contain such evidence. It may be related to increased discharge in response to increased recharge in the area north of the steep hydrologic gradient, as described in Chapter 3, or it may result from locally perched water for which some evidence has been observed.

Recommendations

Further efforts should refocus away from the descending/ascending water controversy. Studies should concentrate on improving the knowledge of the ground water history of the Yucca Mountain area, to ascertain the validity of the widely held view that the isotopic composition of ground water of an area does not change much with time and that, therefore, differences in isotopic composition of present day ground water and carbonates at the surface are not the result of differences in the isotopic compositions of present and past ground waters. To that end, the following studies are recommended:

1. **Characterization of isotopic age and composition of calcites above and below the water table from cores should be supplemented with information on grain size, chemical variation (especially Ca-Mg-Mn-Sr) and D content of fluid inclusions.**

2. **Trenching and drilling of the Site 199 tufa mound should be carried out to describe and document the geology, hydrology, and geochemistry of this spring deposit in order to determine if it is the result of a perched water table and if carbonate is present in veins below the surface.**
3. **Mineralogical, chemical, and isotopic analyses of windblown dust should be conducted in order to determine the magnitude of the contribution of such dust to carbonate deposits.**

CAN IT HAPPEN?

Water Table Response to an Increase in Rainfall

In considering the various mechanisms that could conceivably cause a significant rise in the water table in the Yucca Mountain area, the panel identified a change from an arid to a pluvial (wet) climate and the consequent increased recharge of the saturated zone as a possible scenario. Analysis of the paleoecological and paleoclimatic information of the area suggests that even at the last glacial maximum during the Pleistocene Wisconsin 18 ka the Yucca Mountain area experienced no more than a 40 percent increase in rainfall over the present. Although there exist some uncertainties as to the climatic conditions during the terminal Wisconsin and early Holocene, most of the available data point to semi-arid to arid conditions for most of the last 50 ka. Thus, any models seeking to calculate water table changes due to increased recharge must take such facts into account.

The only existing model that has examined water table changes due to a change in climate assumed a 100 percent increase in precipitation and a corresponding 15-fold increase in recharge to the ground-water system. The approximately 100 m rise of the water table calculated, using these assumptions, is of concern. The panel recognizes that large uncertainties are associated with methods of calculating recharge, especially in arid and semi-arid regions. The assumed increase in recharge was obtained using an empirical procedure that has been widely applied in Nevada with good results; however, its use for calculating recharge under climatic conditions much different from the present must be viewed with caution. Moreover, strong evidence for an increase in precipitation of no more than 40% of present precipitation during the pluvial climatic episode suggests that the model assumption of a 100% increase is overly conservative.

Nevertheless, according to the only modeling to date, the panel must consider climate change to be a mechanism that has the potential to cause a large rise in the water table.

Recommendation

The panel recommends studies aimed at an improved understanding of the in situ properties and characteristics of the three-dimensional hydrologic system, the paleohydrological setting of Yucca Mountain, and the modern processes that control recharge of aquifers underlying the site to constrain better the models of the effects of increased precipitation. The hydrologic model that is used as a starting point and the results of three-dimensional modeling must be internally consistent with chemical and isotopic variations found in waters in the region. In the body of this report the panel recommends several detailed studies aimed at obtaining important information to achieve these ends.

Water Table Response to a Volcanic Intrusion

In assessing what processes are likely to cause a perturbation of the water table, the panel considered the long and complex Tertiary volcanic history of the region. A possible recurrence of the earlier highly explosive silicic volcanism that produced the ash flow tuffs, which are the predominant bedrock of the Yucca Mountain area, was dismissed because the subduction zone that caused it is now extinct in the Great Basin region. Concurrent and subsequent basaltic volcanism, related to the change to extensional tectonics that produced the Basin and Range structure, has experienced a progressive decline in volume, as expressed in the low-volume volcanic eruptions of Crater Flat which bounds Yucca Mountain on the west, and the latest and lowest in volume, Lathrop Wells cone, a short distance to the south.

Thus the geologic record of waning basaltic volcanism indicates that the only likely style of intrusion into the Yucca Mountain area during the lifetime of the repository is a low-volume basaltic dike. Dike occurrences in the area and theoretical considerations of elastic extensional strains discussed in Chapter 4 of this report suggest a near-vertical dike 2–4 m wide. Models of water table responses to a dike intrusion with a top approximately 1 km below the repository horizon, from the points of view of poro-elastic and thermal effects, modeled separately, resulted in rises of the water table of less than 10 m for the former and 12–14 m for the latter. **Thus, dike intrusion appears to be inadequate to cause a rise of the water table level of more than 10–20 m.**

The calculated probability of occurrence of a dike intrusion that would affect the proposed repository is a very small number, on the order of 10^{-8} per year. **Although there is considerable uncertainty**

in the calculation, this low probability combined with the small effect a dike intrusion would have on the water table means that volcanic effects can be discounted as a primary disruptive event.

Recommendations

To provide a broader basis for predicting water table behavior related to volcanic intrusions, and for establishing probabilities for renewed volcanic activity during the life of the proposed repository, the panel recommends the following additional studies.

1. **A study should be undertaken to model the coupling of the poro-elastic and thermal effects of an intruding dike on the water table.** This may provide a more realistic basis for predicting the maximum potential effect on the water table in the vicinity of the intrusion. The likelihood of such an intrusion within a significant distance based on such analysis can then be refined accordingly.
2. Earthquake wave studies have identified a columnar zone of low velocity crustal material under Crater Flat extending from the Moho, about 30 km beneath the surface, to about 12 km below. This suggests the possibility of partially molten rock in the form of intrusions at lower crustal depths. **To determine the presence or absence of molten rock, the panel recommends more detailed, higher resolution seismic measurements and analysis be undertaken, including the analysis of shear (S) waves, which are more sensitive to the presence of fluids, and the use of fluid-sensing seismic reflection profiling techniques.**

Intrusions related to the known Pleistocene basaltic events would not be expected to produce the large volume of low velocity material imaged by the current teleseismic studies. If the material responsible for the velocity anomaly is shown to be partially molten (which could be resolved with the proposed study) it would suggest a different, or at least a more vigorous, style of basaltic intrusion into the crust than is indicated by the recent geologic record.

Water Table Response to Earthquakes

To evaluate the effects of earthquake-induced changes in crustal stresses on the water table, the panel looked at some of the better known, more recent historic earthquake records and at some model calculations, its own and those of others. The panel was unsuccessful in its attempts to obtain information on water level responses to measured earth strains due to underground nuclear explosions on the Nevada Test Site that were monitored and about which information exists. In the panel's view, this information may be quite valuable in estimating likely ground-water responses to a nearby earthquake.

While the information the panel was able to consider within the time limits of the study was hardly exhaustive, it provided some idea of the range of what can reasonably be assumed on the basis of contemporary knowledge. The information upon which the panel based its evaluation therefore is suggestive rather than definitive. Many more data and analyses will be required to reduce the uncertainties inherent in judgments made on the basis of the limited site specific information available. **However, on the basis of the recent historical record and the results of modeling, the panel concludes that a water table response to seismically induced changes in crustal stresses is at least an order of magnitude less than the amount needed to affect the unsaturated status of the proposed repository.**

Given these considerations, along with the apparently low strain rates of the region, the low seismicity (both in magnitude and frequency of occurrence), and the low probability of occurrence of a large earthquake close to Yucca Mountain, the panel finds no reason that site characterization of the area should not proceed as planned.

The panel supports continued site characterization efforts to obtain the critical information necessary for more definitive assessments of the future behavior of the natural systems in the Yucca Mountain region.

Evidence from Historic Earthquakes

Water table changes due to earthquakes of moderate to large magnitudes (M=6–7) do not show a consistent pattern of response. In some cases the water table dropped while stream discharge increased close to the epicenters, as in the case of the Loma Prieta and Anchorage events. However, in the case of Borah Peak, increase in water levels were observed in the epicentral area, including unconfined jets of ground water fountaining to a height of approximately 5 m within 2 km of the fault trace on the down-dropped block, and an increase in hydraulic head in the Clayton Silver Mine 50 km from the epicenter. The causes of the hydrologic changes may not be the same for the three earthquakes, because the type of faulting differed in each case, indicating different stress conditions and crustal changes. **However, the magnitude of the water table changes for these earthquakes is consistent with modeling results and, therefore, provides further evidence that earthquake strain release mechanisms (or "seismic**

pumping") are inadequate to pose a threat to the unsaturated zone location of the proposed repository. It should be noted that estimates of the probability of occurrence of moderate earthquakes (M=5–6.5) within 0.25 of the fault length from the proposed repository site is less than about 15 percent. If larger areas are considered, the probabilities increase.

Earthquake Models

Various earthquake models have been used to analyze the response of the water table to stress changes in the crust resulting from earthquakes. It appears that water table rises of more than a few tens of meters are unlikely.

An analysis of the water table changes based on variations in relative compressibilities of the rock aquifer and its mineral constituents yielded a relationship suggesting that detailed knowledge of the elastic properties of the carbonate aquifer at depth is essential to prediction of the earthquake/water table interaction.

Recommendation

The panel recommends that studies be undertaken to determine the properties of the Paleozoic carbonate aquifer at depth, its extent in the Yucca Mountain area, its elastic and hydrologic properties, and its interconnection with the tuff aquifer, because the modeling was based on assumptions that must be verified if the results are to be credible. This information is necessary to increase confidence in predicting the future behavior of the hydrologic system in the event of a large nearby earthquake. In addition, knowledge of the Paleozoic carbonate properties is essential for the general characterization of the flow regime needed to assess effects on increased recharge as described earlier.

ADDITIONAL ISSUES OF CONCERN

Steep Hydrologic Gradient

Few data are available to constrain the complex hydrologic system acting in the vicinity of the proposed repository in the unsaturated zone. There are a number of specific problems that must be addressed through a comprehensive program of drilling, scientific testing and logging, and core and fluid analysis.

The panel considers an understanding of the local hydrologic system and particularly the nature and source of the steep E-W

trending hydraulic gradient located approximately 1.5 km north of the proposed repository site foremost among the problems that must be addressed early in the site characterization process. Existing hydrologic models of ground-water flow and the hydraulic gradient are somewhat simplistic because of lack of reliable information. The models consider horizontal flow through a layer of uniform thickness and characterize the modern head distribution using blocks with lateral contrasts in transmissivity. These models are then used to predict the impact of increased precipitation related to future climatic changes. However, simply characterizing the lateral blocks does not explain the source of the required enormous (three orders of magnitude) lateral transmissivity contrasts, nor do the models consider the possibility of vertical flow or any interaction between the shallow Tertiary aquifer and the deeper Paleozoic aquifer that is thought to carry the bulk of the flow in this region. Not until the source of the gradient is known can the potential hazard the repository may face due to future climate changes and/or tectonic events be evaluated with a high level of confidence. Specific predictions regarding hydraulic head, head gradients, pore pressure, permeability, thermal gradients and in-situ stress need to be made to distinguish among competing models for the source of this gradient. **The panel recommends that data relevant to these parameters be measured and collected in-situ in boreholes.**

Essential Data for Modeling the Ground-Water Flow System

A focused effort on understanding the source of the steep hydraulic gradient is not enough, however. More data are needed on the regional ground-water flow system. Improved estimates of the hydraulic parameters of the volcanic and carbonate sections, as well as better definition of heads and chemical and isotopic parameters, are essential for improving the calibration of flow models that have been used to evaluate the effects of increased precipitation. Vertical head gradients must be measured so that the three-dimensional nature of the flow field can be assessed. Careful monitoring of fluctuations in head (such as those related to tidal cycles) are also necessary to better define the relationship between rock strain and water table excursions.

The panel regards the general approach to acquiring the data needed for characterization of the Yucca Mountain regional flow system as given in the Study Plan 8.3.1.2.1.3 to be sound. Continued review of available data, coupled with the judicious use of preliminary modeling results, provides a useful framework for guiding and prioritizing future data collection. **However, the panel cautions that the sole justification for data collection cannot be the reduction in uncertainties in existing models of the system. Adequate site characterization for Yucca Mountain will demand an understanding of vertical, as well as lateral, fluxes of ground water and so will require new modeling delineating the flow system in three dimensions, considering the carbonate aquifer, the volcanic aquifers and the unsaturated zone.**

To address the hydrologic information needs, the panel recommends new and additional drill hole data. Planning the depth of such drill holes must be done with the above objectives of testing the flow systems in mind and not simply with the goal of better defining the water table.

Recommendation

Direct measurements of hydraulic head, head gradients, hydraulic parameters, and chemical and isotopic compositions of ground waters of both the Tertiary volcanic and the Paleozoic carbonate aquifers are essential. They require a series of thoughtfully placed deep (about 2000 m or greater) wells extending well into the carbonate aquifer. These wells should be located both in the vicinity of the hydraulic gradient and elsewhere for regional characterization. Current plans for "deep" holes described in Study Plan 8.3.1.2.1.3 are, in the panel's view, inadequate: in the crucial area of the unexplained high hydraulic gradient just north of Yucca Mountain only relatively shallow water table wells are planned.

Scientific Integration/Coordination

During the course of the panel's study, it became increasingly clear that there was a significant lack of communication among project scientists in different disciplines, especially between those of the hydrologic and solid earth sciences, and among the different scientific organizations involved in the study, such as governmental agencies and national laboratories. Moreover, even among the geologists and geophysicists there seemed to be little integration of their individual spheres of knowledge and data. **Because this important site characterization program is large and complex, strong scientific leadership must be provided to the participants and adequate attention must be paid to the continuing coordination and syntheses of scientific results.** It is to Szymanski's credit that he brought to everyone's attention the fact that the various scientific disciplines cannot work in isolation, that the information from one study may be essential to another, and that an integrated approach is the only way in which a true understanding of the complex interactive systems will emerge.

Recommendation

With the foregoing considerations in mind, the panel strongly recommends that DOE appoint a scientist as site characterization project coordinator. Such a person should not be currently associated with any of the participating organizations. That scientist should have a reputation for independence and excellence, as well as the experience in managing and integrating interdisciplinary programs. Such a scientific leader would lend further credibility to these investigations and their results. No large scale multidisciplinary study of this type known to the panel has been undertaken without a strong scientific leader guiding the coordination and integration of the ongoing efforts of the various parts of the project. It is the panel's opinion that had there been such a leader at the inception of this program, the controversy that brought this panel into existence would most likely not have developed, as the various working hypotheses would have been considered and addressed in an earnest and well-coordinated approach early in the program. Moreover, an integrated program guided by a strong scientific coordinator would probably have identified the steep hydrologic gradient early on as a major project-wide concern and would have approached it from a multi-disciplinary point of view.

In the panel's view, the anticipated higher-order systems integration efforts would be more effective if the complex solid earth and hydrological sciences studies for site characterization were coordinated and integrated first.

This recommendation should not be misunderstood as being critical of the dedicated scientists of DOE, the United States Geological Survey, the state of Nevada, the relevant national laboratories, and the private sector, whose integrity, professionalism, qualifications and knowledge are respected and admired by the panel. The concern is with enhancing the excellent individual efforts by integrating the results of the multidisciplinary studies so that all segments of the program are aware of the availability of needed information in a timely manner.

Flexibility in the Scientific Program

The panel recognizes the regulatory requirements that result in the need for carefully detailed study plans that can provide a public record of the methods, data, and results of site investigations. However, plans requiring adherence to a minutely scheduled sequence of observations and a rigid constraint as to analytical methods risk the loss of the use of one of scientists' most valuable tools, their intuition. Moreover, common in scientific investigations is the element of surprise, the unanticipated findings, that may be critical in developing new insights or understanding. The detailed study plans apparently leave little room for possible changes in direction of a study. Such an inflexible approach inhibits scientific progress in achieving the objectives of the studies. **The panel, therefore, wishes to register a plea for greater flexibility in allowing the scientists room to exercise their disciplines as they have been trained and as they know their expertise will be most effective.** Within the framework of a well-coordinated program guided by a strong scientific leader, the panel believes such an approach can provide quality assurance and other regulatory needs while allowing scientific latitude to flourish. It can only result in greater enhancement of the scientific achievements of the program.

Appendixes

Appendix A—

A Review of the Isotope Geochemistry of the Yucca Mountain, Nevada, Proposed Nuclear Waste Repository Site.

Prepared for the National Research Council's Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain

Douglas Rumble
Geophysical Laboratory
Washington, D.C., 20015-1305

Revised March 19, 1992

Summary

It has been proposed that calcite veins near the Yucca Mountain, Nevada, proposed nuclear waste repository site were precipitated from upwelling ground water (Szymanski, 1989). Testing the hypothesis is important because, if it is correct, future upwellings might flood the repository. Tests of the hypothesis carried out with isotope geochemistry show that the calcites did not precipitate from present-day ground water but, on the contrary, from surface waters. Changes in the isotopic compositions of ancient ground waters to bring them to parental compatibility with the calcites are larger than those inferred from available data. Additional information is needed, however, to reach definitive conclusions about the isotopic compositions of paleo-ground waters.

The methods of isotope geochemistry make it possible to test whether or not a particular calcite precipitated from a specific ground water, provided that analyses of both calcite and ground water have been performed. The efficacy of isotope geochemistry methods may be verified by considering the calcite veins of Devils Hole, Nevada, located 40 km SSE of the proposed repository site. Data on the stable isotopes of C and O and on the radioactive decay of Rb, U, and Th show that Devils Hole calcites precipitated from ground waters of the Ash Meadows flow system. Direct observation and sample collecting by SCUBA divers confirm the precipitation of calcite from ground water at Devils Hole.

The contrast between isotope relationships measured at Devils Hole and those at the Repository Site is striking and much greater in magnitude than could have been caused by chance analytical errors. Calcites at the Repository are too rich in ^{18}O to have precipitated from analyzed ground water. The calcites are also too low in $^{234}U/^{238}U$ and too high in $^{87}Sr/^{86}Sr$ to have precipitated from analyzed ground water. The Szymanski hypothesis is directly contradicted by the available data of isotope geochemistry. The isotope data are consistent with precipitation of Repository Site calcites from surface derived waters in the unsaturated zone.

Introduction

Szymanski (1989) has proposed that calcite veins in the vicinity of the Yucca Mountain, Nevada, Nuclear Waste Repository Site were deposited from upwelling ground water. His hypothesis has significant implications because it forecasts possible flooding of the Repository Site. Testing the hypothesis is important in order to evaluate the probability of such an hazard befalling the Repository. Szymanski, himself, has suggested a number of tests to be made of his hypothesis including: (a) monitoring the stability of the water table at Yucca Mountain; (b) measurement of in-situ values of "closure pressure"; (c) establishing the origin and age of "mosaic breccias"; and (d) measurement of the strain rates of wall rock separation during formation of calcite veins (Szymanski, letter of transmittal to R. A. Levich dated July 26, 1989, p.4). The following review discussion addresses test (c), as listed above.

Isotope geochemistry provides an objective means for testing whether or not a specific calcite precipitated from a particular ground water. Note that testing is limited by the availability of data: one has to have analyses of both calcites and ground waters to make the tests. Pairs of heavy isotopes such as ^{87}Sr and ^{86}Sr or ^{234}U and ^{238}U are not fractionated during calcite precipitation: they provide fingerprints of origin. Moreover, secular disequilibrium of ^{234}U, ^{238}U, and ^{230}Th gives age dates for calcite that are valid up to 500,000 years before present. Pairs of light isotopes such as ^{13}C and ^{12}C or ^{18}O and ^{16}O are partitioned between ground water and calcite during precipitation: They make possible estimates of temperatures of formation as well as fingerprint origins.

The following review discussion is divided into three sections: (1) C-O-H isotopes; (2) U-Th isotopes; and (3) Sr isotopes. In each section, the efficacy of isotopic methods to fingerprint the origin of calcite is verified by comparing data on Devils Hole calcite veins with that on ground waters of the Ash Meadows flow system.

Devils Hole is a useful test case. It is located only 40 km SSE of the proposed repository site so environmental factors are similar. Ground water is currently flowing through the caverns at Devils Hole. The precipitation of calcite from ground water has been directly observed and sampled by SCUBA divers. Calcite is presently precipitating above the water table at Devils Hole in the Brown Room, an air-filled cavern isolated from the surface by a natural syphon. I did not find isotopic data on samples from Brown Room. Calcite that precipitated from ground water below the water table occurs in mammary structures of finely-laminated growth layers coating the walls of open fractures. The calcite deposits from below the water table are usually referred to as "vein calcites" to distinguish them from speleothems above the water table. Calcite is observed to precipitate on seed crystals suspended in ground water below the water table. The youngest vein calcite that has been dated so far is 20,000 years old (Winograd, personal communication); the oldest is 566,000 years old (Ludwig, et al. 1990). The vein calcite preserves a continuous record of climate from about 570,000 to 60,000 years ago (570 – 60 ka). A plot of $\delta^{18}O$ vs. time for vein calcites closely resembles the marine $\delta^{18}O$ curve as well as polar ice core records (Winograd et al., 1988).

Devils Hole is a good test case because there is abundant isotopic data on both ground waters and vein calcites. Isotopic methods can be evaluated with confidence because it is well established that calcite did, in fact, precipitate from ground water at Devils Hole.

The isotope values $\delta^{18}O$ and δD are reported relative to VSMOW (Vienna Standard Mean Ocean Water, the isotope reference standard defined by the International Atomic Energy Agency, Vienna, Austria).

$$\delta^{18}O = \frac{[(^{18}O/^{16}O)\ x - (^{18}O/^{16}O)\ SMOW]}{(^{18}O/^{16}O)\ SMOW} * 1000$$

and

$$\delta D = \frac{[(D/H) \times - (D/H)\, SMOW]}{(D/H)SMOW} * 1000$$

Values of $\delta^{13}C$ are reported relative to PDB (Pee Dee Belemnite).

$$\delta^{13}C = \frac{[C^{13}C/^{12}C) \times - (^{13}C/^{12}C)\, PDB]}{(^{13}C/^{12}C)\, PDB} * 1000$$

Values of $^{87}Sr/^{86}Sr$ are reported as atomic ratios. Values of $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ are reported as activity ratios where the activity equals the number of atoms at time "t" multiplied by the decay constant.

Two ground-water flow systems dominate the hydrology of the Yucca Mountain area (see Chapter 3 of this report). The Ash Meadows system has its recharge in the Spring Mountains, near Las Vegas, Nevada, and discharges at Ash Meadows, Nevada, near the California state border. The aquifer is a Paleozoic limestone that is confined by aquitards both above and below in the stratigraphic succession. Owing to uplift and erosion, the aquitards have been breached in a number of fault block mountains throughout the region. The Alkali Flat/Furnace Creek flow system immediately underlies Yucca Mountain. Its recharge area is north and east of Yucca Mountain in the vicinity of Pahute Mesa and Fortymile Wash. Discharge is near Furnace Creek, Death Valley, California, and at Franklin Lake Playa, California. The aquifer beneath the Yucca Mountain area is composed of Tertiary and Quaternary volcanic tuffs and alluvium. Ground water flows primarily through fractures in the tuffs of Yucca Mountain.

Ancient Ground Waters vs. Modern Ground Waters

The data set discussed below consists of isotopic analyses of ground waters sampled over the past several years and calcites that were precipitated during recent times to at least 566 ka. Some of the calcites in the volcanic rocks probably formed during hydrothermal activity associated with active volcanism some 10 to 15 million years ago (Ma). Clearly, calcite isotopic compositions predicted from analyses of modern ground waters are not directly comparable to ancient calcites.

In the discussion that follows it will be demonstrated that known surface calcite deposits at Yucca Mountain did not precipitate from analyzed present-day ground waters. Whether or not the calcites could have precipitated from ancient ground waters cannot be proven because critical data on paleo-ground waters are lacking. The data that are available suggest that isotopic compositions of ancient ground waters have been similar to modern values for the past 300 to 500 ka.

The calcite veins at Devils Hole, Nevada (40 km SE of Yucca Mountain), preserve a record of calcite precipitation over the past 566 ka (Ludwig et al., 1990). The $\delta^{13}C_{PDB}$ values range from -2.8 to -1.5 ‰ (Coplen et al., 1990; Coplen, written communication, 1992) and $\delta^{18}O_{VSMOW}$ from +13.1 to +15.6‰ (Winograd et al., 1988). The range of $^{87}Sr/^{86}Sr$ is from 0.7123 to 0.7128 (Marshall et al., 1990) and that of initial $^{234}U/^{238}U$ activity ratios is from 2.6 to 2.8 over the time interval (Ludwig et al., 1990). Assuming that the temperature of ancient ground waters was 33.7°C, equal to the present value, the range of $\delta^{18}O_{VSMOW}$ of paleo-ground waters was -13.7 to -11.2‰ at Devils Hole over the past 566 ka. These changes are not large enough to justify the ground waters as parental to Yucca Mountain surficial calcite deposits. The Devils Hole data, however, are not directly applicable to Yucca Mountain because the two localities belong to different hydrologic flow systems, e.g. Ash Meadows and Alkali Flat/Furnace Creek, respectively.

Samples of ancient ground water are preserved as fluid inclusions in calcite veins at Furnace Creek, Death Valley, California (60 miles SW of Yucca Mountain). Modern springs at Furnace Creek are among the discharge points of the Alkali Flat/Furnace Creek flow system, the system that underlies Yucca Mountain. U and Th isotopes were analyzed from calcite vein laminae for purposes of age dating. The fluid inclusions were analyzed for D/H ratios (Winograd et al., 1985). The δD_{VSMOW} average concentrations range from -93 to -87‰ over the past 300 ka. Samples from laminae 0.5 to 1.0 Ma average δD_{VSMOW} = -75‰ and those older than 1.0 Ma range from -70 to -45‰. Owing to technical difficulties the analyses for D/H are not as precise as one might like: replicate analyses of fluid inclusions from the same vein lamina gave standard deviations as high as 11‰. Accepting, at least for the moment, the results as published, the variation of 6‰ in δD measured over the past 300 ka years corresponds to a change in $\delta^{18}O$ of less than 1‰ along the meteoric water line. A change of 1‰ in $\delta^{18}O$ of paleo-ground waters is not large enough to make it possible to derive Yucca Mountain surficial calcites from ancient ground waters.

C-O-H Isotopes

O and H:

Sensitive tests for the origins of ground waters may be made by analyzing for the stable isotopes of hydrogen and oxygen. Such pro cesses as evaporation and geothermal heating are also recorded by the isotopes. Figure 1 shows ground waters from the Yucca Mountain area compared to Craig's (1961) meteoric water line. The ground-water isotopic contents occupy a narrow range overlapping and parallel to the meteoric water line. Both the Ash Meadows flow system and the ground waters of the Alkali Flat/Furnace Creek system are indistinguishable in terms of $\delta^{18}O$ and δD. The $\delta^{18}O$ and δD values of the Ash Meadows flow system are controlled primarily by the isotopic composition of winter-spring precipitation over recharge areas in the Spring Mountains. The similar values of the Alkali Flat/Furnace Creek ground-water system suggest a similar control on isotopic content. Note that precipitation collected at stations on the Nevada Test Site (north and east of Yucca Mountain) has higher δD

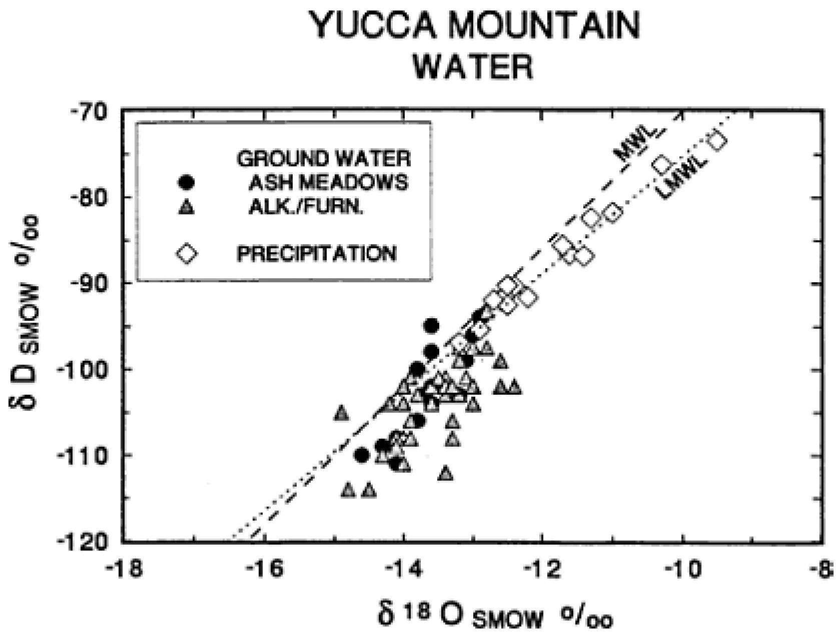

Figure 1
Plot of δD vs $\delta^{18}O$ for ground waters of the Ash Meadows and Alkali Flat/ Furnace Creek (Alk./Furn.) flow systems. Also shown are precipitation on the Nevada Test Site, surface waters and the meteoric water line ("MWL") of Craig (1961). "LMWL" is the local meteoric water line. Data and additional discussion in Claasen (1985, 1986); Benson and Klieforth (1989); Benson and McKinley (1985); Benson et al. (1983); Ingraham et al. (1990); and Lyles et al. (1990). Analytical uncertainty is ±0.2‰ for $\delta^{18}O$ and ±2.5‰ for δD.

and $\delta^{18}O$ concentrations than deep ground water in the Ash Meadows and Alkali Flat/Furnace Creek flow systems (Figure 1). The disparity between the composition of deep ground water and local meteoric water is illustrated in Figure 2. Comparison of water from springs fed from local, perched water tables with ground water from the deeper aquifers shows the springs to have both higher $\delta^{18}O$ and higher δD, consistent with local precipitation (Figure 2). Cane Spring waters show the effects of local evaporation. The important point to remember in the following discussion is this: Both the surface waters at Yucca Mountain and the ground waters are of meteoric origin. Surface and ground waters differ in $\delta^{18}O$ and δD because the recharge areas of the ground water flow system are at higher eleva

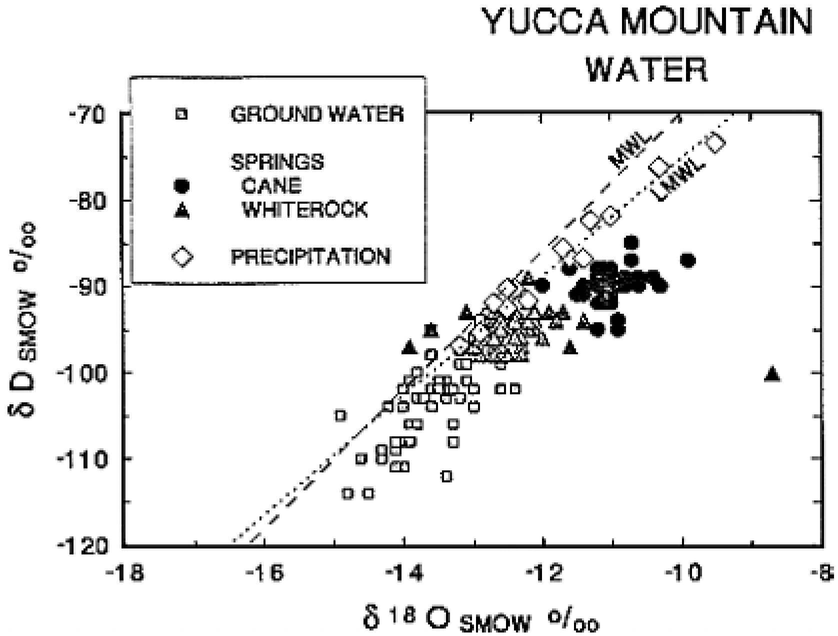

Figure 2
Plot of δD vs. $\delta^{18}O$ Yucca Mountain ground waters, springs and precipitation on the Nevada Test Site. The global meteoric water line is labeled "MWL"; the local meteoric water line is "LMWL". The ground water samples are from the Ash Meadows and Alkali Flat/Furnace Creek regional aquifers. Cane Spring flows from a perched water table beneath the east end of Skull Mountain, 30 km east of Yucca Mountain. Whiterock Spring is 45 km northeast of Yucca Mountain and may be of the same origin as Cane Spring. Data as in Figure 1.

tions and therefore have lower temperatures than Yucca Mountain surface water.

The strong correlation of δD and $\delta^{18}O$ along the meteoric water line is controlled primarily by temperature. Higher values of δD and $\delta^{18}O$ correspond to warmer climates, lower elevations, lower latitudes, and to summer rather than winter precipitation at a given site. Lower values reflect colder climates, higher elevations, higher latitudes, and winter instead of summer precipitation.

Ground waters and surface waters of the Salton Sea Geothermal Field located in S. California 384 km south of Yucca Mountain show the effects of both evaporation and isotopic exchange between waters and wall rocks under conditions of geothermal heating (Figure 3). The isotopic signature of evaporation is illustrated by the linear array of surface water values aligned between local Colorado River

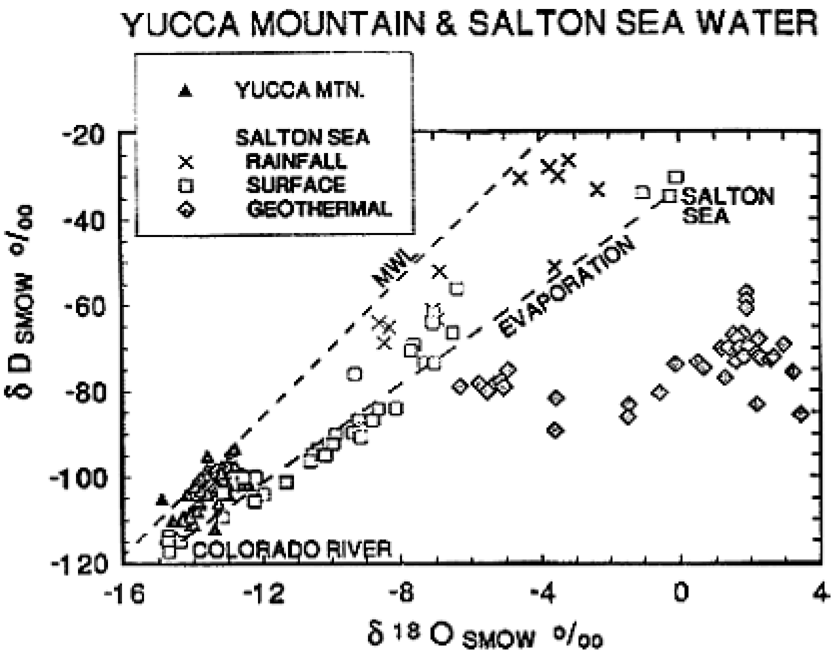

Figure 3
Plot of δD vs $\delta^{18}O$ for Yucca Mountain ground waters in comparison to Salton Sea rainfall, surface, and geothermal waters. The meteoric water line (MWL) of Craig (1961) is shown. Data from Williams and McKibben (1989, Figure 5, p. 1910).

water and Salton Sea water. Evaporation leads to enrichment in both ^{18}O and D in liquid water because of preferential loss of ^{16}O and H to water vapor. Isotopic exchange between ground waters and wall rocks under geothermal or hydrothermal conditions shows small changes in δD but large increases in $\delta^{18}O$ because wall rocks are usually dominated by oxygen-bearing rather than by hydrogen-bearing minerals. Geothermal waters at Salton Sea show enrichments of 12‰ in $\delta^{18}O$ in comparison to surface waters. Compare the small range of variation in δD and $\delta^{18}O$ from Yucca Mountain ground waters with the large variations measured at Salton Sea (Figure 3). There is no evidence for either evaporation or geothermal exchange controlling the isotopic composition of ground waters at Yucca Mountain, except locally, at Cane Springs.

C and O:

The stable isotopes of carbon and oxygen are important in deducing the source of calcites from Yucca Mountain. The $\delta^{18}O$ of ground waters in the area is controlled by meteoric water in the recharge zones, as discussed above. The $\delta^{13}C$ values, however, are subject to localized effects because the total amount of carbon dissolved in ground waters is small. Among the factors influencing the $\delta^{13}C$ of ground waters are biomass in recharge areas including the proportion of C-3 to C-4 plants, soil pH and oxygen fugacity in recharge zones, and isotope exchange between ground waters and carbonate acquifers. Figure 4 shows a plot of analyses of ground waters of the Ash Meadows flow system. The values show a narrow range in $\delta^{18}O$ (-15 to -13‰) but a large variation in $\delta^{13}C$ (-2 to -10‰).

I will first consider the test case of Devils Hole calcite veins and the Ash Meadows flow system to verify that it is possible to accurately predict the $\delta^{13}C$ and $\delta^{18}O$ values of calcites precipitated from ground waters of known isotopic composition. The triangles on the right side of Figure 4 give the calculated values of calcite in isotopic equilibrium with reported ground waters at 25°C. It is assumed that calcite is in oxygen isotope exchange equilibrium with H_2O and is in carbon isotope exchange equilibrium with bicarbonate ion.

The fractionation between calcite and water of ^{18}O - ^{16}O is large (roughly 29 ‰) but the fractionation of ^{13}C - ^{12}C is only about 2‰. For this reason, tie-lines connecting coexisting calcite and ground water are nearly horizontal in the plot. The composition of ground waters at Devils Hole is currently $\delta^{18}O$ = -13.6 ‰ and $\delta^{13}C$ = -5‰. The expected compositions of calcites precipitating from these waters are $\delta^{18}O$ = +15‰ and $\delta^{13}C$ = -3‰. Note that the calculated calcite values plot within the narrow range of measured values for Devils Hole calcite veins. The value of 25°C was chosen as a general reference. If the correct value of ground water temperature at Devils Hole is used in the calculation (e.g. 33.7° C) the calculated $\delta^{18}O$ shifts to 13.2‰, close to the value of 14‰ measured for contemporary calcite. The test case shows that it is possible to accurately predict the isotopic composition of calcite precipitated from analyzed ground waters.

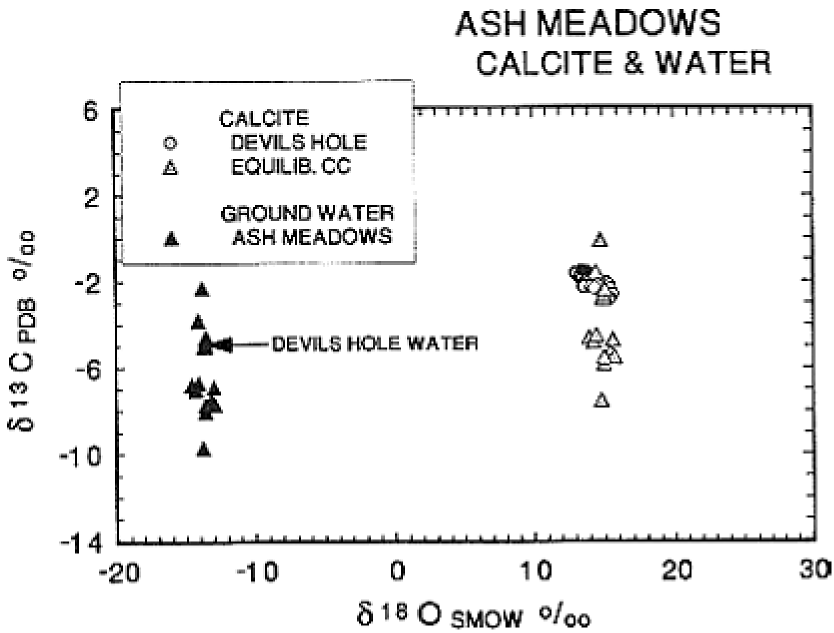

Figure 4
Plot of $\delta^{13}C$ vs $\delta^{18}O$ for ground water of Ash Meadows flow system (references given for Figure 1) and Devils Hole calcite (Coplen and Winograd, personal communication (1990); Coplen et al. (1990)). The values of calcite in equilibrium with analyzed ground waters (equilib. cc.) were calculated for 25° C with 1000. In α ($^{18}O/^{16}O$) for $CaCO_3$ - H_2O = 28.5 and ($^{13}C/^{12}C$) for HCO_{3-} - $CaCO_3$ =-2.2 (Friedman and O'Neil, 1977). The $\delta^{18}O$ values of calcite in equilibrium with analyzed ground waters shift to 20–21 ‰ for water temperature of 0°C and to 9–10‰ at 50°C. Analytical uncertainty is ±0.2‰ for both $\delta^{18}O$ and $\delta^{13}C$.

The next figure (Figure 5) includes the data from the previous figure but also gives the $\delta^{13}C$ and $\delta^{18}O$ analyses of ground waters from the Alkali Flat/ Furnace Creek flow system, i.e. the ground-water flow system in the Tertiary/Quaternary rocks that immediately underlies Yucca Mountain. The ground waters show a narrow range of $\delta^{18}O$, -15 to -12.5 ‰, but a large range in $\delta^{13}C$ of -5 to -13 ‰. The $\delta^{18}O$ values of both Ash Meadows and Tertiary/Quaternary ground waters are closely similar but the latter are typically more depleted in $\delta^{13}C$ than Ash Meadows. Also shown are the calculated $\delta^{13}C$ and $\delta^{18}O$ values of calcites that would precipitate from Tertiary/Quaternary ground waters.

I now show a plot (Figure 6) to demonstrate that the calcite veins of Yucca Mountain did not precipitate from known ground waters. Figure 6 includes data from previous figures but data on calcite veins from Trench 14 and Busted Butte as well as soil calcites have been added. Note that there is no overlap between the values of calculat

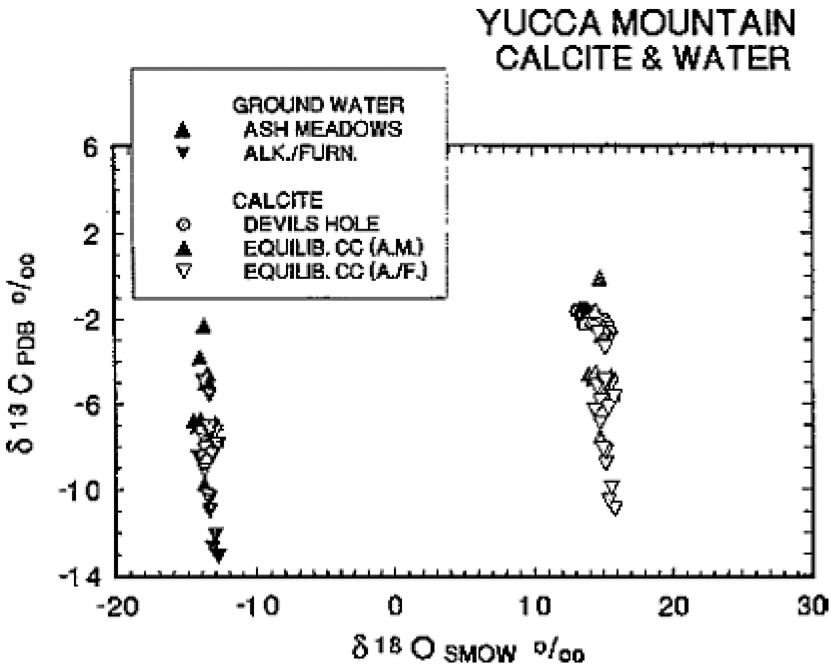

Figure 5
Plot of $\delta^{13}C$ vs $\delta^{18}O$ for ground waters of Ash Meadows (A.M.) and Alkali Flat/Furnace Creek (Alk./Furn. and A./F.) flow systems and Devils Hole calcites. Values of calcites in equilibrium with analyzed ground waters calculated as for Figure 4. Wells drilled at Yucca Mountain give ground-water values of $\delta^{18}O$ from -14 to -12.8 and $\delta^{13}C$ from -12.7 to -4.9.

ed calcites expected to precipitate from analyzed ground waters and the measured calcite veins of Yucca Mountain. There is, however, a significant overlap between Yucca Mountain calcites and analyzed soil carbonates collected from localities surrounding the Repository Site in the southern Great Basin. These results demonstrate that calcite veins at Trench 14 and Busted Butte did not precipitate from analyzed ground waters but were deposited from local surface waters under soil conditions in the unsaturated zone, as deduced by Quade and Cerling (1990). In order to obtain the $\delta^{18}O$ values of Trench 14 and Busted Butte calcites from analyzed ground waters, precipitation would have had to occur at the unreasonably low temperature of 0° to +8°C, hardly indicative of deep upwelling ground water.

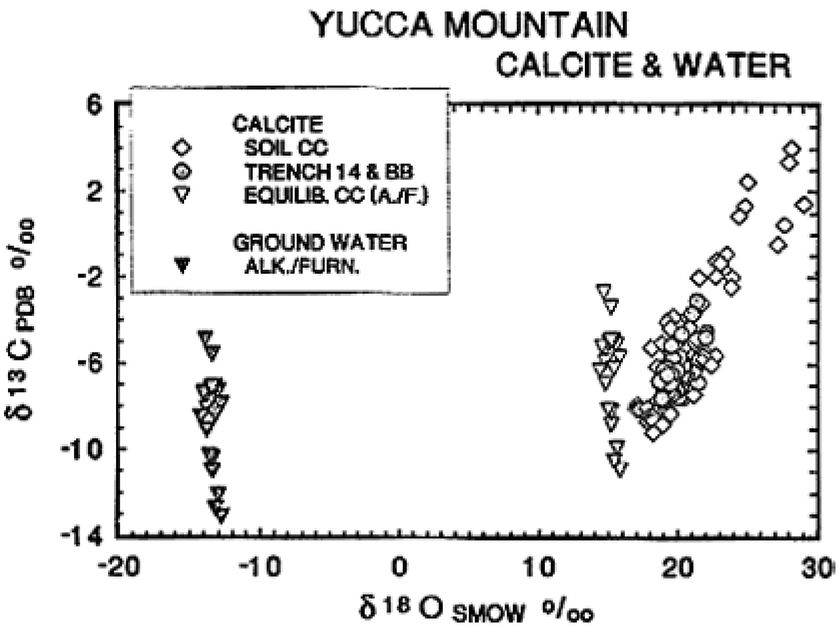

Figure 6
Plot of $\delta^{13}C$ vs $\delta^{18}O$ for ground waters of Alkali Flat/Furnace Creek flow system (Alk./Furn. and A./F.), and Yucca Mountain vein calcites and soil calcites. Yucca Mountain calcite data from Whelan and Stuckless (1990), Quade and Cerling (1990), and Quade et al. (1989). See caption for Figure 4 and 5 for further explanation of values and data sources.

The question arises: Are there absolutely no calcites from Yucca Mountain yet analyzed that bridge the gap between isotope values of calcite precipitated from ground water and those deposited at surface conditions? The answer is that one sample of calcite recovered from a drill hole from a depth of 611 m. below the surface has an isotopic composition consistent with precipitation from ground water. Significantly, the sample comes from a depth 142m *below* the present ground water table. Analyses of drill hole calcites are shown in Figure 7 together with data on Devils Hole, Yucca Mountain, and soil calcites. The values of drill hole calcites overlap those of Yucca Mountain soil calcites but also extend towards $\delta^{18}O$ values as low as 15.4‰.

Figure 8 gives an enlargement of $\delta^{13}C$ and $\delta^{18}O$ data on Yucca Mountain calcites. The drill hole calcites are labeled with either the depth below the water table from which they were collected (-142m) or the height above it (+186m.). Note that calcites collected as close as 186m. above the water table are essentially indistinguishable from

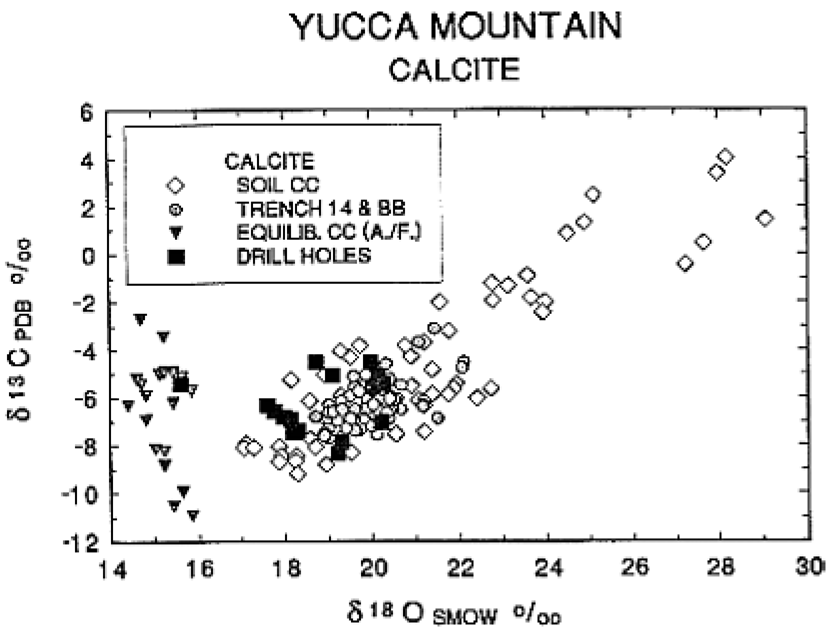

Figure 7
Plot of $\delta^{13}C$ vs $\delta^{18}O$ for Yucca Mountain vein calcites, soil calcites, and drill hole calcites enlarged from Figure 6, compared to calcites expected to precipitate from Alkali Flat/Furnace Creek (A./F.) ground waters. Data sources as in Figure 6 with data on drill hole calcites from Szabo and Kyser (1990). See caption for Figure 4 and 5 for further explanation.

soil calcites (cf. Figure 7). The only calcite with isotopic values consistent with precipitation from analyzed ground waters was recovered 142 m *below* the water table. These data directly contradict the hypothesis that Yucca Mountain calcites were deposited from upwelling ground water. On the contrary, there is a strong implication that calcite isotopic compositions are dominated by surface waters to depths as close as 186m. above the water table, as concluded by Szabo and Kyser (1990).

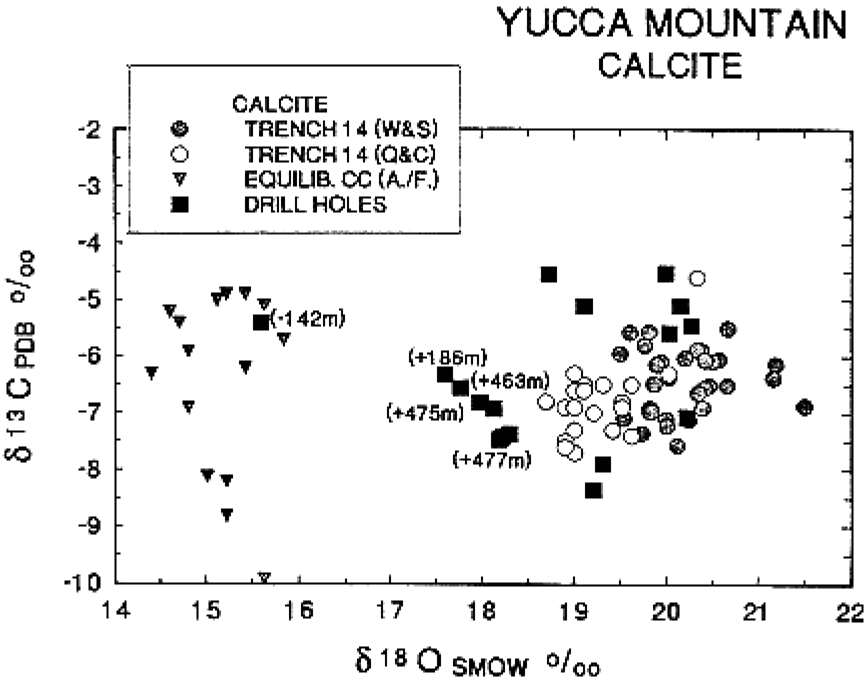

Figure 8
Plot of $\delta^{13}C$ vs $\delta^{18}O$ for Trench 14, Busted Butte and drill hole calcites. Drill hole calcites with lowest values of $\delta^{18}O$ labeled with depth below (-142 m) or height above (+186 m) ground water table. Data sources as in Figure 7. See caption for Figure 4 and 5.

If the reader will kindly continue to refer to Figure 8, I will conclude the discussion of stable isotope data with a brief consideration of interlaboratory standardization of analytical results. The separate analyses of Whelan and Stuckless (1990) and Quade and Cerling (1990) for calcites from Trench 14 are presented in Figure 8. The values occupy the same range in $\delta^{13}C$ but Whelan and Stuckless results are about 0.7 ‰ enriched in $\delta^{18}O$ relative to those of Quade and Cerling.

The results are not a formal interlaboratory comparison because the analysts did not exchange aliquots of the same samples. Nevertheless, there does appear to be a systematic difference in $\delta^{18}O$. An interlaboratory discrepancy of 0.7‰ is a little higher than one might like but is within the range observed in formal intercomparisons (Blattner and Hulston, 1978). In any case, the apparent discrepancy is smaller than the differences in $\delta^{18}O$ discussed above and, thus, does not detract from the conclusions.

U and TH Isotopes

The activity ratios of U and Th isotopes in ground waters and calcites of the Yucca Mountain area are shown in Figure 9. Values of $^{234}U/^{238}U$ for ground waters from both the Ash Meadows and the Alkali Flat/Furnace Creek flow systems are plotted in a stacked histogram on the left-hand side of the figure. The histogram has been rotated 90° to facilitate comparison of ground water with calcite data. The right-hand-side of the figure is a plot of $^{234}U/^{238}U$ vs. $^{230}Th/^{234}U$ for calcites. The dotted curves with gentle slopes are the trajectories followed by calcites as radioactive decay proceeds with increasing age. The steeply sloping solid lines connect calcites of equal age and are labeled with the age in years before present.

It is known that pure calcites precipitating from ground water have the same $^{234}U/^{238}U$ activity ratio as parental ground water but contain no Th. A recently precipitated calcite would plot along the vertical Y-axis at $^{230}Th/^{234}U$ = 0. Over the course of time, the isotopic composition of calcite shifts from left to right across the diagram and parallel to the dotted curves owing to the decay of ^{238}U to ^{234}U and of ^{234}U to ^{230}Th. The change in $^{234}U/^{238}U$ with age is small and, consequently, it is not a sensitive chronometer; it is, however, a reliable tracer of the composition of parental ground water. The activity ratio $^{230}Th/^{234}U$ changes greatly with age; it is a sensitive chronometer for ages up to 300,000 to 500,000 years before present. Ivanovich (1982) gives a clear and thorough discussion of U-Th systematics.

The Devils Hole data on ground water and calcite provide a test case for the geochemical relationships discussed in the preceding paragraph. Devils Hole ground waters have an average $^{234}U/^{238}U$ activity ratio of 2.76 ±(0.09). Devils Hole calcite activity ratios trace out a curved line that lies parallel to and halfway between the decay curves for calcites with initial $^{234}U/^{238}U$ ratios of 2.5 and 3.0 (Figure 9). There is close agreement between the $^{234}U/^{238}U$ of ground water (2.76 ±0.09) and the average of calculated initial $^{234}U/^{238}U$ for calcites (2.70 ±0.07) over an age range of over 300 ka (Winograd et al., 1988). These data validate the use of $^{234}U/^{238}U$ activity ratios to trace parental ground waters of pure calcite.

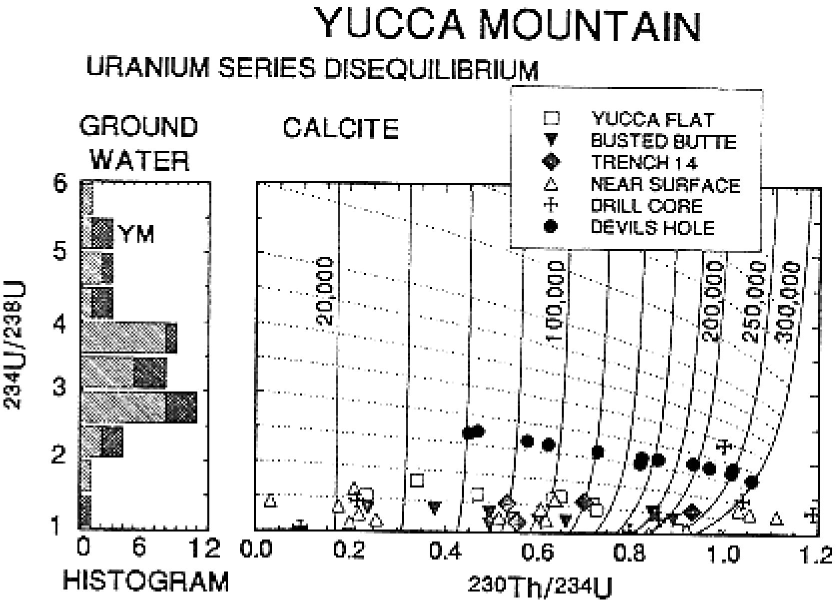

Figure 9
Left-hand side of diagram shows stacked histogram of $^{234}U/^{238}U$ activity ratios for ground waters of Ash Meadows (diagonal ruling) and Alkali Flat/Furnace Creek (cross hatched) flow systems. The symbol "YM" denotes ground waters sampled near Yucca Mountain. Histogram is rotated 90° to facilitate comparison with calcite data. Right-hand side of diagram shows plot of $^{234}U/^{238}U$ vs $^{230}Th/^{234}U$ for Yucca Mountain and Devils Hole calcites. Dashed lines are pathways of radioactive decay for calcites. Solid lines are isochrons labeled with age in years before present. Both dashed lines and solid lines are terminated at 300,000 years for clarity. Data sources are: Yucca Flat-Shroba et al. (1988); Busted Butte-Muhs and Whitney, personal communication (1990); Trench 14-Muhs et al. personal communication (1990); near surface-Szabo et al. (1981); Szabo and O'Malley (1985); drill core-Szabo and Kyser (1990); Devils Hole-Winograd et al. (1988). Analytical uncertainty ±0.02 to ±0.04 for both $^{234}U/^{238}U$ and $^{230}Th/^{234}U$.

The calcite data from Yucca Mountain stand in strong contrast to those from Devils Hole. With but two exceptions, all calcites from near the Repository Site have measured $^{234}U/^{238}U$ less than 2.0. Note the frequency distribution of $^{234}U/^{238}U$ ratios in ground waters: there is only one sample out of a total of 16 analyzed Tertiary/Quaternary waters that is a permissible parent for the analyzed calcites. The anomalous ground water was collected from a well drilled at French man Flat, 60 km to the E of Yucca Mountain. Ground waters sampled in wells drilled near Yucca Mountain have $^{234}U/^{238}U$ activity ratios of 5 to 7 (one higher value of 6.9 is not shown in Figure 9). There are two calcites with high $^{234}U/^{238}U$ out of a total of 40 analyzed. One of these samples has $^{234}U/^{238}U$ = 2.26 and is from a depth of 63m. in drill hole USW G-3. The other sample has $^{234}U/^{238}U$ = 1.47 and is from drill hole UE-25 a#1 at a depth of 283m (Szabo and Kyser, 1990). The projected initial activity ratios of these two samples are about 3.4 and 2.2, respectively. Neither of these values fall within the range (5–7) of ground waters sampled by drilling at Yucca Mountain.

There are two interesting discrepancies between $\delta^{18}O$ data, and U-Th data measured for drill hole calcites. The sample from a depth of 611m in drill hole UE-25 a #1 has a $\delta^{18}O$ value of +15.6‰ suggesting precipitation from ground water (the sample was collected 142m below the water table) but the $^{234}U/^{238}U$ activity ratio of 1.29 is compatible with surface calcites. A sample from a depth of 63m in drill hole USW G-3/Gu-3 (690 m above the ground water table) has $^{234}U/^{238}U$ = 2.26 suggesting a parent of mixed ground water and surface water but its $\delta^{18}O$ value of +20.23 shows no evidence of a contribution from ground water.

The interpretation of raw U-Th data must be done with great care. I am indebted to my colleague Fouad Tera for raising this point very forcefully. A problem arises because of the difficulty in purifying surface calcite deposits such as soil calcites, caliche, and calcrete. The materials are heterogeneous mineralogically. Calcite is present as a cement binding mineral and rock fragments of the host rock or soil. Authigenic minerals such as clay, zeolites, and opaline silica may be present, as well. These impurities are of different ages and origins, thus their inclusion with calcite for analysis would scramble the U-Th isotopic signature. It is difficult to separate calcite from contaminants owing to the intimacy of the intergrowths and their fine-grained size. Acid leaching of samples yields a product that is mostly derived from calcite but that does contain some U and Th from the non-carbonate fraction.

Researchers in the field of U-series age dating are well aware of these problems. The isotope ^{232}Th is routinely monitored to detect the presence of impurities. Isotopic analyses of acid soluble and insoluble residues of the same sample are compared and the activity of ^{232}Th is used as an index of contamination to correct the acid soluble fraction for impurities. The advent of mass spectrometry instead of alpha spectrometry to measure activity ratios has alleviated the purification problem to a certain extent because the size of sample required for analysis has been reduced.

The problem of analysing impure surface calcite deposits has direct bearing on the interpretation of the Yucca Mountain and Devils Hole data. The Devils Hole vein calcites are very pure with less than 0.5 percent insoluble residues. The $^{230}Th/^{232}Th$ ratios show one sample with a value of 25 but in 12 other samples the ratio is greater than 100. The Devils Hole vein calcites, by this criteria, are ideally suited for U-Th series dating. The Yucca Mountain samples, in contrast, have $^{230}Th/^{232}Th$ values predominantly less than 100 with many values less than 10. The data reported in Figure 9 have had the ^{232}Th correction applied but uncertainties remain. As stated by Szabo and Rosholt (1982, p. 260) "There are no absolutely certain ways to assess the correctness of the primary assumptions of this type of dating such as the assumption that the initial ^{230}Th activity is negligibly small in the sample, or that the dated carbonate remained ideally closed with respect to the isotopes of interest."

Despite the uncertainties discussed above, the coherence of the Yucca Mountain data, as shown in Figure 9, argues that the data should be given serious consideration. I conclude that the U-Th data are consistent with stable isotope data that shows Yucca Mountain calcite veins were not deposited from analyzed ground waters.

SR Isotopes

Strontium isotopes (^{87}Sr and ^{86}Sr) are similar in behavior to ^{234}U and ^{238}U in that they are not fractionated when calcite precipitates from ground water. Calcites do not accommodate ^{87}Rb, the radioactive parent of ^{87}Sr, in their crystal lattice. Consequently, once precipitated, the $^{87}Sr/^{86}Sr$ ratio of calcite is fixed. Faure (1986, Chap. 11) gives a clear and thorough discussion of these principles.

The efficacy of $^{87}Sr/^{86}Sr$ ratios to fingerprint the parental ground waters of calcites may be verified by considering the Devils Hole data. The upper panel of Figure 10 is a stacked histogram of Ash Meadows ground water values and Devils Hole calcite values. The measured ground water value at Devils Hole is 0.7123. The calcite values are 0.7123 to 0.7128 for calcites with ages of 100–566 ka (Marshall et al., 1990). These results establish the reliability of Sr isotopes in calcite as tracers of parental ground waters and show that $^{87}Sr/^{86}Sr$ ratios have remained relatively constant in the Ash Meadows flow system for the past 566 ka.

The Yucca Mountain $^{87}Sr/^{86}Sr$ data are shown in the lower panel of Figure 10. Trench 14 calcites and soil calcites share, in part, the same range of values, but, the former are, on average, somewhat enriched in ^{87}Sr. Ground waters sampled in drill holes at Yucca

Mountain have $^{87}Sr/^{86}Sr$ values of 0.7100 to 0.7115. The analyzed ground waters overlap the lower end of the range of soil calcite values but do not overlap the range of Trench 14 and Busted Butte vein calcites. The ground water value of 0.7119 is from a well west of Bare Mtn., about 10km SE of Beatty (Figure 10). It is concluded that vein calcites from Trench 14 and Busted Butte did not precipitate from analyzed ground waters.

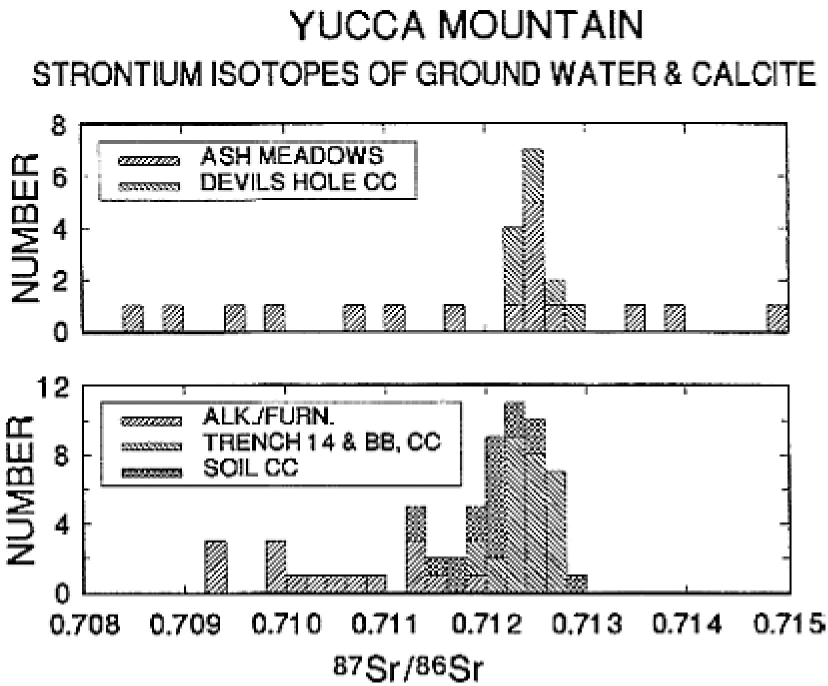

Figure 10
Upper panel shows stacked histogram of $^{87}Sr/^{86}Sr$ values for ground waters of Ash Meadows flow system and Devils Hole calcites. Lower panel gives stacked histogram of $^{87}Sr/^{86}Sr$ for ground waters of Alkali Flat/Furnace Creek (Alk./Furn.) flow system and calcites from Trench 14, Busted Butte (BB), and soil calcites sampled from 1 m deep pits (Marshall et al., 1990). Analytical uncertainty is ±0.00005.

New Data on Calcite from Drill Holes

New isotopic data on calcite in core samples from drill holes USW-G1,-G2,-GU3,-G3,-G4, and UE25b#1 are currently being measured at USGS, Denver. Preliminary reports have been submitted for pre sentation at the Geological Society of America meeting in San Diego, October, 1991 (J. S. Stuckless, personal communication). Drill holes G2 and G1 bracket, from north to south, the hydrologic gradient at the north end of Yucca Mountain. The other holes lie 1 to 4 km south and east of the gradient. Core samples were obtained from the holes over a range of elevations from a height of +600m above the static water level to a depth of -1200m below it. The analyzed samples include secondary calcite from lithophysal cavities and cements in tuffs as well as from fracture walls.

The following comments are based on a graph showing $\delta^{13}C$, $\delta^{18}O$, and depth for some 80 samples, provided by J. S. Stuckless on June 6, 1991 (preprint of J. F. Whelan and J. S. Stuckless). Approximately 40 samples from above the static water level and 40 from below it were analyzed.

Values of $\delta^{18}O$ of calcite show a decreasing trend with depth, similar to that noted by Szabo and Kyser (1990). Samples from above the static water level range from +14‰ to +21‰. Samples from below the static water level lie between +4‰ and +14‰. Many of the samples from the saturated zone appear to be in equilibrium with analyzed ground waters. Temperatures measured at depths of -500 to -1200 m below static water level range from 40°C to 60°C. Calcite precipitating from analyzed ground waters at these temperatures would have $\delta^{18}O$ values of +8‰ to +12‰. There are two samples from below the water table, at -45 m and -130 m, however, that have values of 17.5‰, within the range of samples from the unsaturated zone.

Concentrations of $\delta^{13}C$ of calcite show an increasing trend with depth. Calcites from the unsaturated zone give values of -10‰ to 0‰ similar to the range of values from Trench 14 and Busted Butte. Saturated zone calcites are -2 ‰ to +4‰. There are, however, two samples from the unsaturated zone, at a height of +430 m with values of +0.5 ‰ and +4.8 ‰. Furthermore, eight samples from the saturated zone, at depths of -300 m to -45 m below the static water level, lie in the range -10‰ to -5‰.

The existing data set shows a broad systematic trend but with obvious outliers. The question arises as to how much significance should be attached to outliers in an, as yet, incomplete data set. Another important consideration in interpreting the data is the age of calcites. Szabo and Kyser (1990) found a range of ages from 26 ka to over 400 ka in 29 calcites from drill cores. The two oxygen values from -45 m and -130 m show possible evidence of recharge of water from above the static water level down into the saturated zone. The eight samples with $\delta^{13}C$ of -10‰ to -5‰ support the $\delta^{18}O$ evidence of recharge. The two $\delta^{13}C$ values of +0.5‰ and +4.8‰, however, may indicate a rise in the water table of as much as 430 m. An alternative explanation of the latter two $\delta^{13}C$ values is that ancient surface waters may have been influenced by a biomass with a different ratio of C3/C4 plants, thus giving rise to high $\delta^{13}C$ concentrations (Quade et al., 1989). The oxygen data is likely to be a more reliable hydrologic tracer because oxygen is a major constituent of water. Because carbon-bearing species are not abundant in ground water, their $^{13}C/^{12}C$ composition is subject to local wall rock control as well as contamination. In any event, additional data on the stable isotope composition of calcites from drill cores and, especially, more U-Th age dates are needed.

Preliminary Sr isotope values of some 16 calcites from drill cores show a clear demarcation between saturated and unsaturated zone samples (Z. E. Peterman, J. S. Stuckless, S. Mahan, E. D. Gutentag, and J. S. Downey, preprint). Calcites (9 samples) from +50m to +400m above the static water level are 0.7108 to 0.7128 $^{87}Sr/^{86}Sr$, overlapping the range of soil calcite and Trench 14. Values of seven samples from depths of -600 to -1200m below the static water level are 0.7086 to 0.7089 $^{87}Sr/^{86}Sr$, at the low end of the range for waters from the Tertiary/Quaternary aquifer.

The majority of presently available data for drill hole calcites suggests a stable elevation for the static water level, over the period of time during which secondary calcite was deposited.

Conclusions

Analytical data on both stable isotopes and radiogenic isotopes agree that the calcite vein deposits of Yucca Mountain did not precipitate from analyzed ground waters. The stable isotope data strongly imply that the calcites were deposited from surface waters under soil conditions in the unsaturated zone.

The hypothesis of rising ground water as the origin of the calcites in the Yucca Mountain area has failed the tests of isotope geochemistry and is, in fact, contradicted by the available data.

Recommendations

The importance of deducing the isotopic contents of ancient ground waters at Yucca Mountain has been discussed above. The available data, however, do not support definitive conclusions. Additional data is needed, similar to that measured by Szabo and Kyser (1990) who determined $\delta^{18}O$, $\delta^{13}C$, and U/Th ages on aliquots of the same calcite samples from drill holes. In order to avoid circular reasoning, independent estimates of the temperatures of paleo-ground waters should be made. Calcite veins intersected in drill cores should be searched for fluid inclusions. Microthermometry of the fluid inclusions will provide independent estimates of calcite precipitation temperatures.

The availability of high quality data on a number of unrelated isotope systems leads to more definitive conclusions than might be gained from considering one pair of isotopes, alone. Comparison of the behaviors of geochemically dissimilar isotopes gives cross reference points and provides strict hypothesis testing. It is strongly recommended that research on both stable and radioactive isotopes be diligently pursued.

An important caveat is implied by use of the word "analyzed" to modify the phrase "ground-waters". One cannot test parental ground waters when data are lacking. There is need for additional isotopic data on ground waters so that the density of areal coverage will more closely match that now available for soil and vein calcites. Presumably, collecting additional ground water data will require drilling more wells. Additional isotopic data on calcite from localities such as the WT-7 well pad and the tufa at sample site 199 would be useful to extend mapping the importance of surface vs. ground waters.

The contrast in behavior between isotopes present in dominant amount in water such as ^{18}O and ^{16}O, or D and H and those present in small amounts such as ^{13}C and ^{12}C, ^{234}U and ^{238}U or ^{87}Sr and ^{86}Sr has been noted. It is recommended that additional data be gathered to more fully document the control of local wall rocks on the abundance of trace constituents in ground water. It would be interesting to drill deeply into the saturated zone of the Tertiary/Quaternary flow system and sample both ground waters and wall rocks at closely spaced intervals in the same drill hole. Such a detailed data set might shed light on the specific mechanisms of chemical and isotopic exchange of trace constituents between ground waters and wall rocks.

If it is accepted that Trench 14 calcites did not precipitate from upwelling ground water then how did they form? Additional isotopic data on the calcites should help to answer this question. Isotopic analysis of rainfall and soil moisture at sites where calcite has already been analyzed would directly test the hypothesis that surface calcites precipitated from surface waters in the unsaturated zone. Analysis of wind-blown dust would help to quantify its role in the origin of surficial calcite deposits. New data on drill hole calcites are needed to explore the possibility that some of them may have precipitated from mixtures of ground waters and surface waters. The increased use of mass spectrometry methods (Ludwig, et al., 1990;

Papanastassiou, et al., 1991) to improve U-Th series age dating is needed to provide chronological constraints on surface processes.

The brief discussion of interlaboratory standardization given above suggests that formal intercomparisons of analytical results should be carried out between different laboratories measuring the same isotopes. In cases where only one laboratory has been involved in analyzing a particular isotopic system, it is recommended that additional laboratories be brought in to verify analytical accuracy. I have no reason to doubt any of the data discussed above. The laboratories reporting the data are well known and reputable in the geochemistry community. Nevertheless, in a project of such importance to the public as the Yucca Mountain Repository Site Evaluation it would seem prudent to leave nothing to chance including the verification of analytical data by independent laboratories.

Acknowledgements

The task of gathering data for this review was greatly aided by the work of J. S. Stuckless who presented a review of the isotope geochemistry of Yucca Mountain to the panel on May 30, 1990 in Menlo Park, CA. I am very grateful to T. E. Cerling, T. B. Coplen, D. Muhs, J. S. Stuckless, and I. Winograd who provided preprints of data in advance of publication. My colleagues G. E. Bebout, G. Goodfriend, P. Koch, and F. Tera contributed helpful, constructive criticism.

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Appendix B—

Yucca Mountain: Ground-Water Flow

Sabodh Garg
S-Cubed
San Diego, California
Revised October 3, 1991

Introduction

Yucca Mountain in southern Nevada—the potential site for a repository for high-level nuclear wastes—lies within the Alkali Flat/Furnace Creek subdivision of the Death Valley Ground-water System (see Figure 1). The regional ground-water system also includes the Ash Meadows and Oasis Valley subbasins. The ground-water flow within all the three subbasins is generally in a north-south direction (Figure 1). The principal aquifers in the Alkali Flat/ Furnace Creek subdivision are in Cenozoic (66 Ma-Present) alluvium and tuff formations. Although Paleozoic carbonates are thought to underlie the alluvium/ tuff aquifers, the carbonates have been so far encountered in a single borehole (UE-25p#1) drilled to the southeast of Yucca Mountain. Additional drilling and other investigations are required to clarify the role of Paleozoic carbonates in the vicinity of Yucca Mountain.

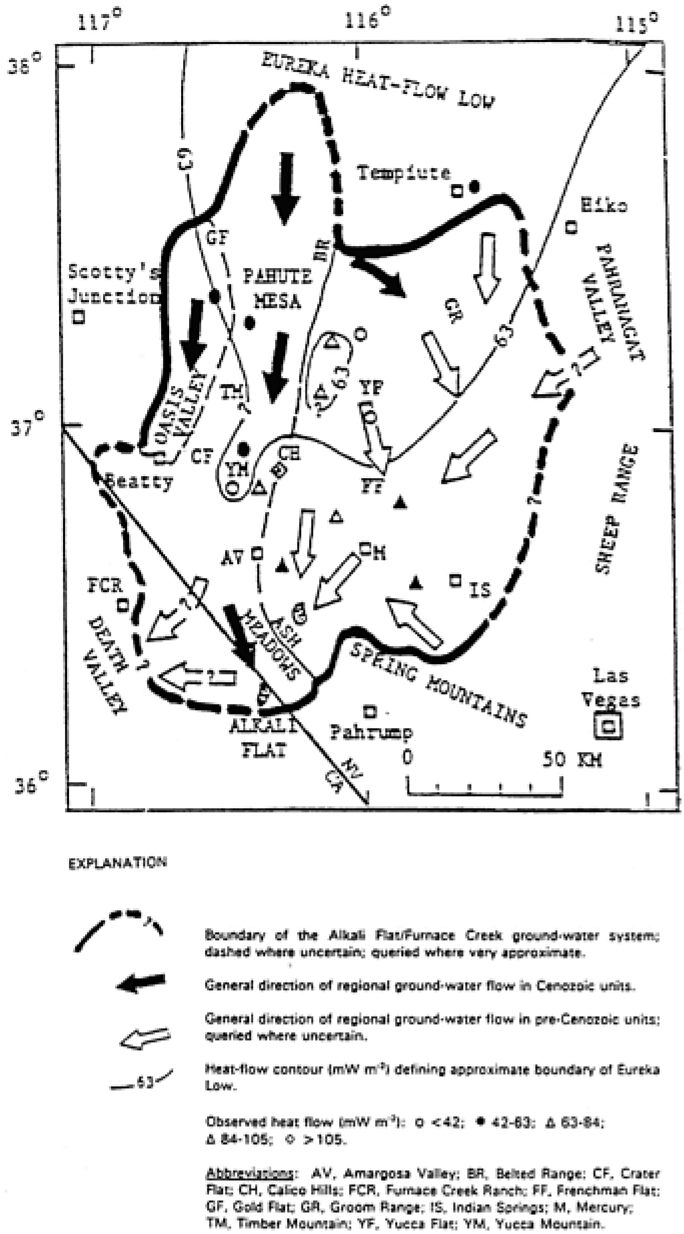

Figure 1
Regional ground-water systems and heat flow in the south-central Great Basin. (From Dudley, 1990a).

The ground-water system in the Alkali Flat/Furnace Creek subdivision has been modeled by Czarnecki and Waddell (1984). These authors used a two-dimensional (areal) finite element model to simulate the *steady-state* ground-water flow occurring in tuffaceous, alluvial and carbonate rocks. The steady-state ground-water model was employed by Czarnecki (1985) to investigate the effects of increased precipitation on ground-water levels in the Yucca Mountain area. Prior to describing these models, it is useful to review the hydrologic data set in the Yucca Mountain area. The principal components of a ground-water model are (1) the amount and location(s) of recharge and discharge, (2) the permeability structure, and (3) the three-dimensional distribution of fluid pressure (or equivalently hydraulic heads). The available relevant hydrologic data in the vicinity of Yucca Mountain are briefly discussed in Section 2. The modeling work is then reviewed in Section 3. Finally, recommendations for further work are outlined in Section 4.

Hydrologic Data Set

The fluid flow in the saturated zone of the Alkali Flat/Furnace Creek subbasin (especially in the northern part of the subbasin) occurs mainly within fractures in the rocks. In a fracture flow system, a well drilled into the aquifer does not simply penetrate a formation with uniform permeability. The permeability of a rock, sediment, or soil refers to the relative ease with which a fluid can flow through, and depends on the amount of interconnected pores or spaces. It is measured in terms of the rate of passage of fluids in a unit called the millidarcy. The bulk of the aquifer permeability is due to a network of fractures. The performance of a bore hole monitoring well depends largely upon whether it intersects one or more fractures, how large each intersected fracture is, and how well it is connected to the rest of the network. The well, for all practical purposes, is open to aquifer fluid only at the depth(s) where it intersects such a fracture, and for the balance of its depth the well penetrates rock that is essentially impermeable. This situation is comparable to a well drilled into a thick sandstone, which has been fully cased, or lined with some impenetrable material, that is perforated at a few unknown depths. The methods for determining the major permeable horizons (also feedpoints or fluid entries) have been discussed, among others, by Grant *et al.* (1982). It is worth emphasizing here that fluid pressure (or hydraulic head) measured in a bore hole, or well, is in equilibrium with the reservoir pressure only at the level at which the water enters the well (the principal feedpoint). Elsewhere, in the well, the pressure (head) measured in the well, will not in general correspond to the overall pressure in the aquifer. For a well with two (or more) feedpoints, the pressure in the well will only equal the aquifer pressure at a depth somewhere in between the two feedpoints.

Permeability Structure

The present knowledge regarding the permeability structure of the saturated zone in the Yucca Mountain area is derived from (1) repeat temperature surveys in wells, (2) measurements on cores recovered from wells, (3) analyses of the response of UE-25C#1, UE-25C#2, UE-25C#3, and UE-25p#1 wells to barometric and tidal loadings, (4) slug tests, and (5) pumping tests. Repeat temperature surveys can be used to deduce the location (or lack thereof) of major feedpoints. Available temperature data (see Szymanski, 1989 plates 4.3.3.3 to 4.3.3.38) indicate multiple feedpoints and internal flow in several wells (J-13, UE-25b#1, UE-25p#1, VH#2, G-2, H-4, H-5, H-6; see Figure 2 of this report for well locations). Significantly, the internal flow appears to be in a downward direction in some cases and in an upward direction in other cases; this implies that there is no systematic increase or decrease in hydraulic potential with depth. Wells G-1 and H-1 (below 650 meters only), drilled to the north of the proposed boundary of the repository, and wells G-3 and H-3, located just south of the boundary, are all characterized by conductive temperature profiles. A conductive temperature profile *generally* indicates poor formation permeability. It is thus possible that tuffs, both to the north and the south of the repository site, have poor permeability.

Permeability measurements made on cores recovered from several wells in the Yucca Mountain area have been tabulated by Szymanski (1989; plate 4.2.2.1). Generally speaking, the core data indicate a low permeability ($K = 3 \times 10^{-7}$ to 10^{-3} meters per day (m/d)), or equivalently $k = 0.3$ microdarcy (μdarcy) to 1 millidarcy (*m*darcy) for the various tuff units. Galloway and Rojstaczer (1988) have analyzed the frequency response of water levels in wells UE-25C#1, UE-25C#2, UE-25C#3, and UE-25p#1 to earth tides and atmospheric loading; the inferred vertical permeability ranges from 0.8×10^{-3} m/d to 5×10^{-3} m/d (or equivalently $k_{\text{vertical}} = 0.9$ to 6 *m*darcy). The tuff vertical permeabilities derived by Galloway and Rojstaczer (1988) are thus comparable to the measured permeability values in cores. While it is by no means certain that the tuff vertical permeabilities are low throughout the Yucca Mountain area, the available data nevertheless indicate a small vertical permeability.

Permeability tests have also been performed in sections (isolated

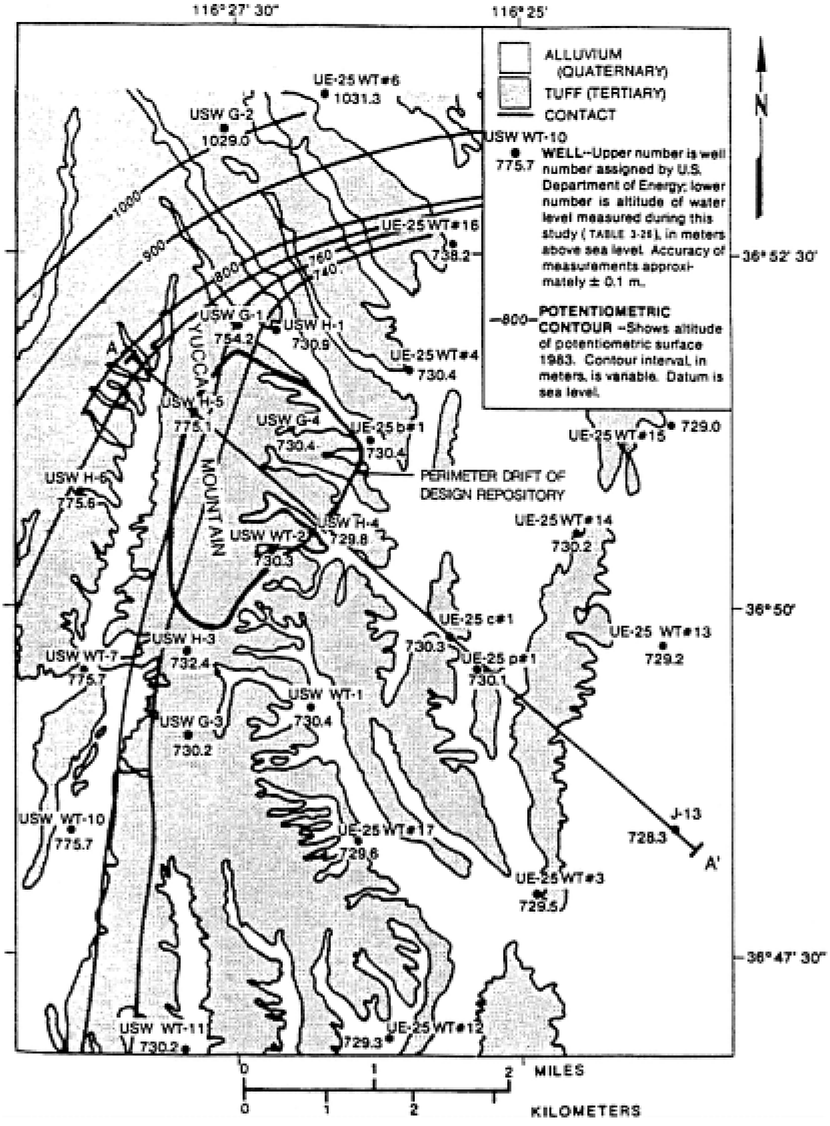

Figure 2
Preliminary composite potentiometric-surface (water table elevations) map of the saturated zone. Yucca Mountain. (From Dudley, 1990b).

by packers) of several boreholes (see Szymanski, 1989; plates 4.2.2.6 to 4.2.2.11C). Data are available from both injection (water forced into the well) and pumping (water discharged from the well) tests. The injection tests were of the "slug test" variety. The "slug tests" data are often influenced by near wellbore effects (well damage and storage), and the inferred permeability values are not very reliable. Some of the slug tests performed in the Yucca Mountain wells (see e.g. plates 4.2.5.4-36 to 4.2.5.4-38 in Szymanski, 1989 for well H-3) exhibited an anomalous fall-off response (i.e. an abrupt break to the right of the graphic representation of the fluid behavior in the well). This anomalous response can be characteristic of a well with multiple feedzones. Szymanski (1989) has interpreted the slug test data to indicate the state of the minimum horizontal stress in the crust. However, there does not appear to be a sufficient theoretical basis for Szymanski's interpretation. The estimates of minimum horizontal stress derived from slug test data by Szymanski (1989) are significantly lower than those obtained from hydraulic fracturing tests whereby water forced into the rocks under high pressure cause the rocks to break in directions that tell something about the crustal state of stress. Despite our misgivings regarding Szymanski's interpretation of slug tests, it is fair to state that the pressure responses seen in "slug tests" have not been satisfactorily explained so far and deserve further investigation.

The available pumping test data for wells (H-1, H-3, H-4, H-6, UE-25b#1 and UE-25p#1) in the Yucca Mountain area have been summarized by Szymanski (1989; plates 4.2.2-6–4.2.2-11C). Permeabilities indicated by pumping tests are generally in accord with interpretations from repeat temperature surveys. Little or no permeability is observed in the "conductive temperature profile" regions of wells. The bulk of the permeability appears to be at or near the locations of major feedpoints. As an example, temperature data for well UE-25p#1 show an isothermal (unform temperature) zone from ~1210 to ~1400 meters; an isothermal zone implies permeability at both its end points. Pumping data indicate that the bulk of permeability in this well is associated with the depth interval 1180–1421 meters. The existing temperature and pumping test data indicate that fluid flow takes place largely through discrete fracture zones. Presumably, these discrete fractures join a fracture network at some distance from the wells. The permeability of the aquifer is determined by the density and connectivity of these permeable fractures. To characterize the aquifer permeability, it would be desirable to perform pressure interference tests (i.e. monitor pressure or hydraulic head changes in other individual wells in response to pumping or injection into other individual wells). It appears that to date pressure interference tests have not been performed in the Yucca Mountain area. It would also be desirable to see if the major feedpoints are correlated with some particular stratigraphic horizons. In our view, the available data do not support the three-layer hydraulic conductivity structure postulated by Szymanski (1989; plates 4.2.2-13 and 4.2.2-14). More specifically, the existing data set indicates that the bulk of the permeability in the saturated zone is associated with discrete fractures. The data are, however, insufficient to draw any definite conclusions as to the distribution of permeable fractures with depth.

Aquifer Pressures (Hydraulic Potential)

Water level data are available from a number of deep wells in the vicinity of the Yucca Mountain (see Figure 2 for well locations); a table of these data is contained in Szymanski (1989, plates 4.2.4.4-2–4.2.4.4-2a). With a few exceptions, only the composite water levels were measured. Stated somewhat differently, there is poor depth control for hydraulic head measurements. As noted above, temperature data indicate internal flow (and hence variations in hydraulic potential with depth) in many of the wells. In any future measurement program, effort should be made to quantify the variation in hydraulic head with depth.

The hydraulic head data have also not been corrected for temperature variations. Temperature changes could account for some of the fluctuations in the hydraulic heads with depth. Three wells (H-1, H-3 and UE-25p#1), however, exhibited very large increases in hydraulic head with depth; this indicates potential for some upflow. Wells H-1 (below 650m) and H-3 are characterized by conductive temperature profiles (and hence poor permeability). In well UE-25p#1, the increase in hydraulic head occurred at about the transition from volcanics to Paleozoic carbonates; a temperature profile taken in the completed well indicates an isothermal zone (and hence internal flow) from ~1210 meters (tuffs) to ~1400 meters (carbonates). The hydraulic potential data from wells H-1, H-3 and UE-25p#1 emphasize the existence of a vertical gradient (and vertical upflow/downflow) in hydraulic heads in the Yucca Mountain area.

The available hydraulic head data are displayed in Figure 2. The present water level in the repository area is about 720–730 m ASL (meters above sea level); the design emplacement zone for the repository ranges from ~950 to ~1100 m ASL. Immediately north of the repository, a steep hydraulic gradient is present. Water level rises from ~730–750 m ASL (wells G-1 and H-1) to ~1030 m ASL (well G-2) over a distance of approximately 2.5 km. At present, the reasons for this large increase in hydraulic head are a matter of speculation. Some possible causes include (1) faults with impermeable fault gauge or that juxtapose permeable against impermeable hydraulic units, (2) change in rock characteristics and/or regional stress field that leads to a change in fracture pattern, and (3) drainage induced by deep Paleozoic carbonates. To further explore these and other possibilities, it will be necessary to drill a series of boreholes in the area between wells G-1/H-1 to the south and wells G-2/UE-25WT#6 to the north. These new wells should be designed to test both the tuffs and the underlying carbonates. Besides providing additional hydraulic head data, the new drill holes should be tested to delineate the permeability structure in this important area. More specifically, we recommend that downhole logs (e.g. sonic, temperature, spinner, etc.) be employed to investigate the fracture pattern. Some pressure interference testing will also be needed to obtain quantitative estimates of permeability.

Discharge and Recharge Areas

Discharge from the Alkali Flat/Furnace Creek subbasin occurs by (1) springs near Furnace Creek Ranch in Death Valley, and (2) evapotranspiration at Franklin Lake Playa (see Figure 3 for locations). The spring waters at the Furnace Creek Ranch are believed to originate from alluvium and/or carbonates that underlie the Amargosa Desert. The total discharge rate at the Furnace Creek Ranch is estimated to be 1.932×10^4 m^3/d (Czarnecki and Waddell, 1984). The present day evapotranspiration at Franklin Lake Playa has been investigated by Czarnecki (1990); the estimates for evapotranspiration range from ~0.1 cm/d during winter months to ~0.3 cm/d during summer months. Assuming a surface area of 14.2 km^2 for the playa, the volumetric discharge rates are in the range from 1.42×10^4 m^3/d to 4.26×10^4 m^3/d. As noted by Czarnecki (1990), it is also possible that part of the ground-water bypasses the Franklin Lake Playa, and discharges at lower topographic elevations elsewhere; no estimates of such a discharge rate are available. The average crustal heat-flow in the Basin and Range province is ~80 to 90 milliwatts per m^2 (mW/m^2). A large area in southeastern Nevada, called the Eureka Low, has, however, a relatively low heat flow (~45 mW/m^2). The Eureka Low overlaps the northern part of the Death Valley ground-water system. The heat-flow deficiency in the Eureka Low area has been hypothesized to be due to descending ground water. Dudley (1990a) presents preliminary calculations to show that the heat-flow deficiency in the

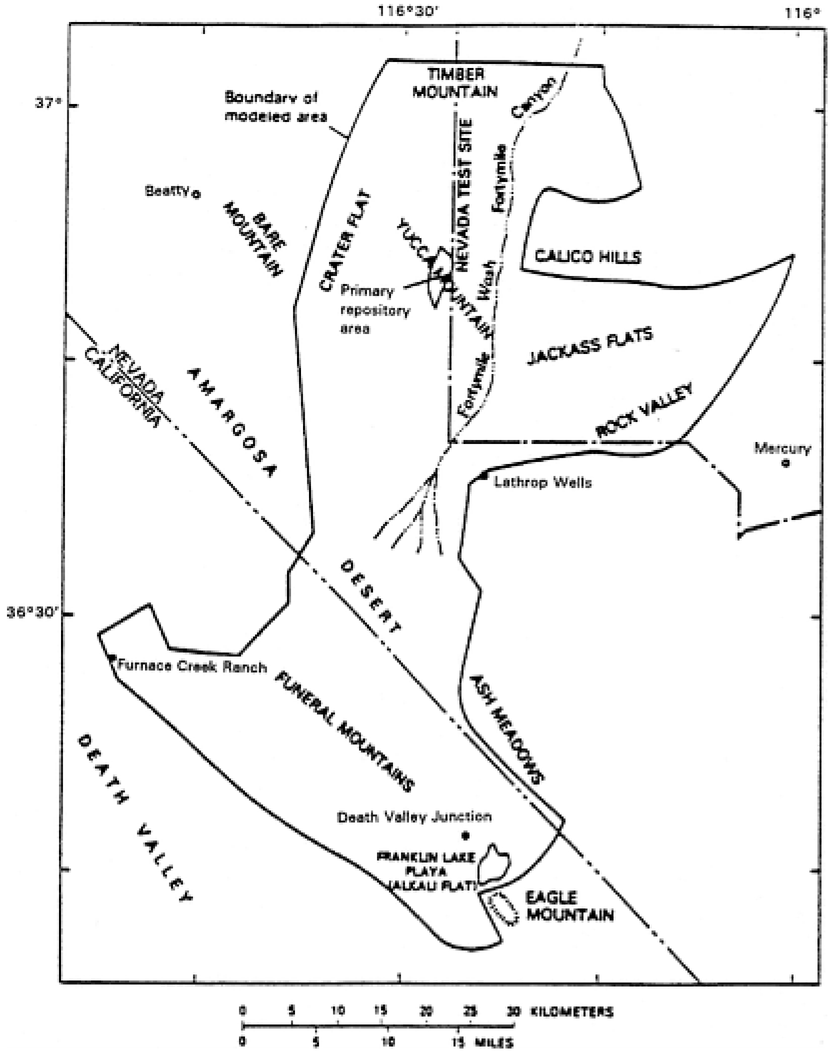

Figure 3
Location of subregional area modeled by Czarnecki and Waddell (1984).

4400 km^2 overlap area of the Eureka Low and the Ash Meadows subbasin equals, within a factor of two or so, the excess heat discharge associated with the springs of Ash Meadows. Because it is difficult to characterize heat discharge associated with evapotranspiration, heat balance calculations have not yet been performed for the Furnace Creek/Alkali Flat subsystem. Given the present information, it is reasonable to assume that the recharge areas, both modern and those in the recent past (say 10–15 ka), for the Furnace Creek/Alkali Flat subsystem lie in the Eureka Low area. The major modern recharge areas, those that supply the ground water, for the Furnace Creek/Alkali Flat subsystem are (1) Pahute Mesa area to the north of the Yucca Mountain, and (2) the Fortymile Wash area to the east of Yucca Mountain. The amount of present day recharge in other recharge areas (Jackass Flats, Crater Flat and the Amargosa Desert) is negligible compared to the recharge from the Pahute Mesa area and the Fortymile Wash (Czarnecki, 1985).

Carbon isotope data imply that the water present in the deeper parts of the Alkali Flat-Furnace Creek Ranch subbasin was recharged about 10–15 ka (Dudley, 1990a). This recharge presumably occurred under conditions that were cooler and possibly wetter than those prevailing now. These ground-water age data raise the interesting possibility that the Alkali Flat/Furnace Creek subbasin is still draining down, and is presumably not in a steady-state (see also Czarnecki, 1990). Sufficient data on ground water age distribution in the subbasin are, however, presently unavailable to describe the evolution of the ground-water system over the past 10–20 ka.

Modeling Studies

Models are useful devices to synthesize the available data and to guide one's thinking. Models can be constructed utilizing various amounts and different qualities of data. Often preliminary model analyses is based upon purely reconnaissance quality information. Such models can often indicate which parameters will influence results and which will not. Used in this context, models can be useful in guiding data collection.

Often preliminary models are used to test hypotheses. For example, the current regional ground-water flow model for the Yucca Mountain does not include the underlying Paleozoic carbonate aquifer. The available data (from outside the Yucca Mountain area) suggests that this aquifer has a transmissivity of at least an order of magnitude higher than the tuffs. It is possible that the regional flow system is largely controlled by the carbonate aquifer. One can test what the influence of the carbonate aquifer is on the regional flow system through modeling.

Our evaluation of the present modeling is that Czarnecki has done a commendable job with the available data. The data are, however, insufficient to answer many of the questions associated with the site.

There is insufficient information to characterize adequately the three-dimensional distribution of permeability and hydraulic heads. In addition, significant uncertainty exists as to the amount (and time) of recharge to and discharge from the ground-water system. Czarnecki and Waddell (1984) used parametric-estimation techniques to model steady areal ground-water flow in the Alkali Flat/Furnace Creek subbasin. A slightly modified form of the latter model was employed by Czarnecki (1985; 1991) to investigate the effects of (1) increased precipitation and (2) removal of the low-permeability barrier north of the Yucca Mountain on ground-water levels in the repository area. These studies are briefly reviewed in the following paragraphs.

The area modeled by Czarnecki and Waddell (1984) extends from Timber Mountain in the north to Alkali Flat and Franklin Lake Playa in the south (see Figure 3). Recharge from the Pahute Mesa area was simulated by prescribing a constant head (or pressure boundary). Some minor fluxes were also applied to account for recharge from Jackass Flats and Amargosa Desert based on the earlier modeling work of Waddell (1982); all these fluxes, however, amount to less than 2.5% of the total recharge (or discharge). The recharge along Fortymile Canyon (zone 8, Figure 4) was represented as a distributed flux. The recharge in the Fortymile Wash area (~2.214×10^4 m^3/d) accounts for approximately 40.3% of the total recharge; most of the rest ($\approx$ 57.3%) enters the subbasin through the constant head boundary along the northernmost end of the modeled region. Discharge from the subbasin was represented (1) as a line sink east of Furnace Creek Ranch and (2) as an areal discharge out of Alkali Flat. The discharge from the Alkali Flat area is 2.214×10^4 m^3/d and equals 64.8% of the total discharge from the subbasin; the remainder of the discharge was assumed to take place in the Furnace Creek Ranch area. All other boundaries were assumed to be no-flow boundaries.

Czarnecki and Waddell (1984) divided the subbasin into 13 regions (Figure 4); transmissivities were assumed to be uniform in each of these regions. As part of a parametric estimation procedure, Czarnecki and Waddell (1984) varied the transmissivities in zones 1 through 9 until a satisfactory match was obtained between the computed and measured hydraulic heads. Final transmissivity values computed by Czarnecki and Waddell are given in Table 1. Considering the uncertainties in head measurements, the agreement between computed and

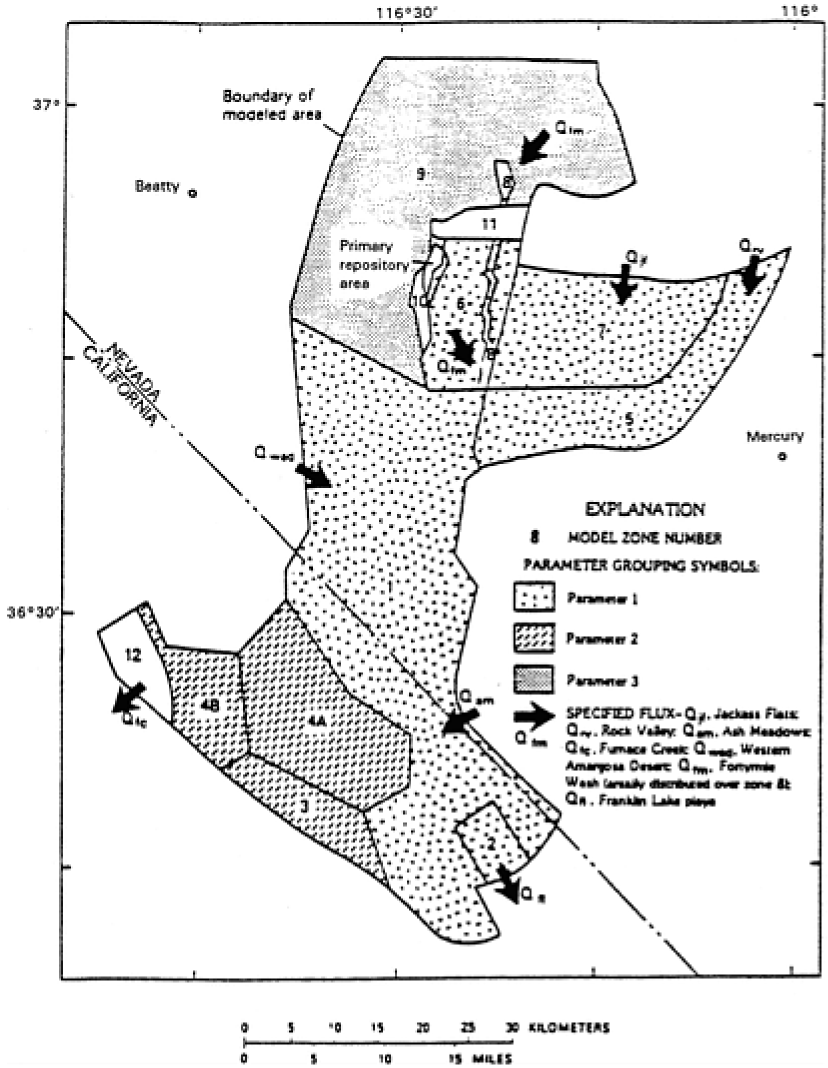

Figure 4
Model zone numbers, parameter groupings, and model boundary fluxes employed by Czarnecki and Waddell (1984).

measured head values is good. Model residuals for simulated versus measured heads range from -28.6 to 21.4 meters; most are less than ±7 meters. The simulated hydraulic heads are shown in Figure 5.

Table 1 Values of Model Transmissivities and Standard Errors. (excerpted from Czarnecki and Waddell, 1984).

[T, transmissivity, in meters squared per day; number following letter T in model variable column is zone number; dashes indicate that value was held constant]

Model Variable	Parameter Number	Value	Standard Error	Coefficient of Variation	
T1, T2	1	1.336 × 103	31.92	0.024	Alluvium
T3, T4a	2	1.282×10^2	2.421	0.019	Volcanic Rocks
T4b	2	1.197×10^2	2.260	0.019	Carbonate Rocks
T5	1	1.169×10^4	2.792×10^2	0.024	Carbonate Rocks
T6, T7, T8	1	3.340×10^3	79.79	0.024	Tuff
T9	3	95.90	0.2711	0.003	Tuff
T10	—	78.62	—	—	Tuff
T11	—	3.888	—	—	Tuff
T12	—	8.64×10^{-3}	—	—	Lakebeds

Despite the impressive match between the measured and computed heads, the model results must be used with great caution. The computed transmissivities in zones 5, 6, 7 and 8 are extremely high; the available permeability measurements do not provide support for these high values. An extremely small transmissivity value was assumed for zone 11 to simulate the large hydraulic gradient north of the Yucca Mountain. As noted elsewhere in this report, at present the cause of this large hydraulic gradient is not understood. The uncertainty in the amount of total discharge from and recharge to the subbasin produces a corresponding uncertainty in the computed transmissivity values. Stated somewhat differently, the presently available data on discharge/recharge and transmissivity distribution in the subbasin provide inadequate constraints for the model.

Czarnecki (1985) presents a slightly modified form of the subbasin model discussed above. The constant head boundary condition along the northernmost boundary was replaced by a constant flux boundary; the prescribed flux was the same as that computed by Czarnecki and Waddell (1984). The prescribed flow conditions along the Furnace Creek Ranch and Alkali Flat were changed to constant head condi tions; hydraulic head values in these areas were estimated from values of land-surface altitudes. Czarnecki employed the empirical approach of Eakin and others (see Czarnecki, 1985, for a detailed discussion) to estimate the increase in recharge associated with a 100 percent increase in modern-day precipitation. The average increase in recharge for the case of 100 percent precipitation was assumed to

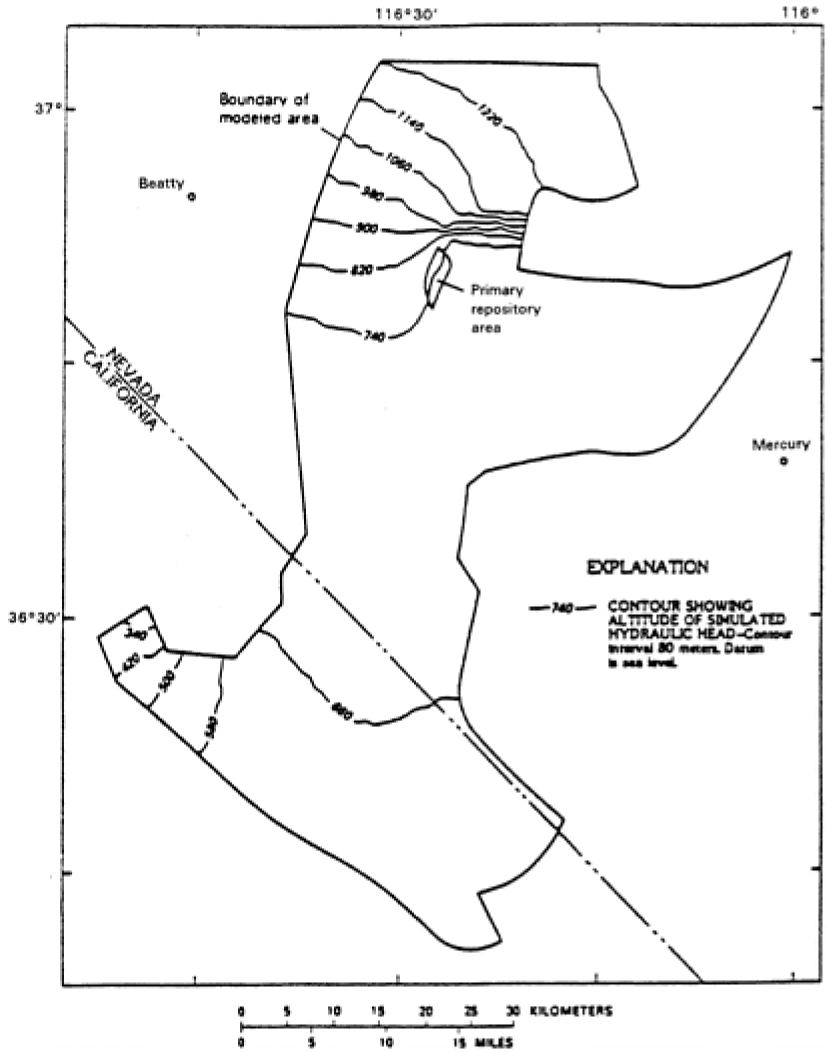

Figure 5
Simulated hydraulic heads. (From Czarnecki and Waddell, 1984).

be 15 times the modern recharge in all areas. The computed rise in hydraulic head is shown in Figure 6. The rise in water level (~130 m) beneath the primary repository area would still leave the water table some 70 meters below the repository horizon. The response of the water table in the primary repository area was found to be most sensitive to recharge along the Fortymile Wash. Because of uncertainties associated with model transmissivities and with the empirical approach used by Czarnecki to compute the increase in recharge, the computed value of 130 meters is at best only an estimate.

As discussed in the preceding, Czarnecki and Waddell (1984) had to utilize a very small transmissivity in zone 11 (see Figure 4) to simulate the large increase in hydraulic gradient north of Yucca Mountain. The trend of this barrier (zone 11) is east-west, normal to the faults in the area. Recently, Czarnecki (unpublished work) has modeled a sudden removal of this permeability barrier. (The removal of the barrier could be due to faulting associated with an earthquake). This "dam break" causes a maximum rise of 20 to 30 meters in water-level at the repository site.

It is conceivable that an increase in precipitation acting in concert with the "dam break" will cause an even larger rise in ground-water level than that caused by climate change alone. Such a "worst case scenario" should be investigated.

Recommendations

Modeling studies by Czarnecki have identified increased recharge associated with increased precipitation as a potential cause for water-table rise beneath the primary repository area. Because of our present uncertain knowledge of the hydrologic regime in the Yucca Mountain area, it is impossible at this time to state with any degree of certainty that the water-table will not rise sufficiently to flood the repository within the next 10,000 years. To reduce the present uncertainty level, it will be necessary to obtain additional hydrologic data to provide constraints on any future modeling efforts.

The following recommendations, if carried out, should help in achieving a better understanding of the present hydrologic regime in the Yucca Mountain area; such an improved understanding is a prerequisite for predicting the response of the hydrologic regime to any future changes in formation transmissivities (e.g. those associated with an earthquake) and/or increased recharge.

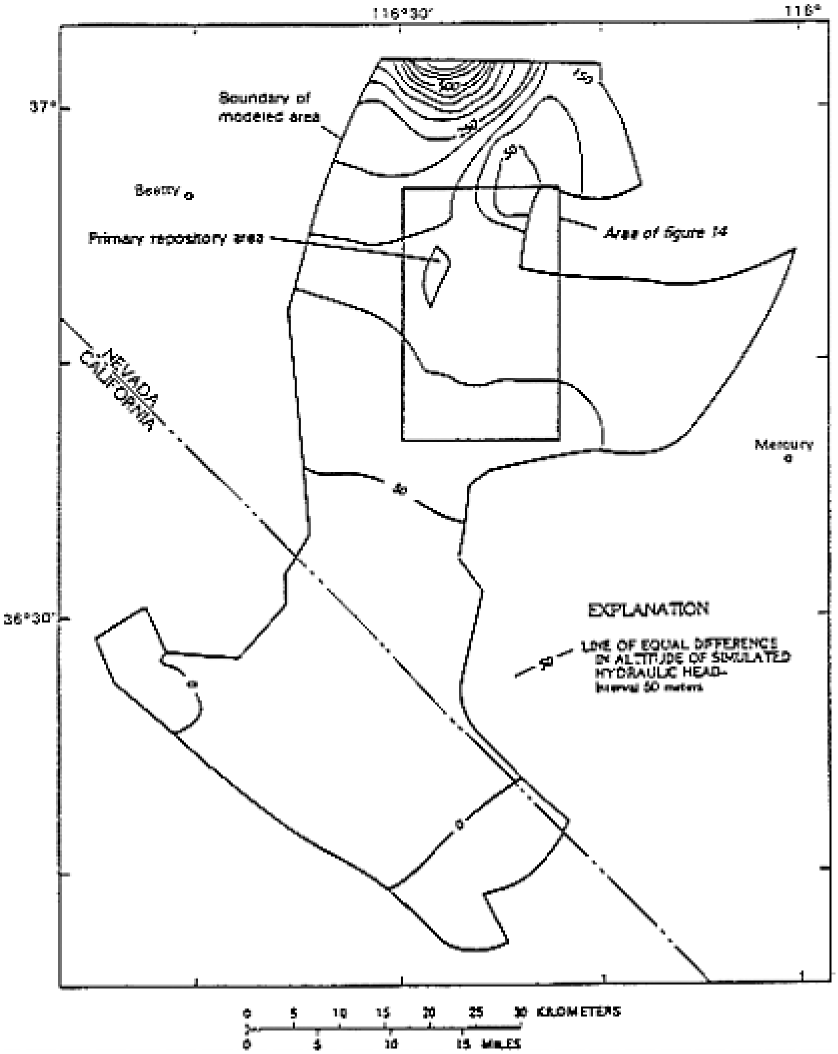

Figure 6
Differences in simulated hydraulic head between baseline simulation representing present day conditions and the simulation involving a postulated 100 percent increase in precipitation. (From Czarnecki, 1985).

Specific Recommendations

1. Existing well data (drilling, stratigraphy, repeat temperature surveys, pumping tests) should be re-examined to determine if the major permeable horizons are associated with specific formations and/or formation interfaces.

2. The anomalous response seen in some of the slug tests should be reanalyzed to determine the cause for the observed behavior.

3. It would be worthwhile to attempt to remeasure hydraulic potential in isolated sections of existing boreholes. A knowledge of the three-dimensional hydraulic head distribution is essential for developing a detailed three-dimensional model of fluid flow in the Yucca Mountain area.

4. Samples of water present at various depths in the Alkali Flat/Franklin Lake subbasin should be dated. A more complete knowledge of water ages will be helpful in developing an understanding of the evolution of the ground-water system over the past 10–15 ka.

5. Effort should be made to characterize more completely the evapotranspiration in the Franklin Lake Playa area. One of the major sources of uncertainty in our present understanding of the hydrologic regime is associated with uncertainties in recharge/discharge rates.

6. A carefully designed set of pressure interference tests is required to delineate the permeability structure in the Yucca Mountain area. Independent determination of permeability is necessary to constrain and guide the modeling studies.

7. A series of wells should be drilled in the steep hydraulic gradient region north of Yucca Mountain. These wells should be drilled deep enough to penetrate the Paleozoic carbonates underlying the tuffs. Hydraulic head and permeability (both pumping and interference tests) measurements in these holes should lead to a qualitative improvement in our understanding of the hydrological regime in this important area.

8. (a) A multi-layered model which includes the Paleozoic carbonate rocks should be constructed using currently available data and used in a sensitivity analysis mode to test the coupling between the tuff aquifer and the Paleozoic carbonates.

(b) Assuming that sufficient data become available, it would be worthwhile to undertake more definite three-dimensional (both steady and transient) modeling studies. A transient three-dimensional model can provide new insights into evolution of the ground-water system over the past 10–20 ka. Such transient modeling is routinely used in geothermal reservoir engineering to model the natural state.

9. If and when a ground-water model, which is well-constrained

by field data, becomes available, it will be possible to obtain more reliable estimates of water level changes associated with climatic changes and/or volcanic/tectonic events.

10. The importance of characterizing the relationship between recharge and precipitation cannot be overemphasized. In particular, it is important to assess the reliability of empirical methods, presumably developed under present arid conditions, to predict recharge under much different climatic (wetter and cooler) conditions.

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Appendix C—

The Effects of Pluvial Climates In The Vicinity of Yucca Mountain: A Summary

Prepared for the National Research Council's Panel on Coupled Hydrologic/Tectonic/Hydrothermal Systems at Yucca Mountain

W. Geoffrey Spaulding
Dames & Moore
Las Vegas, Nevada 89119

Revised September 6, 1991

Introduction

Evidence of former, wetter climatic conditions is widespread throughout the southwestern United States. Among the most striking examples are the wave-cut terraces on the margins of closed valleys; evidence that these basins once supported vast lakes. In the late 19th century Gilbert (1890) was among the first to correlate high stands of these lakes, and the "pluvial" climates that they indicated, with glacial ages. The correlation between pluvial climatic episodes and glacial ages (or stades) has lent a basic time scale to major climatic fluctuations in North American deserts. Although the correlation does not hold true in other of the world's great deserts (in North Africa, for example, the last pluvial climatic episode is broadly correlated with the beginning of the present interglacial; Ritchie et al., 1985; Spaulding, 1991), it applies well throughout the western U.S., from the Great Basin and Mojave Desert, to the Sonoran and Chihuahuan Deserts. Other important issues have been resolved more recently, including what constitutes a pluvial climatic regime in this region, and how much of an impact do pluvial climatic episodes have in terms of increased recharge to the aquifer. The answers to these questions affect assessments of the suitability of Yucca Mountain, or any other proposed locality in the vicinity of the Nevada Test Site, as a potential sub-surface repository for high-level nuclear waste. They also reflect on the validity of assertions concerning the magnitude of impact of pluvial climates on the water table.

Chronological Framework

The design-life of the proposed Yucca Mountain repository is 10,000 yr (10 ka), a time span that lends itself well to consideration within the context of evidence for late Quaternary climatic fluctuations (those that have occurred over the last ca. 130 ka). The historic meteorological record is, of course, too brief to encompass the major changes that take place on such a time span, as is the dendroclimatic record.

The end of the last glacial age, the Wisconsin, is placed at 10 ka (radiocarbon years before present) by international convention (Olausson, 1982). It was characterized by the Early and Late Wisconsin stades, periods of maximum expansion of Northern Hemisphere ice sheets and maximum depression of global temperatures, and the Middle Wisconsin interstade. The two major episodes of global climate change encompassed by the radiocarbon time scale (roughly the last 50 ka) are the Middle/Late Wisconsin transition at 23 ka, and the Late Wisconsin/Holocene transition at 10 ka. The first involved a change to colder and effectively wetter environments, while the second involved a shift to a warmer and effectively drier climate accompanying worldwide deglaciation. The full glacial, or Wisconsin-maximum, at ca. 18 ka witnessed the maximum extent of continental glaciers and maximum lowering of global temperatures (see contributions in Porter, 1983).

Geographic and Paleohydrologic Framework

Located within the southern hydrographic Great Basin, the Nevada Test Site lies astride the climatic and vegetation transition between the warm-temperate Mojave Desert to the south and the cold-temperate Great Basin Desert to the north (Cronquist et al., 1972;

Beatley, 1975). Sparse creosote bush (*Larrea divaricata*)[1] desertscrub occupies the valleys of the Mojave, while relatively productive sagebrush (*Artemisia* subgen. *Tridentatae*) and sagebrush-bunchgrass (*Artemisia-Agropyron* spp.) vegetation typifies many valleys to the north. This environmental transition from arid conditions in the south to relatively moist conditions in the north has apparently persisted through the late Quaternary.

In their study of pluvial (dating to former, effectively wetter climatic intervals) lakes in Nevada, Mifflin and Wheat (1979) note that south of 38° N lat. very few closed basins possess wave cut terraces and, therefore, it is unlikely that they supported pluvial lakes. This observation also applies to basins in adjacent California. The only known exceptions are lakes that were fed by runoff from the east slopes of the Sierra Nevada and Transverse Ranges (such as Pluvial Lakes Mojave and Searles; Figure 1), and a small basin on the northwest end of the Sheep Range, ca. 100 km east-southeast of Yucca Mountain. The widespread paleohydrologic evidence for a drier ice-age climatic regime in the vicinity of the Nevada Test Site, relative to the central and northern Great Basin, conflicts with many popular conceptions of the effect of the last pluvial episode. But there are several lines of evidence that indicate that the last pluvial climatic regime was actually relatively arid.

The data from two sites within the southern Great Basin are relevant to understanding the chronology of paleohydrologic changes: Searles Lake in southeastern California (Smith, 1979; Smith and Street-Perrott, 1983) and the springs of Las Vegas Valley in southern Nevada (Haynes, 1967; Quade, 1986; Quade and Pratt, 1989). Both localities have received careful study, and their chronologies are well controlled through stratigraphy and multiple radiometric dates. Benson et al (1990) have proposed an alternative chronology for Searles Lake that may affect the correlations apparent in Figure 1. However, the data currently available are insufficient to discard the previously established chronology of Smith (1979).

Artesian springs are end-points of a hydrologic system that differ from that of a pluvial lake. High stands of a pluvial lake largely reflect runoff (Enzel et al., 1989), and spring discharge is affected by aquifer recharge (chiefly snow melt in the high mountains). In this case each system should be sensitive to significant pluvial episodes. The Paleozoic carbonate aquifer of the Las Vegas Valley is a confined

[1]See Appendix C Supplement for descriptions and explanations of plant species used as indicators of moisture and temperature in paleoclimate studies.

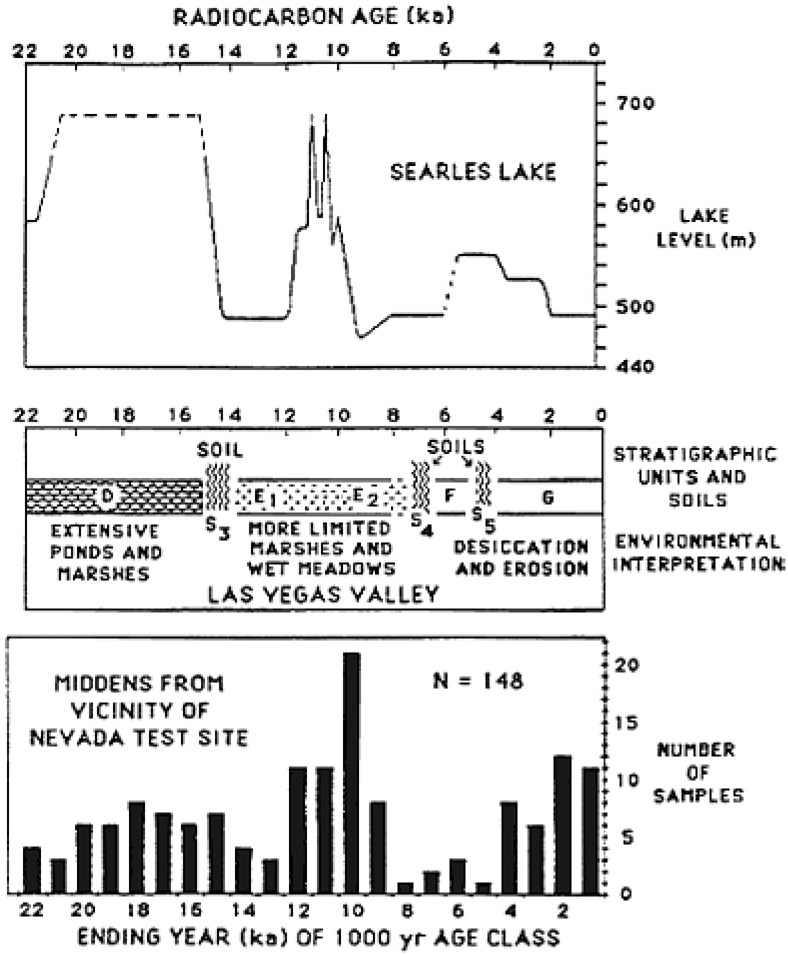

Figure 1
Comparison of paleohydrologic chronologies from the southern Great Basin (Searles Lake from Smith and Street-Perrott, 1983; Las Vegas Valley from Quade, 1986) with the temporal distribution of midden samples from Yucca Mountain and vicinity.

system, and increased recharge in the highlands of the Spring and Sheep Ranges should steepen the hydrologic gradient, resulting in a rapid (relative to radiocarbon-based chronological control which is expressed with standard deviations of up to a thousand years or more) increase in spring discharge at the end of that gradient. Thus, the apparent correlation of major "pluvial" episodes evident in a comparison of the Searles Lake and Las Vegas Valley records (Figure 1) indicates that they may provide a reliable chronology of late Quaternary paleohydrologic changes in the southern Great Basin.

Ancient packrat (*Neotoma* spp.) middens provide much of the data discussed here, and descriptions of these deposits and methods used in their analysis are offered by Betancourt et al. (1990). Composed primarily of mummified plant fragments and fecal pellets encased in a matrix of crystallized packrat urine, they are common in the hills of the region. Plant macrofossils from a midden represent an autochthonous accumulation; most workers assume that a 30 to 50 m radius around the den encompasses nearly all packrat foraging activities. Although normally dominated by the remains of one or two plant species, the assemblages also contain a diverse array of other plants. These assemblages are used to infer climatic conditions at a given time, established by radiocarbon dating organic material selected from the midden sample.

The Paleoecological Record

The paleoecological record provided by both fossil pollen and plant macrofossils from radiocarbon dated packrat middens provides direct evidence of environmental conditions during the last glacial age. Before the development of a comprehensive packrat midden record, the most detailed paleoecological evidence for the region was provided by fossil pollen studies from Tule Springs in the Las Vegas Valley. Wisconsin-age sediments there yielded abundant pine pollen, and were used to reconstruct glacial-age vegetation zonation in which pinyon-juniper woodland (*Pinus monophylla - Juniperus osteosperma*) and pondersa pine - white fir forest (*Pinus ponderosa - Abies concolor*) extended down into the valleys some 1000 m below their current lower elevational limits (Mehringer, 1967). This reconstruction was in accord with paleoclimatic models that were most widely accepted at that time (e.g. Leopold, 1955; Antevs, 1948): a mild and wet pluvial climatic regime with average annual precipitation perhaps double today's meager amount and a decline in average annual temperature of less than 5°C (ΔT_a 5°C).

Fossil sites that provide information on environmental change in the Nevada Test Site area span ca. 2000 m of relief, from low elevations in the Amargosa Desert and Las Vegas Valley, to high elevations in the Sheep Range. Fossil records from such an extensive gradient can be used to illustrate some principal features of the late Quaternary environments of the region, and to demonstrate that the area was relatively dry during the late Quaternary regardless of whether a "pluvial" or "interpluvial" climatic regime prevailed.

The assertion that pluvial climates lead to radical rises (>10 m) in water table elevation during the late Quaternary presupposes that those climates were characterized by substantial (>100 percent above modern) increases in average annual rainfall. The most efficient means of testing this hypothesis is to refer to the existing paleoecological record for evidence of (1) full-glacial climatic conditions, and (2) plants that require wet-ground to exist (phreatophytes) regardless of when they occurred. The first set of data yields insight into climate during the time when conditions were most different from those of the present. The second set of data yields evidence for the extent and timing of effluent ground water where none now exists.

Selected Fossil Records

During the last glacial age juniper woodland extended to the valley bottoms while the driest sites supported shrubs such as shadscale (*Atriplex confertifolia*) and sagebrush (*Artemisia* subgen. *Tridentatae*). Nowhere in the Wisconsin fossil record is there evidence for the desert shrubs that typify the current Mojave Desert. Above ca. 1600 m on tuffaceous substrate, and above 1800 m on calcareous rocks, there existed subalpine conifer woodland dominated by limber pine (*Pinus flexilis*). No macrofossil evidence has been found for ponderosa pine-white fir forest during the last glacial age (Spaulding, 1985, 1990; Spaulding et al., 1983). Such forest vegetation would indicate wetter, milder conditions than those which appear to have prevailed.

The Skeleton Hills-1 (Sk-1) midden, from 910 m elevation in the Amargosa. Desert, is a low-elevation fossil record where the response of vegetation to increased effective moisture can be expected to have been most pronounced. In addition, it is from a north-facing slope and therefore not subject to the drying conditions found on south-facing slopes. The Sk-1A(12) assemblage, dated at 36.25 ±.91 ka, contains abundant Utah juniper, and woodland and steppe shrubs (Figure 2). The full-glacial Sk-1A(2) assemblage is broadly similar in that it is also dominated by juniper, but there are significant differences. The abundance of steppe shrubs in the Sk-1A(2) sample, relative to Sk-1A(12) (Figure 2), indicates a dry and cold climate at ca. 17

ka. In particular, the abundance of shadscale (60% of the total number of identified specimens excluding juniper) on this north-facing slope indicates that relative aridity was still an important feature of this environment. The subsequent early and late Holocene assemblages from the Sk-1 site reflect the importance of desert shrubs in the surrounding vegetation and contain no woodland species.

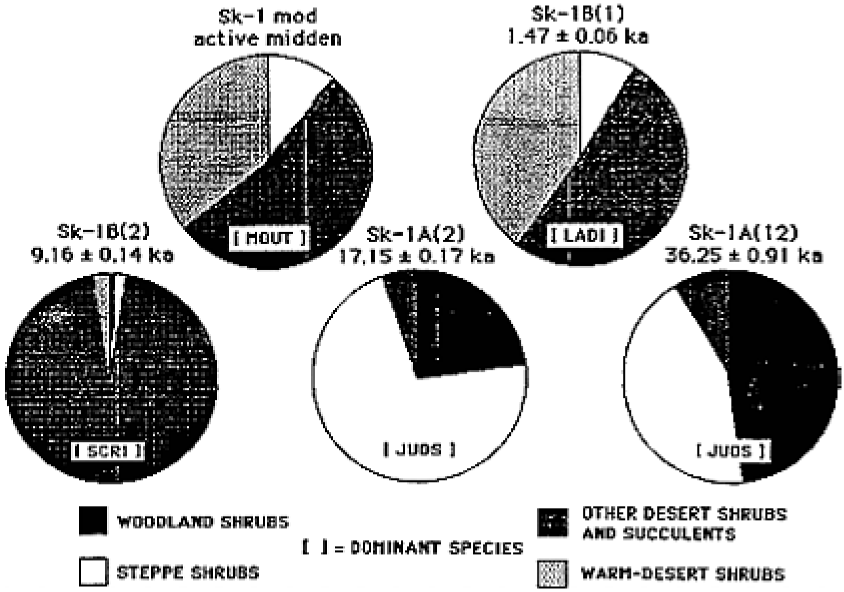

Figure 2
Relative abundance of indicator plant taxa in samples from the Skeleton Hills-1 packrat midden, Amargosa Desert. Abbreviations are: LADI, *Larrea divaricata*; JUOS, *Juniperus osteosperma*; MOUT, *Mortonia utahensis*; SCRI, *Scopulophila rixfordii*.

Similar patterns are seen at higher elevations. Willow Wash-4 (WW-4), at 1580m elevation in the Sheep Range, was near the upper limit of glacial-age juniper woodland. This site, on a north-facing slope, yields two samples that are of probable Middle Wisconsin age. The WW-4E (>44 ka) and WW-4C(1) (24.4 ±.760 ka) midden assemblages contain abundant Utah juniper, but fewer steppe shrubs than do the full-glacial WW-4C(2) and WW-4D samples (19.020 ±.750 and 17.7 ±.740 ka, respectively; Figure 3). Montane and subalpine species also are more abundant in the Middle Wisconsin samples. The abundance of steppe shrubs on this north facing slope, at a relatively high elevation, indicates that full-glacial climates were typified by cold, dry conditions.

A single early Holocene sample (WW-4B) contains abundant juniper like the Wisconsin-age assemblages, but with a suite of desert shrubs that sets it off from the older records (Figure 3). The modern WW-4 sample contains a larger proportion of steppe shrubs than the early Holocene assemblage. The late Holocene climate therefore appears to have been drier and colder than that of the terminal Wisconsin or early Holocene (Spaulding and Graumlich, 1986).

Evidence of Phreatic Environments

The extensive Wisconsin-age spring deposits in the larger valleys of southern Nevada attest to a considerable expansion of wet-ground habitats during the last glacial age (Quade, 1986; Quade and Pratt, 1989). But this geological evidence is restricted to valley-bottom set

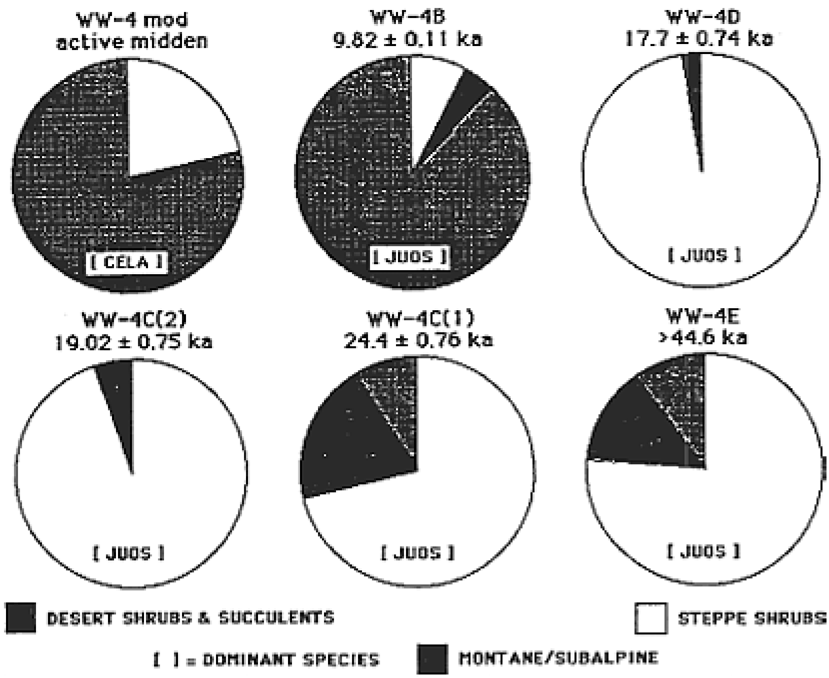

Figure 3
Relative abundance of indicator plant taxa in samples from the Willow Wash-4 packrat midden, southeastern Sheep Range. Abbreviations are: CELA, *Ceratoides Lanata*.

tings. What of the larger drainage systems of the Spring and Sheep Ranges and those of the highlands of the Nevada Test Site?

Wet-ground species appear only rarely in the southern Great Basin midden record. Five records are of "long-distance transport taxa," primarily the isolated seed shells of net-leaf hackberry (*Celtis reticulata*). Hackberry seeds are durable and were probably transported to the midden sites by birds. This tree requires perennially moist conditions to survive in the Great Basin today, and these remains may have been transported from expanded and more numerous springs and water courses.

To date there are but two sites that provide unequivocal records of wet-ground habitat in uplands where none now exists. Abundant hackberry seeds from Deadman Canyon-2 in the Sheep Range indicate the presence of perennial water at 2075m elevation 9.8 ka. The tree is now extinct in the range (Spaulding, 1981). The other site is in Fortymile Canyon (FMC), the major drainage of the western Nevada Test Site. The FMC-7 midden site lies at ca. 1250 m elevation and is a small rock shelter ca. 60 m above the canyon floor. Samples from the top and bottom strata of the FMC-7 midden yielded dates of 47.2 ±3.0 and >52.0 ka (FMC-7(1) and FMC-7(3), respectively).

The twigs and seeds of wild-rose (*Rosa woodsii*) and willow (Salix sp.) were found in FMC-7(1) and FMC-7(3). In addition, FMC-7(1) contained the seeds of marsh knotweed (*Polygonum lapathifolium*-type). Willow and marsh knotweed are obligate wet-ground species while wild-rose is restricted to perennially moist environments in the Great Basin. The relative abundance of all wet-ground taxa is higher in FMC-7(1) than in any other assemblage from the locality (Figure 4). The general composition of the FMC-7 samples suggests a warmer environment than during the full-glacial, based on prior studies (Spaulding et al., 1984). Evidence for perennial water during a warmer climatic episode also applies to the other fossil records of the wet-ground plants, which all date to the early Holocene (Table 1).

Paleoclimatic Reconstructions

Important contrasts between Middle and Late Wisconsin fossil records are (1) wet-ground plant species appear to have been more abundant during the Middle Wisconsin, and (2) steppe shrubs appear to have been dominant during the Late Wisconsin. These suggest that effective moisture and temperature may have been lower during the Late Wisconsin, and particularly during the full glacial. This makes sense on meteorological grounds alone. Enhanced temperatures can lead to increased precipitation through increased atmospheric competence. The ability of the atmosphere to evaporate and transport water ("competence") is strongly affected by air temperature.

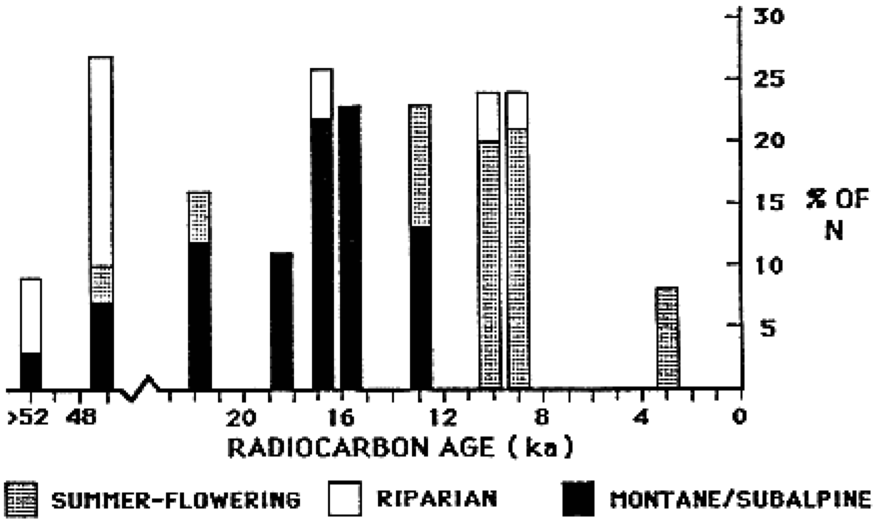

Figure 4
Indicator taxa in packrat midden samples from Fortymile canyon, immediately east of North Yucca Mountain, as percentages of the total number of taxa (N) encountered in those samples. Note the relative abundance of riparian plants in the oldest two assemblages, and the paucity of these species in the younger assemblages.

Full-Glacial Climates

The idea of a relatively cold and dry full glacial climate is not new (Galloway, 1983) but it conflicts with a model of a full glacial characterized by equable temperatures and substantially increased annual precipitation (Van Devender et al., 1987). Issues that are important in this conflict include whether key macrofossil assemblages actually relate to full-glacial climate, and whether paleoclimatic reconstructions derived from one area in the Southwest can be extended to another, bioclimatically distinct area.

Paleoecological data indicating a substantial reduction in winter temperature ($-\Delta T_w$) in the study area during the Wisconsin have been discussed by Spaulding (1985). The exclusion of warm-desert plants from even the lowest and most and sites is consistent with a $-\Delta T_w$ of

Table 1 Packrat Midden Records of Hydrophilic Species from the Nevada Test Site and Vicinity.

Area & Site	N. lat.	W. long.	Elev. (m)	Sample	Species	Source	14-C date (ka)
Amargosa Desert							
Skeleton Hills-1	36° 32'	116° 20'	910	Sk-1B (2)	Celtis reticulata seed	long distance	9.2 ± 0.14
Skeleton Hills-2	36° 38'	116° 17'	940	SK-2(2)	muskrat tooth	long distance	8.17 ± 0.1
Sheep Range							
Willow Wash-4	36° 28'	115° 15'	1585	WW-4B	Populus sp. twig	local (?)	9.82 ° 0.11
Flaherty Shelter	36° 30'	115° 14'	1650	Unit 3/125cm	Celtis reticulata seed	long distance	*
Deadman-2	36° 37'	115° 16'	2075	Dm-2	Celtis reticulata seeds	local	9.56 ± 0.18
North Yucca Mountain							
Fortymile Canyon-7	36° 57'	116° 22'	1250	FMC-7 (1)	Salix sp., Rosa woodsii Polygonum lapathifolium-type	local	47.2 ± 3.0
	36° 57'	116° 22'	1250	FMC-7 (3)	several phreatophytes	local	>52
Sandy Valley							
Sandy Valley-2	35° 53'	115° 42'	935	SaV-2 (3)3	Celtis reticulata seed	long distance	9.4 ± 0.09

*Sample from bioturbated cave sediment, 75 cm below a radiocarbon date of 6.95 ± 0.32 ka (A-1297).

at least 6°C. The prevalence of steppe shrubs and drought-adapted conifers suggests similarities between the full-glacial fossil records from this area and the flora of the northern Great Basin.

Most reconstructions call for a depression of full-glacial summer temperatures ($-\Delta T_s$) in excess of $-\Delta T_w$ (Spaulding et al., 1983). Values of $-\Delta T_s$ derived from elevational depressions of key plant taxa in the Nevada Test Site region range from 6.4° to 9°C. The decline in average annual temperature ($-\Delta T_a$) in the study area during the Late Wisconsin is estimated to have been ca. 7° C (Spaulding, 1985). These reconstructions accord well with the distribution of relict features indicating permanently frozen ground on Great Basin mountain ranges (Dohrenwend, 1984).

Moisture-loving, montane species such as ponderosa pine and white fir were expected in the fossil record when the model of a mild, moist glacial-age climate was thought to apply (e.g., Mehringer, 1967). Subsequent research shows that these plant species were actually rare (white fir) or apparently absent (ponderosa pine) from the fossil record of the southern Great Basin (Spaulding, 1990). An estimated increase in average annual precipitation (P_a) of 40 percent is all that is required to account for the paleobiotic record in this region (Spaulding, 1985). With the fossil record dominated by drought- and cold-tolerant species it is difficult to see how the increase could have been greater.

General analogs and model simulations suggest a reduction in summer precipitation below today's meager amounts (presently □25 percent of the annual total in the Yucca Mountain area), and a substantial increase in winter precipitation to account for the apparent increase in P_a. This strong winter-seasonality of precipitation during the last glacial age is analogous to present conditions in the central and northern Great Basin. What changes in atmospheric circulation forced increased winter precipitation?

The modeled position of full-glacial (18.0 ka) airflow over North America (Figure 5) shows pronounced southward displacement of the mean annual position of the westerly jet stream (COHMAP, 1988). It currently enters North America over the Pacific Northwest, but was deflected southward during the full-glacial by the massive Laurentide ice sheet and an enhanced pole-equator pressure gradient. The fact that it may have entered the continent south of the Nevada Test Site area (Figure 5) could account for evidence of mild-moist conditions at sites in southern Arizona, and colder, drier conditions to the north (Spaulding and Graumlich, 1986). Suppression of summer rainfall as a consequence of reduced T_s is well simulated by climate models (Spaulding and Graumlich, 1986; COHMAP, 1988).

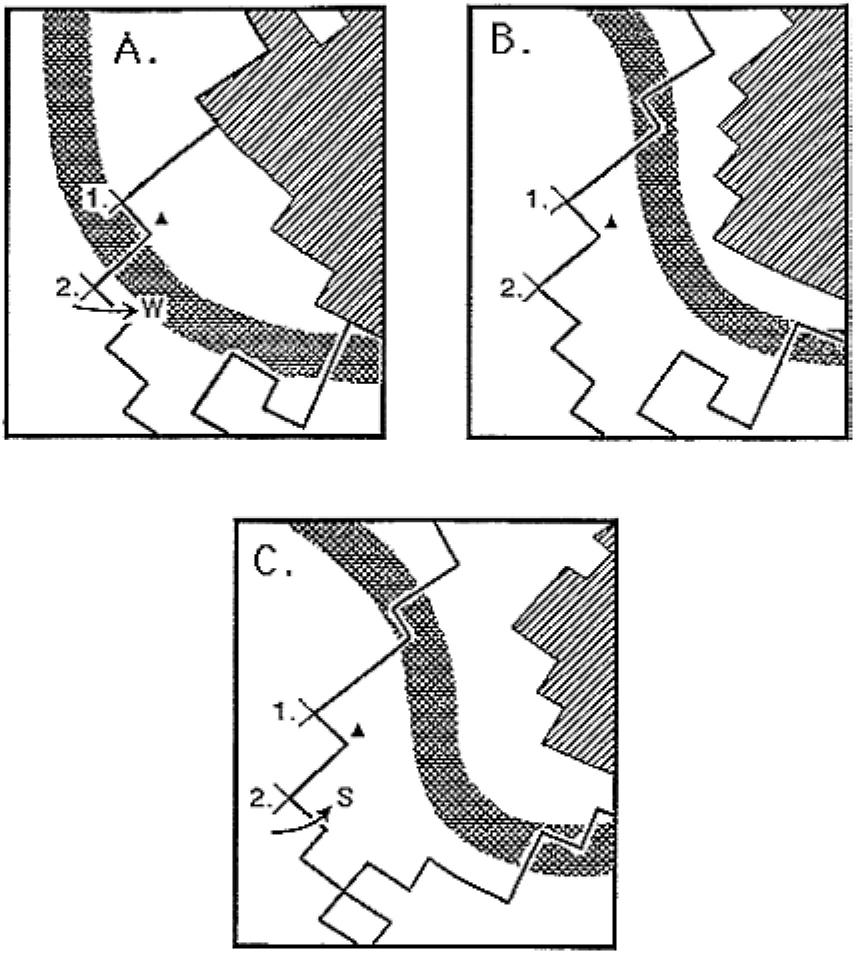

Figure 5
Model simulations of atmospheric circulation at (A) 18 ka (B) 12 ka and (C) 9 ka (COHMAP, 1988). Note that the model resolution is such that the outline of the North American continent is only approximate. Prescribed ice sheet extent indicated by hachured area, modeled mean position of the westerly jet indicated by stippled area. Arrows indicate stronger surface winds than present in winter (W) and summer (S). Δ, Position of Yucca Mountain on the model grid. The numbers are geographic reference points: (1) 35.5° N. Lat., 123.75° W. Long; (2) 26.6° N. Lat., 116.25° W. Long.

The Terminal Wisconsin-Early Holocene

The southern Great Basin paleohydrologic record indicates that there was general decline in effective moisture between ca. 17 and 13 ka (Figure 1), even given the meager amounts that characterized the full glacial. This is consistent with model simulations of late-glacial climate change (Figure 5). Model simulations indicate that the northward retraction of the westerly jet between 18 and 12 ka was largely due to the retreat of the North American ice sheets (COHMAP, 1988). The result in the Nevada Test Site area should have been a decline in the frequency and intensity of winter precipitation events. The later (13 to 14 ka) high stand of Pluvial Lake Lahontan to the north (Benson and Thompson, 1987) may have been caused by increased precipitation associated with the repositioning of the prevailing westerlies at this more northerly latitude.

Despite evidence for the northward retreat of the westerly jet, effective moisture continued to exceed that of the present until the close of the early Holocene in Southern Nevada (Spaulding, 1985; Van Devender et al., 1987). The Searles Lake and the Las Vegas Valley records even indicate episodes of increased effective moisture (Figure 1). What could have caused this? Some suggest that it was due to the persistent southward displacement of the mean position of the prevailing westerlies (Van Devender et al., 1987). An alternative explanation is that a rather different precipitation regime prevailed in the Southwest between ca. 12 and 8 ka (Spaulding, 1990; Spaulding and Graumlich, 1986).

At most sites there was near-complete turnover in community composition between 13 and 11 ka. This involved the reduction or elimination of steppe shrubs and low-elevation conifer populations. Increases in summer-seasonality of precipitation and warmer winter temperatures may account for these changes. Warmer winters also are indicated by the expansion of desert shrubs at higher elevations (e.g. Figure 3). Increased summer precipitation is indicated by the importance of grasses and succulents (agave, yucca, cacti) in low-elevation fossil records between ca. 12 and 8 ka (Spaulding, 1990).

Variations in incoming solar radiation forced by perturbations in the Earth's orbit have ultimate effects on global climate (regulation of the glacial-interglacial cycle; Berger et al., 1984) and more immediate effects on regional climate (e.g., Kutzbach and Street-Perrott, 1985). Among the best documented immediate effects are climate changes associated with the last summer insolation maximum. At about 10 ka orbital perturbations resulted in a ca. 8 percent increase in Northern Hemisphere summer insolation, and a corresponding decrease in winter insolation. The modeled effects of enhanced summer radiation in the northern subtropics are an increase in monsoonal (summer) rainfall, and extension of the monsoonal rainfall regime north of its present seasonal limit. These predictions are confirmed by the global paleohydrologic record (Kutzbach and Street-Perrott, 1985; Ritchie et al., 1986). Model simulations of seasonal precipitation over an area-averaged Southwest also show increased summer precipitation beginning by 12 ka (Spaulding and Graumlich, 1986). Intensified thermal lows would result in enhanced advective flow of maritime tropical air into the desert interior as moister, colder air would be drawn from the ocean into the region of low pressure. The strengthening and northward displacement of subtropical high pressure systems would have provided additional moisture aloft during the summer (Figure 5).

Could a "monsoonal pluvial" account for the record of increased lake levels and the reactivation of artesian springs between 12 and 8 ka? Perhaps not. Today runoff and recharge are critically dependent on winter precipitation (Enzel et al., 1989; Winograd and Thordarson, 1975). Presently, summer rainfall has little effect on the annual hydrologic budget of dry lake basins, and is not thought to contribute significantly to recharge. Thus it is necessary to entertain some alternative possibilities. Perhaps both summer and winter precipitation exceeded present amounts between 12 and 8 ka. It also is possible that non-analogous seasonal insolation regimes (COHMAP, 1988) and ocean-land thermal gradients resulted in non-analogous runoff and recharge conditions. Under these conditions, analogies based on historic hydrologic data may provide imperfect measures of what could have occurred during the terminal Wisconsin and early Holocene.

Given these and other uncertainties, it is premature to offer specific climatic reconstructions for the terminal Wisconsin and early Holocene. Early Holocene records of wet-ground plant species suggest that recharge was still sufficient to support expanded springs and water courses, despite the development of increasingly and vegetation on upland slopes. The contrasting lack of wet-ground plants from full-glacial middens is suggestive, but may be simply due to sample distribution (Figure 1).

Climates of the Last 8000 Years

Essentially modern vegetation and climatic conditions were established in the Southwest between 7.8 and 7 ka. Within the last seven millennia it appears unlikely that ΔT_a exceeded 1.5°C and P_a varied more than 20 percent from current long-term means. However, there were marked variations within these limits. Much of the first half of the middle Holocene (from ca. 7.5 to 5.5 ka) appears to have been effectively more arid than the present (Hall, 1985; Spaulding, 1991). And much of the late Holocene (after 3.5 ka) appears to have been characterized by levels of effective moisture equal to or slightly exceeding those of the present (Cole and Webb, 1985; Spaulding, 1990).

Conclusions and Information Needs

There is virtually no evidence in the glacial-age fossil record for an increase in average annual precipitation exceeding 40 percent of modern amounts. The nature of full-glacial vegetation can be attributed to a relatively cold and dry climatic regime with increased average annual precipitation approximately 40 percent above that of the present, coupled with mean annual temperatures approximately 7°C below those of the present. The paucity of records of wet-ground vegetation, and their absence during the full glacial, is consistent with the assertion that pluvial climates in this region were much drier than that which would be inferred from the standard application of the word "pluvial."

The one record of local wet-ground vegetation in Fortymile Canyon, dated to the Middle Wisconsin, is consistent with modeled responses of ground-water to increased recharge north of a steep drop in the calculated position of the potentiometric surface north of Yucca Mountain (Czarnecki, 1985). This record deserves further consideration in part because it lies ca. 60 m above the present floor of Fortymile Canyon, and it points to the need for additional investigations of paleohydrologic conditions in the vicinity. However, it is not evidence for a radical change in the elevation of the water table in the vicinity of the Yucca Mountain, south of the break in elevation of the potentiometric surface. Moreover, full-glacial middens from the same area provide no evidence of wet-ground vegetation.

Along with a need for continued search for evidence of perennially moist conditions in presently-dry water courses in the area, there is also need for high-elevation (>2000 m) fossil records contemporaneous with a possible latest Wisconsin-early Holocene pluvial episode to resolve the apparent contradiction between increased discharge (presumably as a consequence of increased high-elevation recharge) and evidence for increased aridity in existing fossil records. There is also a need for information and techniques that would allow more sophisticated climatic interpretation of the fossil data. The known climatic affinities of plant species within a given fossil assemblage could be used for quantitative derivation of paleoclimatic parameters, if standardized data existed. Establishment of a database relating species' ranges to measured climatic parameters, and its application to the macrofossil record, would provide a great deal of new information on climatic stability of the Nevada Test Site and vicinity.

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Appendix C Supplement

Indicator Plant Species in Paleoclimate Studies

I. Warm desert plant species:

Frost-sensitive plants generally restricted to elevations between 1700 m and sea level, and to latitudes south of 38°N in the Mojave Desert. These species were absent from the Yucca Mountain region before 10 ka. They are indicative of a warm-temperate, desert environment.

creosote bush (*Larrea divaricata*). The most widespread shrub in the warm deserts of North America, creosote bush did not arrive in the Yucca Mountain area until sometime after 8.2 ka. Its absence from even the most arid habitats during the last glacial age is attributed to minimum winter temperatures that were at least 7°C lower than present winter minima (Spaulding, 1985).

II. Cold desert or steppe plant species:

Frost-tolerant plants generally restricted to elevations above 1000 m, and to latitudes north of 38°N in the Great Basin. These species were present in the Yucca Mountain region during the last glacial age, and persist there today, although they are not as widespread. They are indicative of a cold-temperate desert environment.

bunchgrass (*Agropyron* spp.). A large grass frequently associated with sagebrush.

sagebrush (*Artemisia* subgen. *Tridentatae*). In the southern Great Basin this subgenus, includes *A. tridentata* (big sagebrush) which is common on alluvial fans and sandy bottoms of the higher (>1500 m) valleys of the Great Basin, and *A. nova* (black sagebrush) which is common on rocky substrate and is frequently associated with dry woodland communities (pinyon-juniper and subalpine conifer woodland). These two species are indistinguishable based on the leaves and twigs preserved in macrofossil assemblages.

shadscale (*Atriplex confertifolia*). This desert shrub is commonly found today near valley bottoms at elevations above 1000 m. It is not known to occur in woodland vegetation today. However, glacial-age macrofossil assemblages indicate that, on calcareous substrate, it commonly occurred in juniper woodland. This anomalous association is attributed to shadscale's extreme tolerance of freezing temperatures (relative to other desert shrubs; Beatley, 1975), and the absence of many other shrub species during the last glacial age that likely compete with it today (Spaulding, 1985).

III. Woodland plant species:

Woodland is a term applied to plant communities dominated by short trees, less than 10 m in height, that typically display open spacing and, therefore, possess a diverse shrub component in the well-lighted areas. There are two types of woodland in this region: pinyon-juniper woodland that occupies intermediate elevations immediately above desert scrub vegetation, and sub-alpine conifer woodland that occupies the highest-elevation peaks and ridges.

limber pine (*Pinus flexilis*). Today limber pine is found above 2600 m elevation only in the highest mountain ranges of the region, and extensive populations are known to occur only in the Spring Range, with more limited populations in the Sheep Range and the Groom Range. This tree was the most common subalpine conifer in the region during the last glacial age, and subalpine woodland dominated by limber pine occurred above 1800 m elevation in the Yucca Mountain area. Elsewhere, on mountain ranges with calcareous soils derived from limestone and dolomite, bristlecone pine (*Pinus longaeva*) shared dominance with limber pine in ice-age subalpine woodlands. Limber pine is drought tolerant, and the widespread occurrence of subalpine conifer woodland dominated by this tree, usually associated with sagebrush, indicates a relatively dry and cold climate.

pinyon pine (*Pinus monophylla*). Although there are other species of pinyon pine in western North America, single-needle pinyon pine is the widespread pinyon of the Great Basin, and it is the pinyon species that occurs in the glacial-age fossil record of the Yucca Mountain area. Today restricted to elevations above ca. 1700 m, it occurred as low as 940 m in the vicinity of Yucca Mountain during the Late Wisconsin. It is less drought tolerant than Utah juniper, and is less frequently encountered in the fossil record than juniper, its common modern associate. Ranging as far north as ca. 42°N lat. today, the northern-most record of pinyon for the full-glacial comes from the Skeleton Hills on the eastern border of the Amargosa Desert (36° 38 N lat.; Spaulding, 1990).

Utah juniper (*Juniperus osteosperma*). Together with pinyon pine, this tree species comprises the pinyon-juniper woodland which covers vast areas at middle elevations in the hills and mountains of the Great Basin. Presently restricted to elevations above ca. 1600 m, it occurred as low as 400 m during the last glacial age. Although it often shares dominance with pinyon in today's woodlands, the apparent scarcity of pinyon during the last glacial age indicates that juniper woodland, rather than pinyon-juniper woodland, occupied the hills and valleys of the region that today support only desertscrub, vegetation.

IV. Forest plant species:

Forest is rare in the region today, and is restricted to the higher elevations (>ca. 2200 m) of the Spring and Sheep Ranges in southern Nevada. Initial reconstructions of vegetation and climate based on pollen analysis during the 1960's portrayed forest vegetation as occupying the valley flanks of the Mojave Desert (Mehringer, 1967), consistent with the concept of a pluvial climatic regime characterized by greatly increased precipitation (perhaps 100% of present average annual amounts) and a modest decline in temperature (4°C below present average annual temperature). Subsequent research based on plant macrofossil assemblages from packrat middens indicates that forest may have been absent, and drought-adapted woodland was widespread.

ponderosa pine (*Pinus ponderosa*). This tree is unknown in the glacial-age macrofossil record of the region. The oldest record of ponderosa pine is dated to ca. 10 ka and comes from a site within its modern elevational range at 2400 m elevation.

white fir (*Abies concolor*). Occasional glacial-age fossil records of this species are usually associated not with ponderosa pine, its common modern associate, but with the subalpine conifer limber pine (*Pinus flexilis*). A single needle of white fir from a packrat midden dated 15.9 ka. from the eastern flank of North Yucca Mountain indicates that this tree probably occupied higher elevations in the area.

V. Wet-ground plant species:

Also known as phreatophytes, these plants require perennially moist soils in order to grow and reproduce. Obviously, they are rare in the Mojave Desert today. Tests for their presence in macrofossil assemblages provide one means of assessing the impact of climates of the last glacial age on the hydrology of this area.

net-leaf hackberry (*Celtis reticulata*). This plant occurs either as a tree or shrub near springs and along rivers in the less and portions of the Southwest. Not recorded by Beatley (1976) for the Nevada Test Site and vicinity, it was recently discovered grow ing on a small seep in the middle reaches of Fortymile Canyon. The seeds of this tree are widely transported by birds, and are occasionally present in early Holocene macrofossil assemblages from the region, but have not been encountered in glacial-age macrofossil assemblages.

marsh knotweed (*Polygonum lapathifolium*). An herb found only on moist ground, it is not known to occur in the region today. Its macrofossils have been recovered from one site, located in Fortymile Canyon immediately east of North Yucca Mountain at 1250 m elevation. The carbon isotope dates for this record are 47.2 and >52 ka, placing it well before the last glacial maximum(ca. 18 ka).

wild rose (*Rosa woodsii*). A thorny shrub found today along springs and seeps above 1650 m elevation, its macrofossils have been recovered from only one locality, the same one that yielded the remains of marsh knotweed (above).

willow (sp.). A shrub or small tree that occurs around many springs in the area, its macrofossils were recovered from the same assemblages that yielded the remains of wild rose (above).

Appendix D—

Response of the Ground-Water System at Yucca Mountain to an Earthquake

J.D. Bredehoeft
U.S. Geological Survey
Menlo Park, California
Revised February 12, 1992

Abstract

The volume strain produced by a normal fault earthquake, of approximate magnitude 6, is computed using dislocation theory. The head change produced by the change in volume strain associated with the earthquake is also computed. Using the head change as an initial condition the three dimensional ground water flow is modeled.

Flow is found to occur from areas where the rock is compressed to areas where the rock was put into tension. In the dislocation calculations the volume put into compression equals the volume put into tension. The calculations suggest that the head change produced by the earthquake is quickly dissipated by local flow (in approximately 1 day). The water table is relatively unaffected in these calculations.

Introduction

The question has been asked: *what would be the effect of an earthquake on the water table beneath Yucca Mountain?* One hypothesis is that such an event could raise the water table dramatically causing a potential hazard for the proposed nuclear repository. As currently designed, the repository at one point is approximately 200 meters above the water table; the depths will range from 200 to 390 meters.

The purpose of this report is to examine the impact of an earthquake on the ground-water system at Yucca Mountain. A set of calculations is presented; the purpose of these calculations is to examine the *order of magnitude* of potential effects. These results are not intended to predict exactly the effects beneath Yucca Mountain; they are an attempt to investigate if there is a potential problem.

There are two models for the deformation that would accompany a nearby earthquake: (1) a strain produced by a regional change in the state of stress caused by the earthquake, and (2) a dislocation strain model for the earthquake. In this paper I will examine the implications of the dislocation model. If one integrates the change in stress, or the strain, produced by the dislocation model over a sufficiently large volume of rock, it sums to zero. In other words, the usual dislocation calculation does not produce a regional change in either the stress or the strain. In the dislocation model local changes in both the positive and negative directions balance each other.

Rocks at Yucca Mountain are continually loaded by changes in the barometric pressure and are continually strained by the earth tide. Both conventional hydrologic tests and the effects of barometric loading and earth tide strain have been analyzed in 4 drill holes. This provides one reasonably complete set of data from which one can estimate the response to both stress and strain. We will attempt to put these data in perspective before attempting an analysis.

Earth Tides and Atmospheric Loads

Near the earth's surface rocks are subjected to earth tide strain and changes in atmospheric pressure. The response of the groundwater system to these effects can be used to investigate both the elastic and the hydrologic parameters of rocks in the area. In the case of earth tides, the disturbance has such a long wave length that the response is determined by material properties deep into the mantle. Near-surface crustal rocks are along for the ride. In analyzing the tidal response of water wells the best assumption is that horizontal strains are imposed (Bredehoeft, 1967; Hsieh et al., 1988). Analysis of the tidal and atmospheric effects indicate how the groundwater system responds to both imposed stresses and strains.

Elastic and Hydrologic Parameters

Galloway and Rojstaczer (1988) analyzed the response of 4 water wells at Yucca Mountain to both atmospheric loading and earth tides. Figure 1, taken from Galloway and Rojstaczer (1988), shows schematically the stratigraphic section open to each well. A summary of the

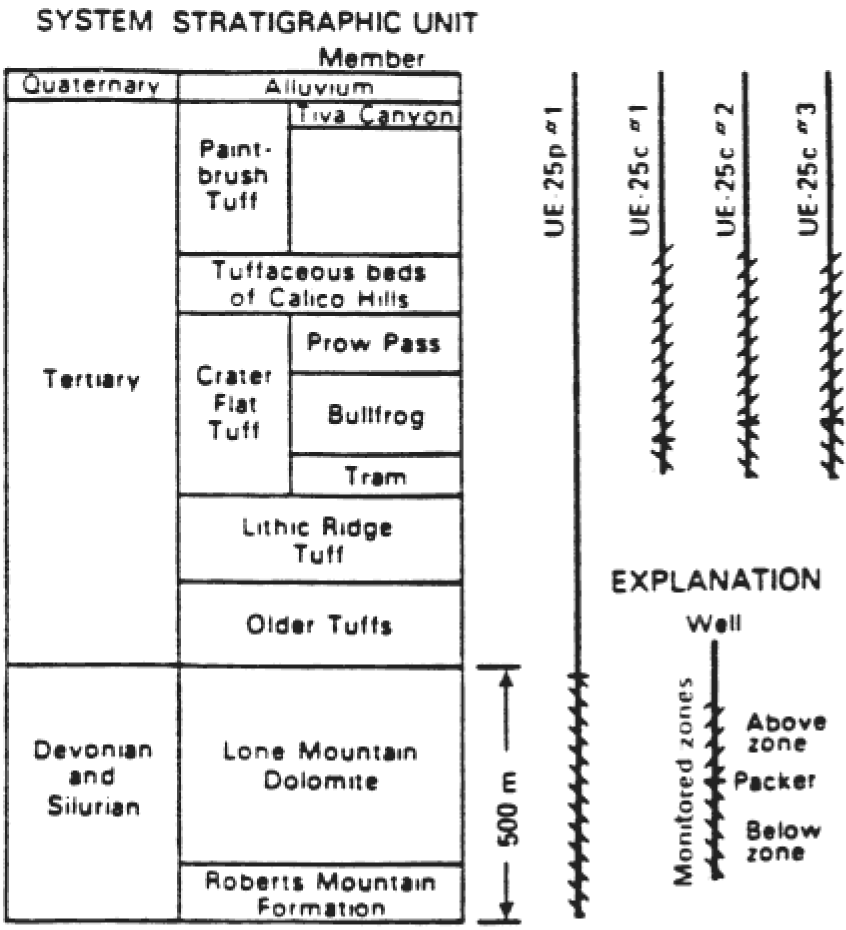

Figure 1
Schematic stratigraphic section of the rocks penetrated at the UE-25 drill site (after Galloway and Rojstaczer, 1988).

necessary elastic and hydrologic parameters is presented in Table 1; much of the information is taken directly from Galloway and Rojstaczer (1988).

A few comments are in order regarding the data in Table 1. The carbonate aquifer has a high sensitivity to volume strain: approximately two meters change in head (pore pressure) per microstrain. The specific storage for the carbonate aquifer is also low.

Galloway and Rojstaczer point out that this low value indicates a stiff rock with low porosity; they estimate the porosity at 6×10^{-4} or less. The permeability of the carbonates is high, approximately an order of magnitude or more higher than that of permeable tuff. These data are consistent with a fractured, permeable carbonate aquifer.

Galloway and Rojstaczer use a well sensitivity to tidal strain, A_s, that is a sensitivity to only the horizontal strain. It is more useful in this analysis to have the sensitivity to strain expressed in terms of the total strain. One can show that for an undrained Poisson's ratio of 0.33 the sensitivity to total strain, A_t, will be twice the sensitivity to the horizontal strain: $A_t = 2\ A_s$. Galloway and Rojstaczer's analysis also indicates a tight confining layer overlying the carbonate aquifer. This unit is approximately 4 orders of magnitude less permeable than the overlying tuffs. The unit makes a significant difference in the hydraulic response of the system.

One other important question is: *what are the conditions just above the water table?* Data from Montazer and Wilson (1984) indicate that the unsaturated pore space maybe approximately 5 percent. However, many tuffaceous rocks above the water table have moisture contents near 100 percent saturation; this is especially true of the less welded units. For this analysis, I assume that the rock just above the water table has 1 percent porosity that is unsaturated with moisture. Assuming 1 percent is a conservative assumption. A larger unsaturated porosity reduces the response of the water table; conversely a smaller unsaturated porosity would increase the response.

The stratigraphy of the volcanic sequence at the Yucca Mountain site is well known (see Figure 1). However, the deeper stratigraphy below 1.5 kilometers is not well known. The UE-25p#1 hole penetrates 500 m. of the Paleozoic carbonate rock. I will assume that 500 meters of saturated tuffaceous rock overlies Paleozoic carbonate rocks that extend to a depth of 17 kilometers. The properties of these rocks are described in Table 1. As discussed above, this appears to be a conservative assumption useful for purposes of computing the order of magnitude of expected changes in the water table.

Table 1 Elastic and Hydrologic Properties of the Yucca Mountain Site.

	Matrix* Compressibility $B \times 10^{-12}$ (cm^2/dyne)	Strain* Sensitivity $At \times 10^{-9}$ (cm/strain)	Vertical* Hydraulic Diffusivity K_v/S_s cm^2/sec)	Specific* Storage $S_s \times 10^{-9}$ (cm^{-1})	Vertical* Hydraulic Conductivity $K_v \times 10^{-6}$ (cm/sec)	Horizontal Hydraulic Conductivity $K \times 10^{-6}$ (cm/sec)
Water Table				[.01]**		
Upper Tuffs	5.7–5.9	.026–.060	330–420	14–15	4.6–6.3	[5]†
Lower Tuffs	2.9–3.7	.058–.072	180–390	4.9–9.6	0.9–3.7	
Confining Layer			18	[.037]	0.0007	
Carbonate Aquifer	1.6–1.7	.24–.26		.037	[50]†	50‡

[ ]Brackets indicate estimates.

*Data from Galloway and Rojstaczer, 1988.

**The unsaturated zone is assumed to have 1% unsaturated porosity.

†The permeability is assumed to be isotropic in both the tuff and the carbonate aquifer.

‡Data from Craig and Robinson, 1984.

Fault Dislocation

Most geophysicists consider an earthquake to be a more-or-less instantaneous displacement on a finite fault plane. One classic model of this process is a slip on the finite plane in an elastic half-space. The displacement on the rupture plane causes the half-space to deform to accommodate the slip. Several investigators have used this formulation to calculate strains and tilts accompanying earthquakes (Chinnery, 1961; Chinnery, 1963; Maruyama, 1964; Press, 1965).

One justification for an elastic analysis is that seismic waves propagate outward from the hypocenter of an earthquake. One also observes permanent coseismic deformation which accompanies the earthquake. This permanent deformation can often be fit, at least to a first approximation, by an elastic deformation model (Roeloffs and Bredehoeft, 1984; Roeloffs and Quilty, 1989)

In the analysis presented here an elastic model is used to calculate the volume strain accompanying a magnitude 6+ earthquake. The volume strain causes an increase in pore pressure in the deformed zone near the fault. A three dimensional flow model is then used to investigate the propagation of the pore pressure transient created by the earthquake. We are especially interested in a potential rise in the water table.

For the purposes of analysis I assume a simple geologic model. The model chosen consists of a section of tuff approximately 1 kilometer thick underlain by carbonates to a depth of 17 kilometers. Because I have chosen to use grid cells 2 × 2 × 2 kilometers, I have arbitrarily made the thickness of each rock layer a minimum of 2 kilometers. This restriction is arbitrary and can be removed should it seem desirable. I also assume both the overlying tuff and the underlying carbonate to have isotropic permeability. As discussed above, Galloway and Rojstaczer's (1988) analysis suggests that there is a low-permeability confining layer overlying the carbonate aquifer (see Table 1); this confining layer is included in the hydrologic model.

Given a compressibility and a Poisson's ratio one can calculate the volume strain associated with a given fault displacement. For this calculation we have used a normal displacement of 1 meter along a 30 kilometer fault plane, dipping 60° to the vertical, and extending to a depth of 10 kilometers. Such a fault displacement is comparable in size to the sequence of Parkfield earthquakes, a magnitude 6+ earthquake. A cross-section normal to the strike of the fault is shown in Figure 2. For these calculations we have taken the bulk compressibil ity of the entire rock section as, $B = 5 \times 10^{-12}$ cm^2 / dyne, and Poisson's ratio, v = 0.25.

The maximum volume strains occur near the lower tip of the fault plane. Regions of negative volume change (compression) balance zones of positive volume change (extension) on opposite sides of the fault. The maximum volume strains are about 100 microstrain units (10^{-4}). One can imagine this hypothetical fault oriented more-or-less north-south along the east side of Yucca Mountain, dipping to the west below the mountain.

One also can estimate the change in the average stress associated with the displacement. At depths of 5 kilometers and more, the volume strain ranges from -5 to -10 microstrain units (in the convention used here a - sign indicates compression). This suggests a change in mean stress (octahedral stress) of approximately 3 to 6 bars; if this change was produced by a change in only one principal stress, the total stress change would be three times as large.

Using the strain sensitivities determined by Galloway and Rojstaczer, A_t, I calculate the fluid pressure changes that will be produced by the dislocation. These pressure changes are plotted as changes in hydraulic head in Figure 3. Again, increases in head are balanced locally by the decreases.

Starting with the initial condition, as shown in Figure 3, one can simulate the change in head following the earthquake. I make the calculations using a 3 dimensional flow simulation model, which has 9 layers with grid blocks of 2 × 2 × 2 kilometers. The region modeled

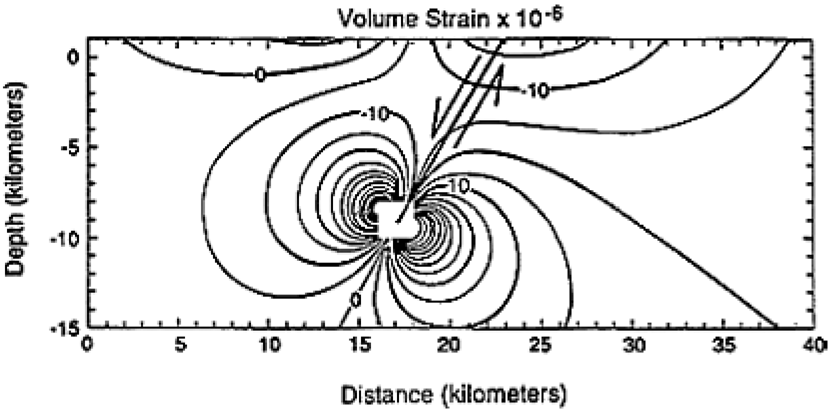

Figure 2
Cross-section normal to the strike of the fault indicating the volume strain. The volume strain is in units of microstrain ($\times 10^{-6}$). A negative value indicates compression.

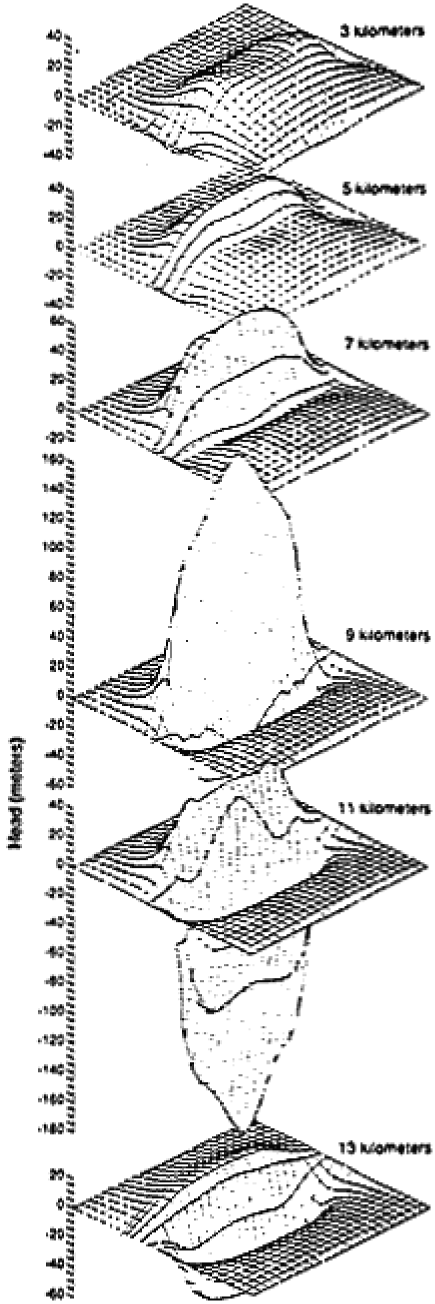

Figure 3
Initial change in hydraulic head resulting from a hypothetical earthquake. Head is plotted at various depths in the system.

extends out to 20 kilometers both east and west of the fault and 5 kilometers beyond both the north and south tip of the fault. The model grid is also plotted on Figure 3. The bottom of the region simulated is at a depth of 17 kilometers. All the flow calculations are done on a 286 personal computer (PC) using a code developed by Bredehoeft (1990).

In the flow modeling there was no attempt to make the hydraulic conductivity a function of the pore pressure change. In the model I assume the fault plane to have the same hydraulic conductivity as the surrounding rocks. Both the upper tuff layer and the lower carbonate rocks have isotropic hydraulic conductivity.

In the base case simulation the tight confining layer is not included. The decay of the hydraulic head is shown in Figure 4. The head

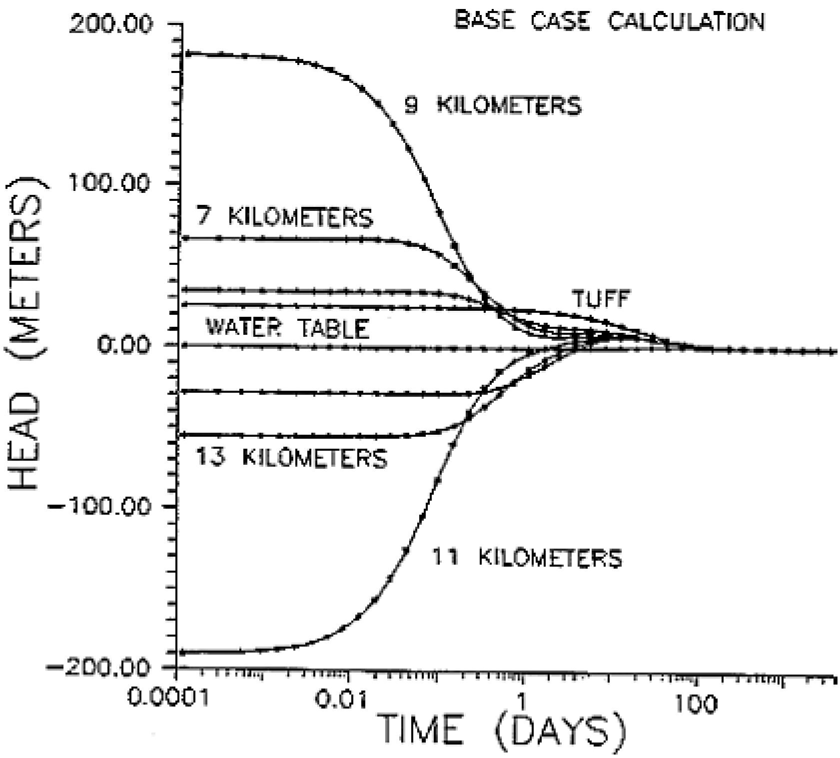

Figure 4
Transient head plotted as a function of time at various depths in the system (*base case*). The points of observation are taken at points of maximum initial head change in each model layer.

produced by the volume strain decays rapidly from the system. The decay is rapid because the specific storage indicated for the deeper system is small (Table 1). (The storage coefficient plays an analogous role in ground-water problems as the specific heat in heat-flow problems. With a small storage coefficient very little water is stored for a given change in head). The rise in the water table in what we designate the base case, is of the order of 1 meter.

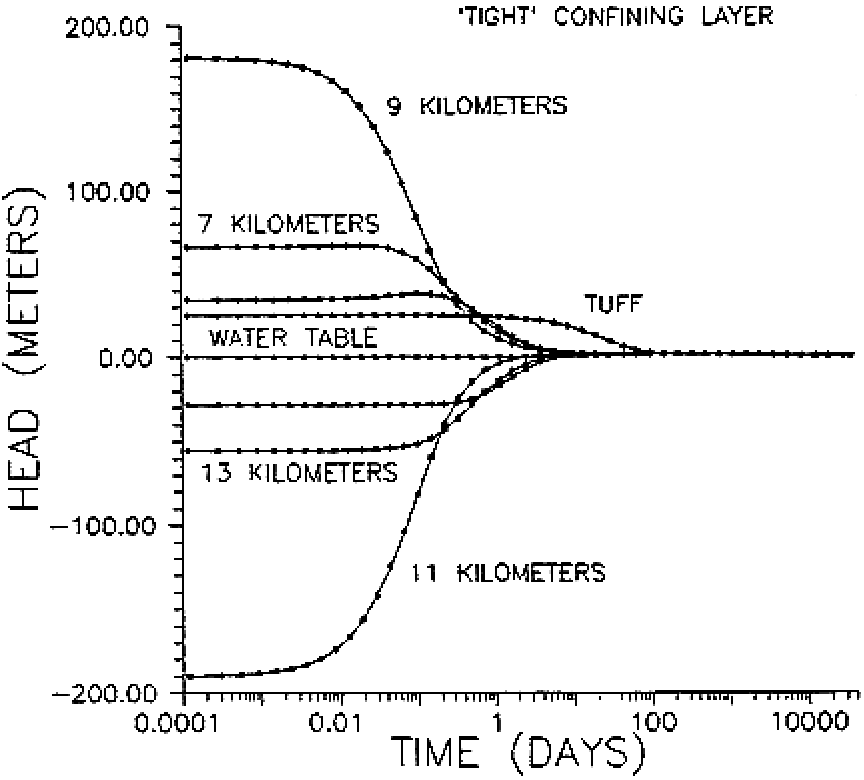

Figure 5
Transient head plotted as a function of time for the dislocation model in which the *tight* confining layer is included.

I also simulated the effect of the tight confining layer; this result is shown in Figure 5. Because of the tight confining layer the deeper carbonate aquifer is insulated from the overlying tuff and the water table. Compressive regions balance regions of tension. The system quickly comes back to its initial state through local flow. The tuff unit, because of its larger specific storage and lower permeability, takes longer to reach equilibrium. Again the response of the water table is of the order of 1 meter.

Conclusion

A rise in the water table of approximately 200 meters is required to endanger the repository. The Dislocation Model indicates a small rise in the water table caused by a magnitude 6+ earthquake near the repository—of the order of 1 m.. The approach taken here is one of an elastic continuum. It seems unlikely that a more sophisticated model would produce water table changes an order of magnitude larger.

Acknowledgment

I thank Bob Simpson, USGS, Menlo Park, for calculating the volume strain for the dislocation model; and Bill Brace and Amos Nur for their discussions of the role of a regional change in stress following an earthquake.

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Appendix E—

Probabilities of Earthquakes Near Yucca Mountain, Nevada

Robin McGuire
Risk Engineering
Denver, Colorado
Revised January 18, 1992

Purpose

To put into perspective the likelihood of earthquakes in the vicinity of the proposed high-level waste repository at Yucca Mountain, we can make quantitative estimates of probabilities of occurrence of earthquakes within certain distances of the proposed repository. This is done by using estimates of slip rates on faults and standard seismological and probabilistic models. These techniques provide insight into how likely are earthquakes that might result in significant water-table changes under the proposed repository through changes in crustal stress.

Given the data available in the study region, we have made some arbitrary but reasonable assumptions, in particular regarding rates of slip on identified and unidentified faults. It should be emphasized that the resulting calculations are preliminary and are made for perspective only. A large amount of work, including collection of field data, needs to be pursued before the inputs to, and hence results of, an analysis such as this have wide credibility. In spite of these qualifications, it is instructive to see where the calculations lead, given a set of reasonable assumptions on the input.

Faults and Parameters

Identified and suspected Quaternary faults in the region of the proposed repository (Fox, personal communication, 1991) are shown on Figure 1. The seven named faults have been widely identified and are considered currently active for the purposes of this study. The Ghost Dance and Abandoned Wash faults are assumed to be a single, continuous fault with a length of about 9 km.

Slip rates for the late Quaternary on most of these faults are not available. One exception is for the Windy Wash fault, for which a vertical slip of 40 cm on a 270,000—year old gravel is documented (Whitney et al, 1984), leading to a vertical slip rate of 0.0015 mm/yr. Movement on this fault is probably oblique; assuming equal amounts of vertical and strike-slip movement, the total current slip rate on this fault is estimated as 0.0021 mm/yr.

In addition to the named faults on Figure 1, there is evidence of slip on lesser features that have offset units of the Paintbrush Tuff (e.g. Scott and Bonk, 1984). These have been represented as Faulted Zones 1, 2, 3, and 4 on Figure 1; these zones are an aggregation of many minor faults shown in Scott and Bonk, 1984. The slip on each individual fault is minor, but the cumulative slip is as large and, in some cases, larger than on the named faults.

In order to make estimates of slip rate on faults (other than the Windy Wash Fault) and faulted zones, we have made several assumptions about the responses of these faults to tectonic processes currently active near Yucca Mountain:

1. On average, all faults and faulted zones have a slip rate equal to that observed on the Windy Wash fault.
2. The current slip rate is proportional to the total displacement observed on the Topopah Spring Member of the Paintbrush Tuff, as represented by Scott and Bonk, 1984. (This unit is approximately 13 million years old and is not a reliable indicator of the current slip rate, but is used to estimate relative rates of current deformation.)
3. All moderate earthquakes (magnitude 5 to 7) that might affect

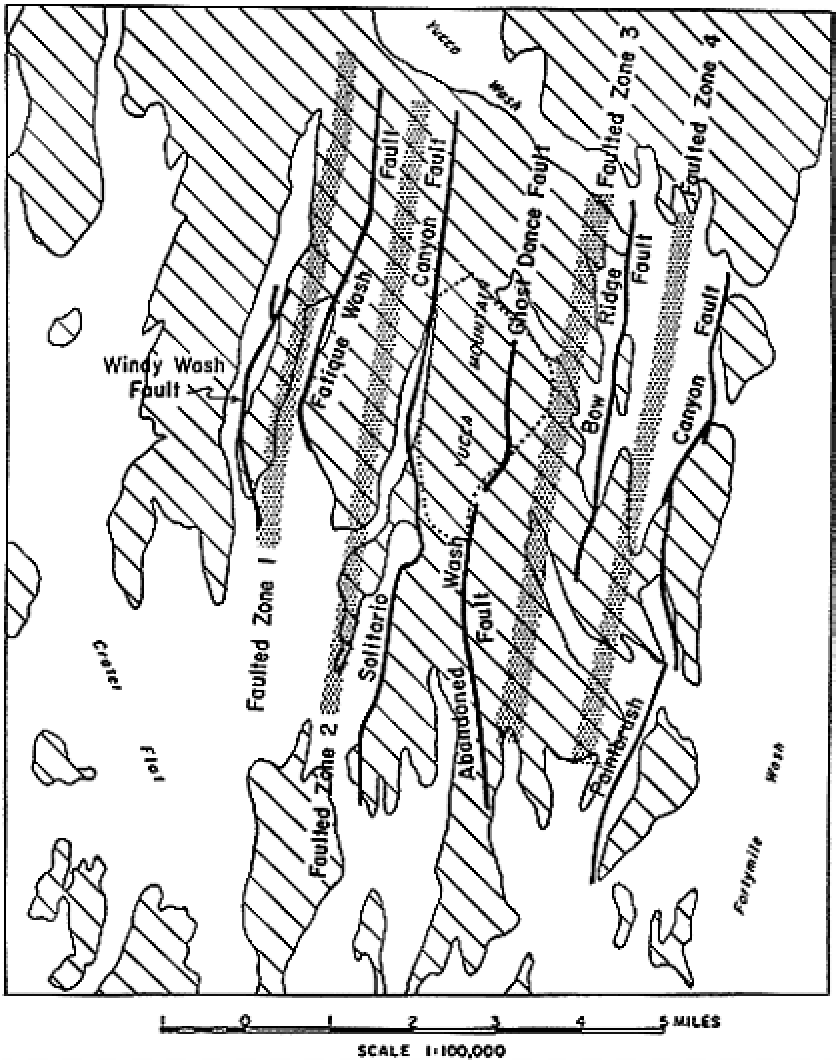

Figure 1
Active faults and faulted zones in the vicinity of Yucca Mountain. The proposed repository boundary is shown dotted; rock units in the area are shown hatched.

crustal stress conditions and the water table near Yucca Mountain will occur on one of the identified faults or faulted zones.

The most critical of these assumptions is the first; it says that the slip rate on the Windy Wash fault is typical of slip rates on other faults in the region. In fact the resulting estimated slip rates are comparable to those inferred by other investigators, as is noted below.

Table 1 shows, for each fault and faulted zone, the length of the fault, the offset of the Topopah Spring Member, and the slip rate estimated as described above. For this Table, and for computations, the Ghost Dance and Abandoned Wash faults have been assumed to be one continuous fault. By way of comparison, Coppersmith and Youngs (1990) estimated slip rates between 0.002 and 0.006 mm/yr for the six named faults, and a total slip rate of 0.0275 mm/yr. All tectonic activity was ascribed to the named faults by Coppersmith and Youngs, with other movement being secondary faulting subsequent to the main rupture. The total rate of 0.0275 mm/yr is of the same order as the total of 0.021 mm/yr shown in Table 1. Again, the purpose here is to make reasonable estimates of slip rate, that are not low or high by an order of magnitude. If alternative slip rates are preferred, their effects on the probabilities reported here would be proportional, at least at the lower probability levels. That is, if slip rates were doubled, the probabilities reported below would approximately double.

It should be noted that apparent slip rates over the past 13 my are an order of magnitude larger than those described above. This can be concluded from two independent interpretations. First, vertical offsets of the Topopah Spring Member shown on Table 1 total 1880 m; dividing this by the 13 Ma age of this unit gives a total vertical slip rate for the faults in Figure 1 of about 0.15 mm/yr. Assuming oblique slip with equal components of horizontal and vertical movement gives a total slip rate of 0.21 mm/yr.

A second, independent estimate of total slip rate can be obtained from paleomagnetic declination data in the region. These data (taken from Rosenbaum et al., 1991) indicate that the southern portion of the Yucca Mountain rotated 20° to 30° clockwise about a vertical axis since the emplacement of the 13 my old Tiva Canyon tuff. Assuming that this rotation was accommodated by block rotations and strike-slip on faults between the blocks and assuming a spacing between the active faults, one can estimate the long-term average fault slip rate. For rotations of 20° and 30°, and fault spacing of 5 km, average strike-slip rates are found in the range of 0.25 to 0.35 mm/yr. Assuming equal components of normal and strike-slip movement would yield a total slip rate of 0.35 to 0.49 mm/yr over a 5 km width.

Table 1 Faults and Parameters Used In Analysis of Slip Rates

Fault	Length, km	Offset of Topopah Spring Unit m*	Slip rate,** mm/yr
Windy Wash	4.6	400	0.0021
Faulted Zone 1	10.0	70	0.00090
Fatigue Wash	7.1	60	0.00077
Faulted Zone 2	10.0	225	0.0029
Solitario Canyon	13.7	205	0.0027
Ghost Dance-Abandoned Wash	9.2	50	0.00064
Faulted Zone 3	10.0	338	0.0043
Bow Ridge	7.4	196	0.0025
Faulted Zone 4	10.0	130	0.0017
Paintbrush Canyon	12.0	206	0.0027
		Total	0.0212

*Taken from Scott and Bonk (1984) for all faults except Windy Wash, which was taken from Carr (1984).
**Estimated over the last 270 ka, based on slip rate for Windy Wash fault.

Those high slip rates, if they apply to the present and if they are entirely seismic, imply that three to five earthquakes with a total oblique slip of 1 m would occur over the 5 km faulted zone within 10,000 years. However, seismic slip in relatively low strain regions may be one-third or less of the total geologic slip rate. This would imply one to two tectonic events per 10,000 years in the 5 km faulted zone.

All of this points to the large uncertainties in estimating fault slip rate, given current information. These uncertainties undoubtedly can be reduced with further site specific fault investigations. For perspective here on rates of earthquake occurrence, we use the slip rates shown in Table 1 with the understanding that further fault-specific site investigations likely will increase or decrease those estimates.

The maximum magnitudes allowed on the ten faults in Table 1 range from 6.5 to 7, depending on the hypothesis considered in the next section. These values may be conservative in that the length of faulting mapped on Figure 1 may not support such large events. On the other hand, there is no conclusive evidence that these faults do not extend farther north or south, nor that they join with other mapped faults to the north or south.

In three dimensions the faults are modeled with surface traces as shown on Figure 1, and with an assumed dip of 60° to the west. This is a typical geometry for faults in this region.

Analysis

With these faults and parameters, the procedure used was to calculate the rate and distribution of earthquakes on each fault, given the slip rate. Then we calculated the probability that the repository site would lie within a units of the rupture, where α is a fraction of the earthquake rupture length. (a is varied below to determine the sensitivity of results to this distance.) The formal equation used is:

P [Repository within a rupture lengths of causative fault, per year] =

$$\Sigma_{fault\ i}\, v_i \int_m \int_{loc(r<\alpha R_L)} f_L(l)\, f_M(m)\, dl\, dm$$

where v_i is the annual rate of occurrence of earthquakes in the magnitude range of interest, M is moment magnitude, *l* is location, and the integral over location includes only those rupture locations such that the distance *r* between the repository and the closest part of the rupture is less than α times the rupture length. For the purposes of this calculation the repository is considered as a single point (located at the center of the proposed repository block), not an area. This has a minor effect, given that the repository dimensions are significantly smaller than dimensions of the ruptures being considered. It is also a reasonable assumption, because it emphasizes earthquakes that might affect a substantial portion of the repository.

For this calculation the rupture area was taken to be square, with a dimension R_L calculated as $R_L = 10^{0.515\ M-2.12}$. This is derived from the data and relationship compiled by Wells et al (1990) shown in Figure 2. It leads to the following rupture lengths for different magnitudes, which appear reasonable:

M	R_L, km
5.0	2.8
5.5	5.2
6.0	9.3
6.5	16.7
7.0	30.5

The thickness of the seismogenic crust was taken to be 10 km, and in cases where hypothesized earthquakes would have a down-dip rupture length that extends to the base of the crust, the rupture was truncated at a depth of 10 km. For small earthquakes that do not break the entire crust, a uniform distribution on depth was assumed.

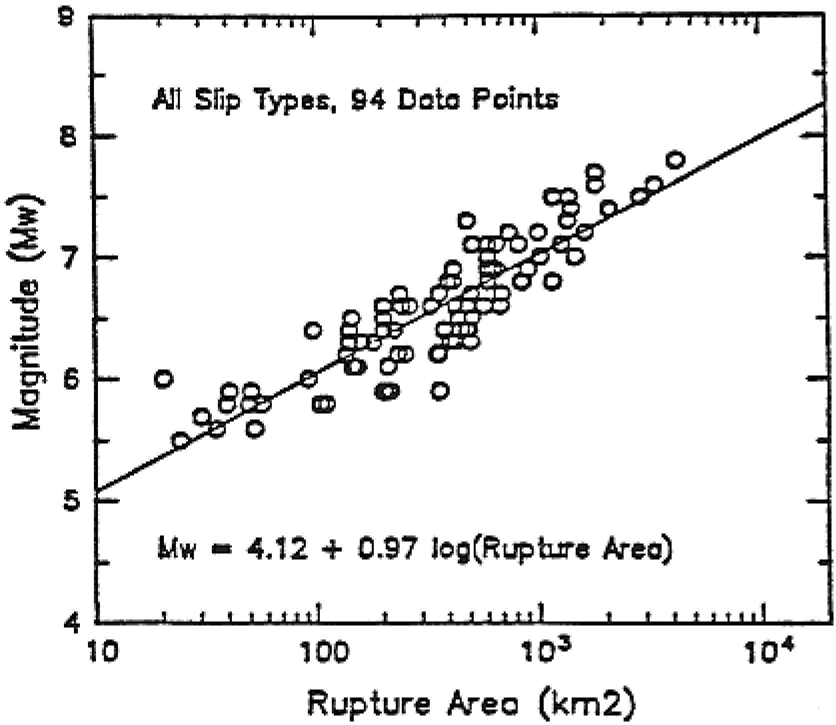

Figure 2
Magnitude vs. rupture area for all slip types (after Wells et al., 1990).

For all faults, a Richter b-value of 0.9 was used, which is typical of earthquake distributions in many parts of the world.

There are several considerations in specifying the range of earthquakes over which calculations will be performed. First, of course, the largest earthquake used in calculations on each fault should reflect the maximum earthquakes thought possible. Second, the minimum earthquake should be selected based on the smallest earthquake that could lead to major changes in the water table. For this study neither the smallest nor the largest earthquake is well-constrained. We have therefore used several ranges of magnitudes, to illustrate how the probability calculations change with choices of the smallest and largest earthquake.

These types of calculation are standard in seismic hazard analysis, and available computer programs have be used to perform them. The three-dimensional geometry of the faults and the probability calculations are correctly handled by these programs, and the important questions are in the specification of inputs, and interpretation of results.

Results

Calculated probability values are presented in Table 2 for five magnitude ranges and four values of α, indicating the probability that an earthquake within the stated magnitude range will occur within a rupture lengths of the repository. The original calculations were made on an annual basis; an assumption of Poisson arrivals was made to calculate total probabilities over the repository lifetime of 10^4 years.

The last row in Table 2 shows results for a pure "characteristic" model that accounts for all fault slip, and all earthquake occurrences, with $M = 6.5$ events. This is a limiting case; since all faults are within 4 km of the repository, the calculated probabilities (for $\alpha \geq 0.25$) just reflect the rate of occurrence of a magnitude 6.5 on any fault in 10^4 years. For $\alpha = 0.1$, the calculated probability just reflects the rate of occurrence on the Ghost Dance and Solitario Canyon Faults, and in faulted zones nos. 2 and 3 (these faults and faulted zones are within 1.6 km of the proposed repository).

Amo ng the results shown in Table 2, the values for $6.0 \leq M < 6.5$ and for $\alpha = 0.25$ and 0.1 are the most realistic. It is unlikely that magnitudes as large as 7.0 have occurred or will occur on these faults, based on their lengths and observed offsets, and it is likely that the proposed repository would have to be very close to a moderate earthquake (e.g. within several km of a magnitude 6.5 event) for crustal stress changes to be significant enough to have the potential to change water levels.[1] Thus the numbers in the third row, under $\alpha = 0.25$ and 0.1, indicate that it is unlikely (but not impossible) that the proposed repository would be close (within 4–5 km) to a moderate earthquake (magnitude about 6.5) during its design lifetime of 10^4 years.

Summary

A straightforward seismic hazard analysis has been conducted to examine the probability that the proposed repository at Yucca Mountain might be close to a moderate earthquake originating on one of the nearby faults. To estimate rates of activity on these faults, the

[1] This is also the interpretation of Archambeau and Price (1991), who present in their Figure 1 a scaled schematic of the "Yucca Mountain system," which is 10 km in lateral dimension.

observed slip rate on the Windy Wash fault has been assumed to apply, on average, to other faults and faulted zones in the area, with modifications based on reported offset of the Topopah Spring unit of the Paintbrush tuff.

Table 2 Calculated Probabilities of Earthquakes Near Proposed Repository Over 10,000 Years

magnitude range	Value of α			
	1.0	0.5	0.25	0.1
5.0 to 6.5	≃1.0	0.39	0.15	0.028
5.0 to 7.0	0.41	0.23	0.11	0.030
6.0 to 6.5	0.14	0.14	0.11	0.028
6.0 to 7.0	0.10	0.10	0.082	0.029
6.5	0.13	0.13	0.13	0.071

The results indicate that, if effects of an earthquake occur in a surrounding region that is limited to within one-quarter of the earthquake rupture length from the fault, the probability of the repository being within such a distance of a moderate earthquake ($5 \leq M < 7$) is on the order of 3 percent to 15 percent during a lifetime of 10^4 years. The calculated probabilities depend somewhat on the magnitude range selected; they increase if larger influence distances are considered, or if higher slip rates are used.

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