9

Climate Change at Yucca Mountain: Lessons from Earth History

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Yucca Mountain's suitability as a nuclear waste repository stems largely from its very dry climate and deep water table (Bodvarsson et al. 1999). The facility's ultimate goal is to isolate waste materials for more than ten thousand years (Whipple 1996). And there lies a crucial question: How can we tell whether the climate and hydrologic conditions at Yucca Mountain will be stable enough beyond the next ten millennia so that the site remains a safe repository for radioactive materials?

If one were planning for the next decade or two, one might look at instrumental records of precipitation and river discharge from the southwestern United States to determine the range of climate variability in the region. But if one must consider the future climate over thousands of years, the historical record is not as useful; climate fluctuations, such as catastrophic floods, may occur so infrequently that they are not captured in the last century or so of human observations. An alternative method for evaluating future climate and hydrologic conditions is to consider the geologic record of climate change. This record comes from a variety of archives. Sedimentary cements and deposits that form from groundwater in caves tell us about temperature, rainfall, and recharge. Remains of flora and fauna in sedimentary layers record details about moisture and climate. Flood and lake deposits hold information about water levels, shorelines, floods, and droughts. Such geologic and geochemical information on past climates may not be as precise as historical observations, but it has the advantage of extending the time scale of observations back over thousands or even millions of years.

This approach has been applied to the assessment of Yucca Mountain by investigating climate variations over the last few hundred thousand years (U.S. Geological Survey 2000). Proponents of this method of assessment argue that because climate is cyclic, the variability observed over this period of time should provide a good indication of what could happen beyond the next ten thousand years. In this chapter, however, we propose that consideration of the geologic record over just this time period offers an incomplete portrayal of the full range of climate change possible at Yucca Mountain beyond the next ten thousand years. We suggest, based on an expanded view of the geologic record, that there are substantial uncertainties and risks not adequately considered by previous studies.

Paleohydrology and the Pleistocene

During the Pleistocene, which comprises the last two million years of Earth history, climate has oscillated between cold glacial periods and warm interglacial ones. The timing of these cycles is linked to changes in Earth's orbital parameters, which affect the intensity of sunlight reaching the planet (Hays et al. 1976). For the last ten thousand years (called the Holocene), Earth has been in an interglacial climate. Twenty thousand years ago, Earth was experiencing a maximum glacial climate, commonly called an ice age. Ice sheets covered large parts of North America and Europe, sea level was 130 meters lower than today, and Earth's mean surface temperature was about 5°C (Fairbanks 1989; Bard et al. 1990; Broecker and Hemming 2001). A complete glacial-interglacial climate cycle is approximately one hundred thousand years in duration (Hays et al. 1976). Thus, the U.S. Geological Survey (2000) investigation of the last four hundred thousand years covers the past four cycles.

Hydrologic conditions during previous interglacial periods were generally similar to modern climate. During glacial maxima, however, many independent lines of evidence indicate that the now-arid environment of the southwestern United States was much wetter. For example, the presence of extensive pluvial lakes in basins of the western United States during the last glacial period is well documented (Smith and Street-Perrott 1983; Benson and Thompson 1987). Vegetation remains preserved in packrat middens from the southern Great Basin indicate that at the peak of the last glacial period, the region received as much as 40 percent more annual rainfall than it does now (Spaulding 1985). Uranium-series dating of travertine and cave deposits from the Southwest support wetter conditions during glacial periods for the entire region (Musgrove et al. 2001; Brook et al. 1990; Szabo 1990). In southern Nevada, water table fluctuations during glacial periods reconstructed from subterranean calcite deposits indicate higher water levels and a wetter climate (Szabo et al. 1994). A rigorously dated vein calcite deposit from Devils Hole provides a continuous half-million-year record of the paleohydrologic and paleoclimatic conditions in the vicinity of Yucca Mountain (Ludwig et al. 1992; Edwards et al. 1997). Geochemical variations in this calcite, which formed from groundwater, correlate with global ice and marine records, and are suggestive of cooler and wetter conditions in southern Nevada during glacial periods (Winograd et al. 1988, 1992). Records from playa lake salt deposits in Death Valley and southern Great Basin fossil spring deposits support this view (e.g., Li et al. 1996; Quade et al. 1995).

The U.S. Geological survey (2000) assessment of Yucca Mountain acknowledges wetter climates for the southwestern United States in the geologic past associated with glacial intervals. This assessment concludes that the climate at Yucca Mountain for the next ten thousand years will be dominated by a cooler and wetter glacial-transition climate. It suggests that annual precipitation rates will increase, although not significantly. Water infiltration, however, will increase due to cooler temperatures and decreased evapotranspiration. This potential increase in water infiltration into Yucca Mountain is a critical component in evaluating the site because the infiltration and movement of water through the unsaturated zone (that is, the soil and the rock between the surface and the water table) will determine how long it may take waste canisters to corrode and for water to leach radionuclides from the waste (Whipple 1996). Consequently, there has been a continuing effort to develop and refine a model of unsaturated zone hydrology (Flint et al. 2001a, 2001b; Bodvarsson et al. 1999).

There has been considerable controversy over the origin of carbonate and opal deposits found in fractures of the unsaturated zone (see chapter 10, this volume). If these deposits were formed by upwelling waters from the deep aquifer, then this might mean that the water table fluctuates over time, and could possibly rise again in the future and inundate the waste facility (Szymanski 1989). Following many years of study, the preponderance of evidence indicates that these deposits were formed by surface processes and meteoric waters percolating down through the unsaturated zone (Wilson et al. 2003).

One climate scenario that has been considered and investigated with the unsaturated zone model uses conditions that may have approximated the climate of the last glacial period. This scenario models a fivefold increase in infiltration, which results in an increase of percolation water reaching the potential repository (Ritcey and Wu 1999). This study also examined changes that might occur due to anthropogenic climate change by considering a scenario with a doubling of atmospheric carbon dioxide (CO_2), resulting in a twofold increase in infiltration. Infiltration estimates in these scenarios are based on precipitation results from a regional climate model (Ritcey and Wu 1999). These estimates, however, are uncertain due to a variety of modeling complexities. Regardless, given the extremely low infiltration rates estimated for the current climate—from zero to a maximum of forty millimeters per year (Ritcey and Wu 1999)—even a fivefold increase still results in extremely low infiltration.

Predicting Future Climate Change

The investigation of Pleistocene climates for the Yucca Mountain region provides useful information on how hydrologic conditions may change in response to large changes in global climate and is therefore important for assessing the site's suitability for long-term waste storage. But the climate variability of the Pleistocene is not necessarily a good indicator of what Earth will experience over the next one hundred years—much less the next ten thousand years. In fact, projecting Yucca Mountain's climate variability based on the Pleistocene climate may seriously underestimate the possibility for large changes in the climatic and hydrologic regime.

Atmospheric greenhouse gases, such as carbon dioxide (CO_2), absorb infrared radiation and maintain Earth's temperature, and are thus a crucial component of Earth's climate. The CO_2 levels during the Pleistocene ranged from a low of approximately 200 parts per million during glacial maxima to as much as approximately 280 parts per million during interglacial periods—a variation that contributed to changing global climate (Petit et al. 1999). Bubbles trapped in the Vostok ice core document that CO_2 never exceeded 300 parts per million over at least the last 420,000 years (Petit et al. 1999). Ever since the Industrial Revolution, however, humans have been conducting an extraordinary experiment. The combustion of fossil fuels has driven atmospheric CO_2 concentrations above 380 parts per million—a level that continues to rise. Projections for the year 2100 range from a low of 500 parts per million, if we implement extreme reductions in fossil fuel consumption, to over 1,200 parts per million, if the developing world accelerates its industrialization (Houghton et al. 2001). Any serious assessment of the climate at Yucca Mountain over the next several thousand years must surely take such enormous changes into consideration.

What are the expected effects of increased atmospheric CO_2 on global climate for the next one hundred years? Based on a wide range of scenarios, by 2100 the global average surface temperature is projected to increase by 1.4°C to 5.8°C, and the average sea level is projected to rise by nine to eighty-eight centimeters (Houghton et al. 2001). These changes will significantly affect the global hydrologic cycle. Higher temperatures will increase the amount of atmospheric water vapor, which may in turn increase global precipitation; more intense precipitation events are likely to occur over much of the Northern Hemisphere (Houghton et al. 2001; Hennessy et al. 1997). Looking beyond 2100, the changes could be much greater. Even if global CO_2 emissions are held constant at present-day values, atmospheric concentrations would continue to increase for hundreds of years before stabilizing. Global temperature and sea level would continue to rise due to the thermal lag associated with the oceans.

How might predictions of global climate change potentially affect the Yucca Mountain region? At a regional scale, predictions of climate change are hampered by many uncertainties. These include the many complexities of the hydrologic cycle, such as the formation and distribution of clouds, as well as processes that occur on spatial scales smaller than general circulation model grid cells (Water Sector Assessment Team 2000). Although many of these regional effects are currently known with less certainty than global predictions, regional assessments do provide some information on climate change at Yucca Mountain. Future climate scenarios for the southwestern United States predict a mean temperature increase of 4°C to 5.5°C over the next one hundred years (National Assessment Synthesis Team 2001; Water Sector Assessment Team 2000). Models predict that higher temperatures will result in overall wetter conditions, evidenced by increased winter precipitation and annual precipitation increases of approximately 30 to 70 percent (Water Sector Assessment Team 2000; Watson et al. 1998). At Yucca Mountain, winter precipitation presently provides the bulk of groundwater recharge water as well as unsaturated zone infiltration (Winograd et al. 1998). Thus, predicted increases in both overall precipitation and specifically winter precipitation may significantly affect how much moisture the waste disposal facility will encounter.

Another way to assess future climate change at Yucca Mountain is to consider the correlation of climate variability in the southwestern United States with larger patterns of climate variability. The largest source of climate variability from one year to the next is the El Niño/Southern Oscillation (ENSO), which is centered in the tropical Pacific but affects weather patterns worldwide. During ENSO warm phases (El Niño events), the eastern Pacific warms as trade winds slacken and the depth of the thermocline increases. El Niño events bring droughts to Southeast Asia and floods to the hyperarid coastal deserts of Peru. El Niño events also bring higher than average levels of winter precipitation to the southwestern United States (e.g., Cayan and Webb 1992). This relationship has allowed for the development of ENSO indexes based on tree ring chronologies from the southwestern United States (Cook 1992).

Over the last decade, there has been growing concern about whether ENSO is being affected by anthropogenic climate change. Trenberth and Hoar (1996, 1997) have suggested that the 1976 "climate shift," which involved a deepening of the thermocline in the eastern Pacific (Guilderson and Schrag 1998), and led to stronger and more frequent El Niño events in the 1980s and 1990s, is related to anthropogenic climate change. Others, however, have disputed this claim (e.g., Rajagopalan et al. 1997; Harrison and Larkin 1997).

Most climate models now used to predict the effects of increasing CO_2 over the next century do not have high enough resolution to accurately simulate ENSO variability. But Timmermann and colleagues (1999), using a new model with better resolution, found that an increase in CO_2 levels over the next century would not change the frequency and intensity of El Niño events by much. Still, in this study, because the eastern Pacific warmed considerably relative to the western Pacific, the mean state became more like an El Niño event. If correct, this prediction would indicate that the mean precipitation in the southwestern United States could be closer to the anomalous winter precipitation associated with El Niño events. This would add to concerns of wetter conditions over the next century in the Yucca Mountain region.

An Extended View of Climate Change

The CO_2 levels projected by the Intergovernmental Panel on Climate Change for 2100 (Houghton et al. 2001) have not been seen on Earth for millions of years. If one extends the projections forward several centuries from now, the scale of the anthropogenic climate experiment is even more astounding. Direct observation of ancient levels of atmospheric composition are not possible beyond the age of the Vostok ice core (~420,000 years). More indirect methods suggest that the CO_2 levels have been similar to modern levels over at least the last twenty million years (Pagani et al. 1999; Pearson and Palmer 2000).

Evidence from fossil seashells, however, indicates that during the early Eocene—fifty million years ago—CO_2 levels may have been considerably higher than today.

The boron isotopic composition of calcium carbonate shells of marine animals reflects the pH of the seawater in which the animals lived; the pH is in turn strongly dependent on CO_2. Changes in the boron isotopic composition of these shells from fifty-two to thirty-eight million years ago suggest an increase in the pH over this interval, consistent with a decrease in CO_2 levels from one thousand to three thousand parts per million, down to near-modern levels (Pearson and Palmer 2000). Thus, the CO_2 levels we may see over the next several centuries have not occurred on Earth for fifty million years.

What lessons can we learn from this ancient time of high CO_2 that are relevant to our current predicament and Yucca Mountain in particular? The early Eocene was extremely warm. Deep ocean temperatures were 10°C to 12°C above what they are today (Miller et al. 1987). The world was essentially ice free with little or no polar ice and no continental glaciation (Sloan and Barron 1992). Antarctica was covered with pine forests (Case 1988). The Northern Hemisphere's continental interiors and high latitude regions were warm enough to support subtropical vegetation such as palm trees as well as cold-blooded reptiles such as crocodiles (Spicer et al. 1987; Estes and Hutchinson 1980; Marwick 1998). Geologic evidence from the Eocene, such as an abundance of the clay mineral, kaolinite, which commonly forms in warm and humid conditions (Robert and Kennett 1992, 1994), suggests that the climate was wetter than it is today.

In the western United States, oxygen isotope measurements of mammalian teeth from the early Eocene Bighorn Basin are consistent with wetter conditions in this region (Koch et al. 1995). Fossil leaves are another source of information about Eocene climate and rainfall in the western United States. The morphology of leaves is strongly influenced by the available moisture, which in turn can be used to assess climate conditions such as precipitation (Richards 1996). Estimates of precipitation for the western United States during the Eocene from fossil leaves consistently indicate much wetter conditions than currently exist (Wing and Greenwood 1993; Wilf et al. 1998; Wilf 2000). Overall, the climate of the Eocene western United States resembled that of a warm, wet, low-latitude region such as today's western Amazonia (Koch et al. 1995).

When climate modelers attempt to simulate the Eocene climate (or the earlier greenhouse climates of the Cretaceous) using models designed for the modern climate, they have difficulty simulating the warm conditions implied by the fossil and geochemical records. When the CO_2 levels in the model are raised even to four times the modern values or higher, the models are incapable of producing temperatures at the poles as warm as what the paleoclimate data suggest (e.g., Bush and Philander 1997). Moreover, the models are unable to keep the winter temperatures warm at high latitudes, particularly in the continental interiors (Sloan and Barron 1992). These problems with the models are troubling as they suggest that certain feedbacks are missing from the current climate models that may be important as CO_2 levels increase. Recently, Sloan and Morrill (1998) proposed that optically thick polar stratospheric clouds could produce these two features of Eocene climate if the clouds formed at times of higher CO_2. They suggested that the clouds formed due to the increased production of methane from tropical wetlands and the subsequent oxidation of that methane in the stratosphere. Kirk-Davidoff and colleagues (2002) proposed that stratospheric clouds might form through a direct feedback following increased CO_2, through a change in stratospheric circulation. If either of these hypotheses is correct, they imply that predictions of future climates may be underestimating the climatic response to high levels of CO_2 over the next several centuries. This uncertainty must also be acknowledged in the assessment of future climate conditions at the Yucca Mountain repository.

The extreme climate of the early Eocene, and the inability of most models to adequately simulate those conditions, raises the specter of more extreme changes in the hydrologic conditions at Yucca Mountain over the next several thousand years. These conditions may be far more extreme than the fivefold increase in infiltration rate simulated by Ritcey and Wu (1999). Nonetheless, it is probably not appropriate to use the Eocene as a direct analog for future conditions at Yucca Mountain over the next few centuries. First, there have been several large changes in physical geography that could have contributed to the regional climate in the western United States. Although the configuration of the continents during the Eocene was similar to today, the regional topography was quite different. The Great Basin's arid climate stems from its current location in the rain shadow of the Sierra Nevada; the uplift of these mountains is generally considered to have occurred in the last ten million years, or well after the early Eocene (e.g., Wolfe et al. 1997; Wernicke et al. 1996). Much of the volcanic activity in the southwestern United States has occurred in the last fifty million years. Even the location of the coastline was different in the Eocene, as much of California has been accreted onto the North American plate since that time. Due to the lack of continental ice sheets, Eocene sea level was more than one hundred meters higher than it is today. All these factors could have affected the position of the jet stream and the moisture balance in the southwestern United States, and contributed to wetter conditions.

But most important is the difference between a warm climate in the Eocene that persisted for millions of years, allowing local vegetation, ice sheets, and the deep ocean to reach a quasi-steady state, and the perturbation from a relatively cold climate that we are now experiencing as a result of anthropogenic increases in CO_2. The time scale for the deglaciation of the polar regions or the establishment of new ecosystems is difficult to calculate exactly, but it is probably on the order of thousands of years. This is similar to the time scale for the deglaciation of North America and shifts in ecosystems during the termination of the last ice age. The time scale for heating the deep ocean is similar, although the possible reduction of thermohaline circulation adds complications (Manabe and Stouffer 1999).

It is unlikely that we will see the complete demise of ice on Antarctica or the establishment of a rain forest in Nevada over the next few centuries. But the design of the Yucca Mountain repository is supposed to anticipate conditions beyond the next ten thousand years. Over this time scale, the possibility that Earth may experience a drastic climate change to conditions more similar to the Eocene must be considered seriously. There are of course abundant uncertainties in this assessment, most significantly the actions that society may take over the next century to reduce the emissions of CO_2 from the combustion of fossil fuels. But the risk of such CO_2-induced change under the conditions that exist today is not trivial. The design and construction of the repository must respond to this risk.

Conclusions and Implications

Scientists cannot predict the future climate or hydrologic conditions at Yucca Mountain with absolute certainty. Nevertheless, the DOE must consider the possibility that the climate over the next several thousand years will be very different from anything experienced by humans, as levels of atmospheric CO_2 are likely to be higher than have existed for millions of years.

The most recent time in Earth history when the CO_2 levels approached what is anticipated to occur in the next few hundred years was the Eocene. As a result, a consideration of Eocene-like climate scenarios may provide some useful lessons about the full spectrum of possible climate changes resulting from increased CO_2. The design of the repository should account for this more complete assessment of risk of dramatically wetter conditions at Yucca Mountain.

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