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Future climate analysis — Source link

R.M. Forester

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11. Responsible Manager	For Robert W. Craig	[signature]	3/14/00

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Revision 00C	3/7/00 AP-2.14Q Concurrence draft
Revision 00D	3/14/00 Final Check Copy
Revision 00	3/14/00 Approved AMR

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TABLES

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ACRONYMS

AMR	Analysis/Model Report
CRWMS M&O	Civilian Radioactive Waste Management System, Management and Operating Contractor
DTN	Data tracking number
ET	Evapotranspiration
ka	Thousands of years before present
m	Meter
MAP	Mean annual precipitation
MAT	Mean annual temperature
MIS	Marine Isotope Stages
NOAA	National Oceanic and Atmospheric Administration
OLCC	Older long climate cycle
SR	Site Recommendation
TBV	To Be Verified
TDMS	Technical Data Management System
TDS	Total dissolved solids
TSPA	Total system performance assessment
U.S.	United States
USGS	United States Geological Survey
VSMOW	Vienna Standard Mean Ocean Water
YLCC	Younger long climate cycle
YM	Yucca Mountain
YMP	Yucca Mountain Site Characterization Project

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1. PURPOSE

This Analysis/Model Report (AMR) documents an analysis that was performed to estimate climatic variables for the next 10,000 years by forecasting the timing and nature of climate change at Yucca Mountain (YM), Nevada (Figure 1), the site of a potential repository for high-level radioactive waste. The future-climate estimates are based on an analysis of past-climate data from analog meteorological stations, and this AMR provides the rationale for the selection of these analog stations. The stations selected provide an upper and a lower climate bound for each future climate, and the data from those sites will provide input to the infiltration model (USGS 2000) and for the total system performance assessment for the Site Recommendation (TSPA-SR) at YM.

Forecasting long-term future climates, especially for the next 10,000 years, is highly speculative and rarely attempted. A very limited literature exists concerning the subject, largely from the British radioactive waste disposal effort. The discussion presented here is one method, among many, of establishing upper and lower bounds for future climate estimates. The method used here involves selecting a particular past climate from many past climates, as an analog for future climate. Other studies might develop a different rationale or select other past climates resulting in a different future climate analog.

This AMR was prepared in accordance with the "Work Direction and Planning Document for Future Climate Analysis" (Z. Peterman 1999) under Interagency Agreement DE-AI08-97NV12033 with the U.S. Department of Energy (DOE).

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2. QUALITY ASSURANCE

The activities documented in this AMR were evaluated in accordance with QAP-2-0, *Conduct of Activities*, and were determined to be subject to the requirements of the DOE Office of Civilian Radioactive Waste Management (OCRWM) *Quality Assurance Requirements and Description* (QARD) (U.S. Department of Energy 1998). This evaluation is documented in Wemheuer 1999 (*Activity Evaluation for Work Package WP 8191213UU1 UZ PMR Rev 0 for SRCR Analysis & Writing*). This AMR has been prepared in accordance with procedure AP-3.10Q, R2 *Analyses and Models*.

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3. COMPUTER SOFTWARE AND ANALYSIS USAGE

No software or models were used in performing this analysis.

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4. INPUTS

This document may be affected by technical product input information that requires confirmation. Any changes to the document that may occur as a result of completing the confirmation activities will be reflected in subsequent revisions. The status of the input information quality may be confirmed by review of the Document Input Reference System database.

4.1 DATA AND PARAMETERS

Data sets used in this analysis are summarized in Table 1.

Table 1. Summary of Data Sets Used as Data Inputs

Data Inputs	Data Tracking Number
Diatom Data from Owens Lake 1984-1992 Cores.	GS970708315121.001.
Ostracode Data from Owens Lake 1984-1992 Cores.	GS970708315121.002.
Supplementary Data to Ostracode Data From Owens lake 1984 – 1992 cores.	GS991008315121.001.
Supplementary Data to Diatom Data From Owens Lake 1984-1992 cores	GS991008315121.002.
Earthinfo, Inc. Western U.S. Meteorologic Station weather Data – NCDC Summary of Day (West 1) and NCDC Summary of Day (West 2).	GS000100001221.001.
Earth Orbital Parameter Data for the Present to 100,000 year in the Future.	GS000200005121.002.
Earth Orbital Parameter Data for the Last 10 Million Years.	GS000200005121.001.
Radiometric Dating and $\delta^{18}O$ Data from Devils Hole, Nevada.	GS000200005121.003.

These data sets were used because this analysis provides a rationale for a specific set of climates and, from that, a basis for other analyses and models using this information to evaluate uncertainty within the confines of these climate characteristics in order to determine if this degree of climate change is adverse to the site. The parameters of past climate were used for a select set of representative meteorological stations to estimate values for future climates. These parameters are appropriate because they are the input parameters needed for the analysis of infiltration at the site. Specifically, the appropriateness of the data inputs listed in Table 1 dealing with the diatom, ostracode, and depth to age relationship data are discussed in Section 6.5. The appropriateness of data inputs covering radiometric dating from Devils Hole, Nevada is discussed in Section 6.3; for data inputs summarizing the day observations from the National Climatic Data Center the appropriateness is discussed in Section 6.6; and for the earth orbital parameter data, it is discussed in Section 6.4.

4.2 CRITERIA

Formal criteria have not been established for the development of this AMR; however, this analysis complies with the DOE interim guidance (Dyer 1999). Subparts of the interim guidance that apply to this analysis or modeling activity are those pertaining to the characterization of the Yucca Mountain site (Subpart B, Section 15), the compilation of information regarding hydrology of the site in support of the License Application (Subpart B, Section 21(c)(1)(ii)), and the definition of hydrologic parameters and conceptual models used in performance assessment (Subpart E, Section 114(a)).

4.3 CODES AND STANDARDS

No specific formally established codes or standards have been identified as applying to this analysis.

5. ASSUMPTIONS

Four key assumptions are fundamental to the future climate analysis. The basis for each of the assumptions is discussed in the subsections of Section 6, except for assumption 4, which is assumed for the time frame in question:

1. Climate is cyclical, so past climates provide insight into potential future climates; in other words, the past is the key to the future (Section 6.3).

2. A relation exists between the timing of long-term past climate change (the glacial/interglacial cycles) and the timing of changes in certain earth-orbital parameters. This establishes a millennial-scale climate-change clock, which provides a possible way to time future climate change (Section 6.4).

3. A relation exists between the characteristics of past climates and the sequence of those climates in the long, approximately 400,000-year, earth-orbital cycle. The characteristics of past glacial and interglacial climates within the long earth-orbital cycle differ from each other, and appear to do so in a systematic way. This climate sequence relation provides a defensible criterion for the selection of a particular past climate as an analog for future climate (Section 6.5).

4. Long-term earth-based climate forcing functions, primarily tectonics, that operate on the million-year time scale have remained relatively unchanged during the last long earth climate cycle, and will not change during the next 10,000 years. Consequently, the potential and unpredictable impact of long-term, earth-based forcing functions on climate need not be considered for understanding climate change during the past 400,000 years or the next 10,000 years.

The first three assumptions cannot be confirmed by testing, analysis, or design because of the inherent nature of estimating or predicting future climate states. The second assumption builds on the first, and the third builds on the second. Only the passage of 10,000 years will tell if the assumption that a particular past climate is a viable analog for the future climate.

The assumption (number 4) that long-term, earth-based forcing functions will not change during the next 10,000 years, and therefore, impacts on climate need not be considered for understanding climate change during the next 10,00 years is consistent with EPA proposed rule 40 CFR 197 (EPA). In speaking of the 10,00 year compliance period, the EPA states, "(2) There are likely to be no exceptionally large geologic changes during that time", (Federal Register, Vol. 64, No. 166/Friday, August 27, 1999/Proposed Rules, page 46994).

Further verification of these assumptions is not warranted.

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6. ANALYSIS

6.1 INTRODUCTION

Past climate was analyzed to select representative meteorological stations that can be used to estimate climate values for future climates, such as mean annual and seasonal precipitation, and mean annual and seasonal air temperature, at Yucca Mountain, Nevada for the next 10,000 years. These climate values then provide the input terms for the infiltration model (USGS 2000) at YM. The analysis depends on the assumptions of climate cyclicity, of the accuracy of an earth-orbital parameter climate-change clock, of the repetition of particular past climate states in the future, and of relative tectonic stability during the past long earth-orbital cycle and for the next 10,000 years. The basis for each of the first three assumptions is discussed below along with the general nature of modern-day climate, which serves as a reference for comparison with past climates. The constancy of tectonic scale climate change will be assumed for the 10,000-year time frame, but can not be assumed for million-year time scales past or future.

The causes of climate change in the past between glacial and interglacial conditions are not known, but this analysis attempts to establish timing relations between earth-orbital parameters that can be calculated and climate–cycle relations that can be recognized from the past and used to forecast the future. Any future climate analysis is uncertain, but perceived relations between measurable cycles enable an attempt to forecast estimated future climate conditions.

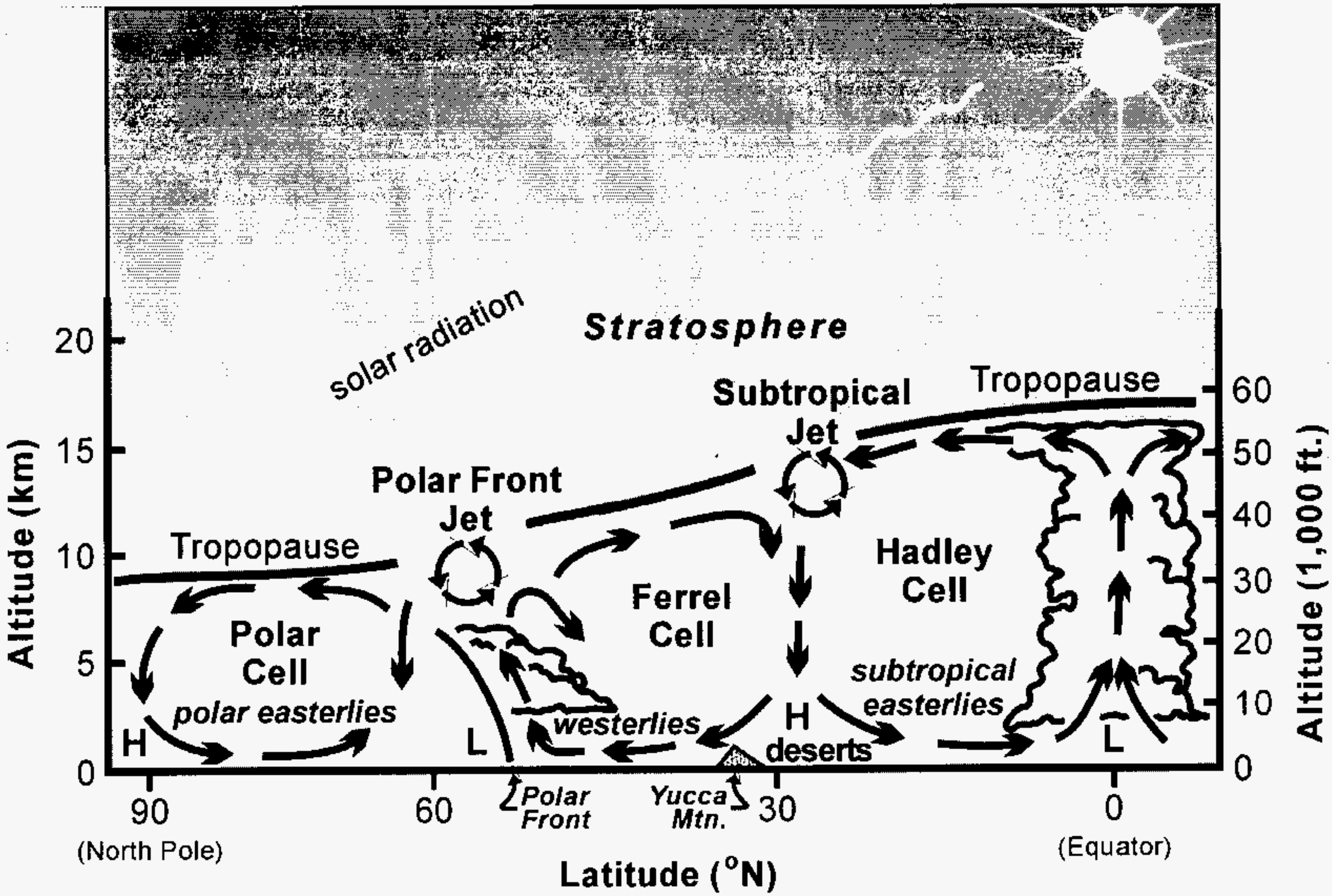
A map of the Western United States (U.S.) showing the locations of specific sites discussed in this AMR is provided in Figure 1.

a	Cascade Range	f	Owens (dry) Lake, Calif.	k	Searles (dry) Lake, Calif.
b	Death Valley, Calif.	g	Owens River, Calif.	l	Sierra Nevada Mountains
c	Devils Hole, Nev.	h	Pahranagat Lakes, Nev.	m	Sprague Lake, Wash.
d	Great Salt Lake Basin, Utah	i	Panamint Basin. Calif.	n	Transverse Ranges, Calif.
e	Haiwee Reservoir, Calif.	j	San Agustin Basin, N. Mex.	o	Yucca Mountain, Nev.

Figure 1 Western United States Showing Localities Discussed in the Text

6.2 MODERN AND PAST CLIMATE

A generalized schematic of modern day atmospheric circulation (climate) is shown in Figure 2. For the purposes of this analysis, the modern-day earth climate system may be thought of as a three-component system, consisting of two active components, the tropical (Hadley) and polar cell air masses, and of a more passive mixing zone between them, the westerlies (Ferrel cell). The northern edge of the tropical air masses, the Subtropical Highs, consist of high-pressure, descending air that creates a hot, dry and, hence, low precipitation and high evaporation climate. The Subtropical Highs define the global hot desert belts and dominate the climate of the YM region today. Regions south of the Subtropical Highs fall under the influence of the much wetter subtropical easterlies.



Source: modified from Ahrens (1985, fig. 15.7)
NOTE: Time approximates Autumnal Equinox; H = high pressure dominates; L = low pressure dominates; arrows show dominant direction of air

Figure 2. Generalized View of Atmospheric Circulation

The southern edge of the polar air masses, the Polar Lows, consist of low-pressure, rising air that creates a cool, wet and, hence, high precipitation and low evaporation climate. The average seasonal position of the Polar Lows approximately defines the Boreal Forests and also dominated some past glacial climates in the YM region. The central (northernmost) part of the polar air mass is characterized, especially in winter, by dense, cold, descending air creating lower tropospheric high-pressure cells. Air streams flow southward from these high-pressure cells producing the Arctic (Polar) easterlies. Arctic (Polar) Highs are typically characterized by cold, dry air, and hence low-precipitation and low-evaporation climates. The Arctic Highs also dominated some past glacial climates in the YM region.

The mixing zone between the tropical and polar air masses, the westerlies, have a complex weather system consisting of high- and low-pressure air masses or cells that often produce storms along the air-mass boundaries. These high- and low-pressure cells may be short lived (hours or days) or may persist for a week or more. The precipitation and temperature characteristics within the westerlies are typically seasonal, and related to the proximity of the tropical or the polar air masses. The southern edge of the Polar Lows, along the boundary with the westerlies, is commonly called the polar front and is the area where the polar jet stream resides. The polar jet stream acts as a steering current for westerly storms. Similarly, the northern edge of the Subtropical Highs may be referred to as the subtropical front and is the location of the subtropical jet stream.

Regional climate in the conterminous U.S. is a result of the seasonal expansion and contraction of the tropical and polar air masses. In southerly areas of the U.S. tropical air masses and warm westerlies dominate the annual climate, whereas in northerly areas climate is dominated by polar air masses.

The general climate characteristics associated with the global air masses are often modified by regional features such as topography, large lakes, and the oceans. The Sierra Nevada Mountains and the Transverse Range have exerted significant control over past YM climate, continuing to the present day. Fundamentally, these mountain ranges cut the YM region off from its major moisture source, the Pacific Ocean, and especially from the subtropical Pacific Ocean. By creating and sustaining a major rain shadow in the YM region, the mountain ranges also have amplified the evaporative action of the Subtropical Highs during modern-day and past interglacial climates.

Today in the YM region, from late spring through early fall, climate is dominated by the northward movement and intensification of the Subtropical Highs. Present-day subtropical high activity, in the YM region, does not, however, intensify to the point of creating a strong monsoonal weather pattern, as happens in southern Arizona and New Mexico and in Mexico. Rather, the subtropical high activity commonly produces convective thunderstorms, typically of only local importance, and intense evaporation, which is enhanced by the mountains to the west and southwest.

During late fall through early spring, the Subtropical Highs weaken and retreat south, leaving the region largely under the influence of the westerlies, whose moisture potential is greatly reduced by the Sierra Nevada Mountains, and to a lesser extent by the Transverse Range. Polar Low and occasionally Arctic High pressure may intrude into the area, resulting in wetter and less evaporative conditions. The wettest winters are often associated with the El Nino years, when the polar front moves south over the Pacific Ocean, steering subtropical moisture into the YM region. El Nino years are also high infiltration years (Winograd et al. 1998), but the El Nino circulation is usually not sustained, and the Subtropical Highs return to exert their evaporative influence over the region's hydrology. This Subtropical-High-dominated climate regime has dominated regional climate for about the past 9,000 to 10,000 years, with some episodes being hotter and drier, and others being cooler and wetter, than modern (see, for example, Forester et al. 1999, Figure 14).

The modern interglacial climate, and that of the past 8,000 years or so, is not typical of climate during the last several hundred thousand years. Past climates have included glacial periods, and a variety of climates intermediate between glacial and interglacial, all of which may be simplistically thought of in terms of dominance of the polar and tropical air masses. The expansion of continental ice into the U.S. means that the polar air masses expanded and became persistent in more southerly areas throughout the year, otherwise the continental ice and snow would have melted. Because the basic physical laws of atmospheric circulation are conserved, when the polar air masses expand and become more persistent, the Polar Lows must also move southward, both in the sense of the seasonal extreme and their average position. As the Polar Lows expand southward, the wet, cool "boreal" realm moves southward, resulting in wetter and cooler conditions in places that today are warmer and drier. Local topography and air-mass dynamics will modify the polar low climate, such that, for example, the very wet northwest U.S. climates do not get literally transposed southward.

In the YM region a glacial climate would mean longer winter seasons and shorter summer seasons. Subtropical Highs would be less persistent, so mean annual temperature (MAT), summer temperature, and the high summer evaporation would be lower, resulting in the potential for more infiltration, even if mean annual precipitation (MAP) remained constant. MAP, however, won't remain constant, because there would be more frequent and persistent incursions of polar-low activity, bringing more rain and snow during glacial periods than today. Infiltration is further increased during these periods, because winter precipitation, as melting snow, would be less likely to evaporate or be used by the vegetation, so evapotranspiration (ET) would be much lower. During some glacial periods, when large continental ice sheets existed, Arctic Highs were likely resident in the YM region for much or perhaps all of the year, resulting in very cold and dry conditions, with limited evaporation (Whitney and Harrington 1993; Thompson et al. 1999c). Relative to modern climate, infiltration would be higher during these cold, dry climates, because evaporation would be lower.

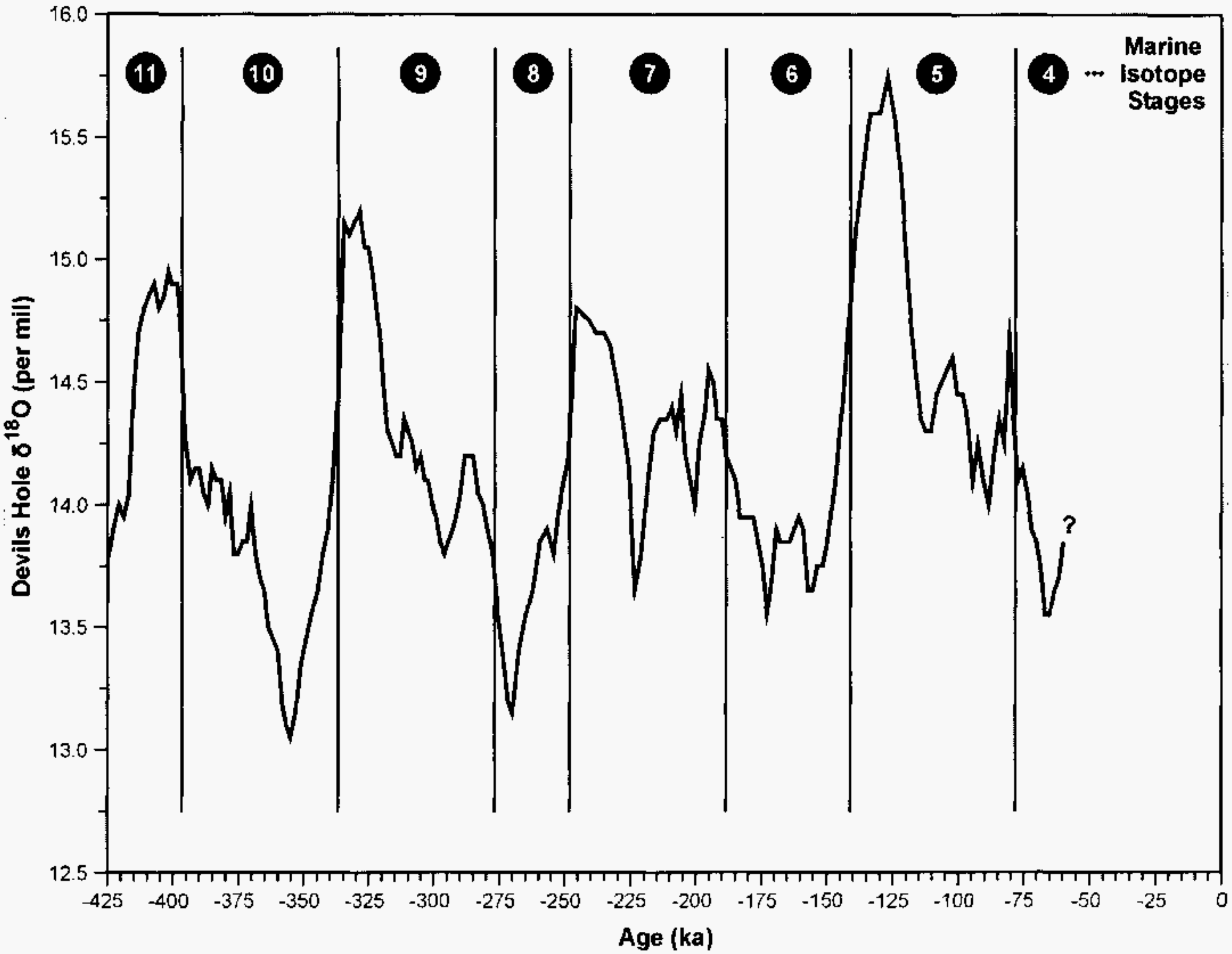
There were also interglacial periods in the YM region, especially during transitions from or to a glacial period, that appear to have been warmer and wetter than the "typical" interglacial period (Forester et al. 1999). During these periods, the Subtropical Highs would have expanded and/or intensified, resulting in a northward shift of the southwestern monsoon. Summer precipitation probably increased dramatically, resulting in higher MAP, but because this was summer precipitation, much of it likely was lost to ET, due to higher air temperatures, and active transpiration by the vegetation community. Conversely, there also were times during glacial-transition climates when the climate was wetter than during some glacial periods and cooler than the interglacial period (but not extremely cold), potentially enhancing infiltration.

On time scales of hundreds of thousands of years, climate change is large, and hence change in climate parameters affecting infiltration also is large. The largest amounts of infiltration probably occurred when very large continental ice sheets existed, resulting in cold, low evaporative conditions in the YM region. Although the interglacial (modern-like) climates only persisted for about twenty percent of the documented interglacial/glacial history (Forester et al. 1999; Winograd et al. 1997), the times when very large ice sheets existed also were limited, so much of the YM climate history is dominated by intermediate climates. For example, the full ice-maximum of the last glacial period, around 21,000 years ago, lasted only a couple of thousand years. By contrast, the penultimate glacial period from about 140,000 to 175,000 years ago may have sustained a large ice sheet for as much as 35,000 years, with cold, low-evaporative, and possibly wet conditions in the YM region. The importance of the penultimate glacial in the YM region is shown by the existence at that time of a large, 175-m-deep lake in Death Valley (Ku et al. 1998), now one of the driest areas in the U.S. Other glacial climates, for example those about 300,000 to 400,000 years ago, were cool and wet, rather than cold and either dry or wet, in the YM region. Each glacial and interglacial period appears to have a characteristic climate with unique infiltration characteristics. The nature of all climate change can be simplified as a seasonal interplay of the polar, tropical, and westerly air masses.

6.3 THE CYCLICAL NATURE OF CLIMATE CHANGE—DEVILS HOLE

The first assumption for this analysis is that climate is cyclical, and thus the past can be used to forecast the future. That is, if climate change exhibits some rhythmic pattern, then future climates will repeat, or at least approximate, past climates. For this particular assumption, that is that climate is cyclical, the only issue is whether or not the present-day interglacial period will be followed by a climate change toward glacial and then eventually into a glacial climate. Past climate cycles are a series of glacial/interglacial couplets. To illustrate the cyclic nature of past climate, the delta oxygen-18 ($\delta^{18}O$) isotope record from a calcite core at Devils Hole, Nevada, about 90 kilometers (km) south of YM (Figure 1), provides the best information about climate change in the region (Landwehr et al. 1997). Stable isotope compositions are typically reported in delta (δ) notation as the per mil deviation of the ratio of the heavy to light isotopes ($^{18}O/^{16}O$) in the sample to that of a reporting standard (VSMOW, Vienna Standard Mean Ocean Water, for $^{18}O/^{16}O$).

Devils Hole is an active extensional fracture in the Paleozoic limestone that composes the regional Paleozoic aquifer. During the last 500,000 or more years calcite has precipitated on the walls of the fracture, leaving an isotopic record of the regional ground water flowing through the fracture (Winograd et al. 1992). The calcite has been cored, and the core has been extensively dated (Ludwig et al. 1992). The $\delta^{18}O$ data (Landwehr et al. 1997, DTN: GS000200005121.003) from one core show an irregular cyclicity between high and low values for the last 425,000 years (Figure 3).



Sources: Devils Hole $\delta^{18}O$ and radiometric data from DTN: GS000200005121.003, Marine Isotope Stage data from Imbrie and Imbrie (1986)

NOTE: Stable isotope data are reported relative to VSMOW. High Devils Hole $\delta^{18}O$ values represent warm climates and low values represent cold climates. Odd numbered Marine Isotope Stages (MIS) correspond to interglacial climates, even numbered MIS correspond to glacial climates.

Figure 3. Devils Hole Stable Isotope Record Showing the Timing and Cyclical Nature of Climate Change

The $\delta^{18}O$ isotopic composition of ground water flowing through the Devils Hole fracture (Figure 3) (Landwehr et al. 1997) records the isotopic composition of infiltration in the recharge area of the regional aquifer (Winograd et al. 1992). The isotopic values of infiltration are related to three factors: 1) The isotopic composition and temperature of the source water, the tropical and subtropical Pacific Ocean; 2) The path that the water vapor takes from the source to the recharge area, and the amount of precipitation that occurs along the path; and 3) The temperature at which the precipitation in the recharge area forms.

When water evaporates from a source water the degree of fractionation (under equilibrium conditions) depends on the temperature of the source: the colder the source, the greater the fractionation (Kim and O'Neil 1997). The resulting vapor has a $\delta^{18}O$ value that is equal to the source minus the fractionation factor, so the vapor has a lower value than the source water. Equilibrium conditions often do not exist in the source areas, resulting in vapor values that are even lower than those that result from equilibrium conditions (Grootes 1993). Some of the ocean-derived vapor moves over the continent forming precipitation as snow or rain and over time that precipitation returns to the ocean, completing the hydrological cycle. During glacial periods, however, a significant amount of the precipitation is stored as snow and ice, and thus does not return to the ocean. Consequently, the isotope value of the ocean becomes higher during glacial periods. The cycle in $\delta^{18}O$ values in marine carbonates between low and high values records the storage or loss of continental ice, and hence glacial or interglacial climates. There may be a corresponding change in the isotope values of precipitation in the Devils Hole recharge area, reflecting changes in the isotope values of the source areas. But, a source area signature, because it would be small relative to the path effects, is not evident in the Devils Hole $\delta^{18}O$ record (Landwehr et al. 1997, DTN: GS000200005121.003).

The path and conditions along the path taken by vapor as it moves from the source area toward the recharge area have an important effect on the $\delta^{18}O$ values of precipitation in the recharge area. As vapor is chilled, whether from rising through the atmosphere due to thermal expansion or over topography or due to mixing with cooler air, some vapor turns to rain or snow. The fractionation as vapor turns to precipitation reverses that of evaporation, so precipitation has a higher $\delta^{18}O$ value than its vapor source. Following each precipitation event, the remaining vapor has an ever-lower value. If the path to the recharge area involves extensive precipitation, then the precipitation in the recharge area will have low $\delta^{18}O$ values, and if the vapor path does not involve extensive precipitation, then the precipitation in the recharge area will have relatively high values. Typically, interglacial precipitation has higher $\delta^{18}O$ values than glacial precipitation because the glacial path involves more precipitation, so in the carbonate $\delta^{18}O$ record from Devils Hole (Landwehr et al. 1997, DTN: GS000200005121.003), high values represent interglacial climates, and low values represent glacial or glacial-transition values (the opposite of the ocean).

Finally, because fractionation between vapor and precipitation is temperature dependent, the $\delta^{18}O$ values of precipitation from very cold snow should be higher than those of warm snow and those of warm snow should be higher than those of rain. Thus, if all other factors along the vapor path were constant, a very cold glacial period would have higher $\delta^{18}O$ infiltration values, which are close to precipitation values, than a warm glacial period. Because all other factors are not constant, recognition of temperature differences for precipitation in the recharge area between different glacial climates is not probable.

The cycles in the $\delta^{18}O$ data from Devils Hole for the past 425,000 years (Landwehr et al. 1997, DTN: GS000200005121.003) reflect a cyclic change from interglacial to glacial climates, each of which can be identified by a number (Figure 3) for a marine isotope stage (MIS), where odd numbers are interglacials and even numbers are glacials. The MISs are derived from the marine carbonate $\delta^{18}O$ records that reflect changes in $\delta^{18}O$ values of ocean water as continental ice sheets expand and contract (see discussion in CRWMS M&O 1998, p. 4.2-9 to 4.2-12; Shackleton and Opdyke 1973). The MIS and Devils Hole chronologies are not correlated exactly, and, in particular, differ in the timing of the glacial terminations (Winograd et al. 1992). The Devils Hole chronology is assumed to be most appropriate for the Yucca Mountain region and is used in this report.

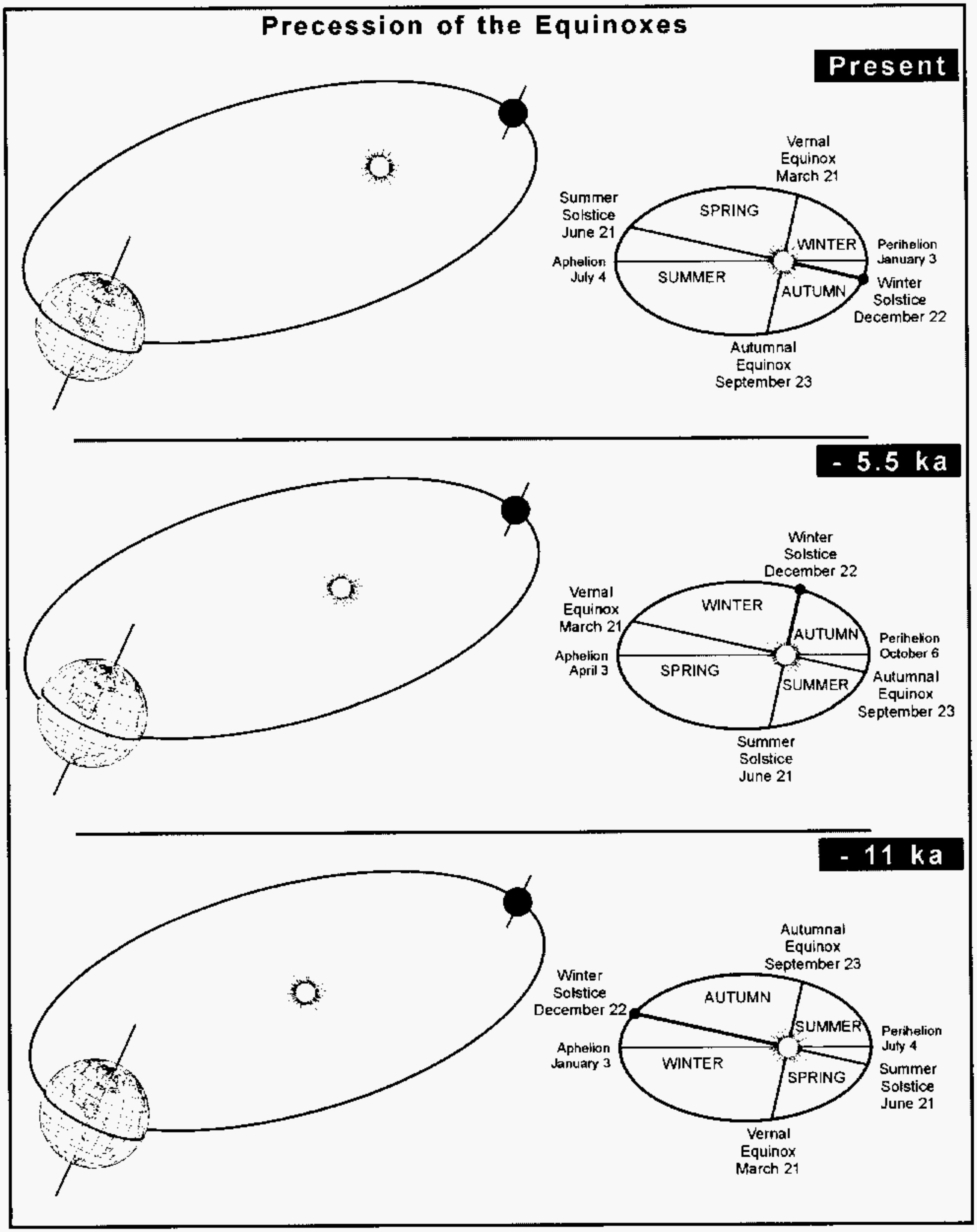
The Devils Hole $\delta^{18}O$ record (Landwehr et al. 1997, DTN: GS000200005121.003), as interpreted in terms of changes in isotopic values of infiltration in the recharge area, shows that climate is cyclic on a millennial time scale. The cycles, however, differ in duration (see also Winograd et al. 1992; Ludwig et al. 1992; Winograd et al. 1997).

6.4 TIMING OF PAST-CLIMATE CHANGE AND EARTH-ORBITAL PARAMETERS

The second key assumption in this analysis is that the timing of past climate change provides a rationale for timing future climate change. Timing future climate change requires that such change be based on parameters whose future values can be accurately calculated. Earth-orbital parameters, whose past and future values are readily calculated from basic celestial mechanics, provide the necessary values, if and only if a relation exists between the timing of climate change and those parameters. Using identifiable relations between orbital parameters and the timing of past climate change to forecast future climate change is within NRC acceptance criteria (U.S. Nuclear Regulatory Commission 1997). Because the causes of past change from interglacial to glacial and back to interglacial climates remain unknown, using the timing of past climate change as a basis for the future timing of climate change should be viewed with caution.

Recognition of relations between climate change and orbital parameters demands a well–dated, long, earth-based climate record, a record with a very accurate internal chronology. A good earth-based climate chronology allows for confident comparison of the timing of change between the climate and the orbital parameters. The timing of orbital parameters is derived from basic celestial mechanics, and is discussed by Berger and Loutre (1991), whose values are used in this discussion (Figures 4 and 5). The time under consideration is the past 400,000 years, because that interval of time is about equivalent to the long earth-orbital cycle, also known as a long eccentricity cycle. The long eccentricity cycles are not exactly 400,000 years in duration (Figure 5). For example, the time between the high value of eccentricity just before 400,000 years ago and the high value before 0 years is about 391,000 years. The exact time between the corresponding eccentricity values of earlier cycles is not constant, but for simplicity of discussion all will be referred to herein as 400,000-year cycles. Imbrie et al. (1992) and Imbrie, Berger et al. (1993), among many authors, provide a discussion of the perceived relation between orbital dynamics and climate change (SPECMAP, see discussion in CRWMS M&O 1998, p. 4.2-10). Winograd et al. (1992) have challenged the linkage between orbital forcing of climate change based on the difference between timing of climate change in the Devils Hole record

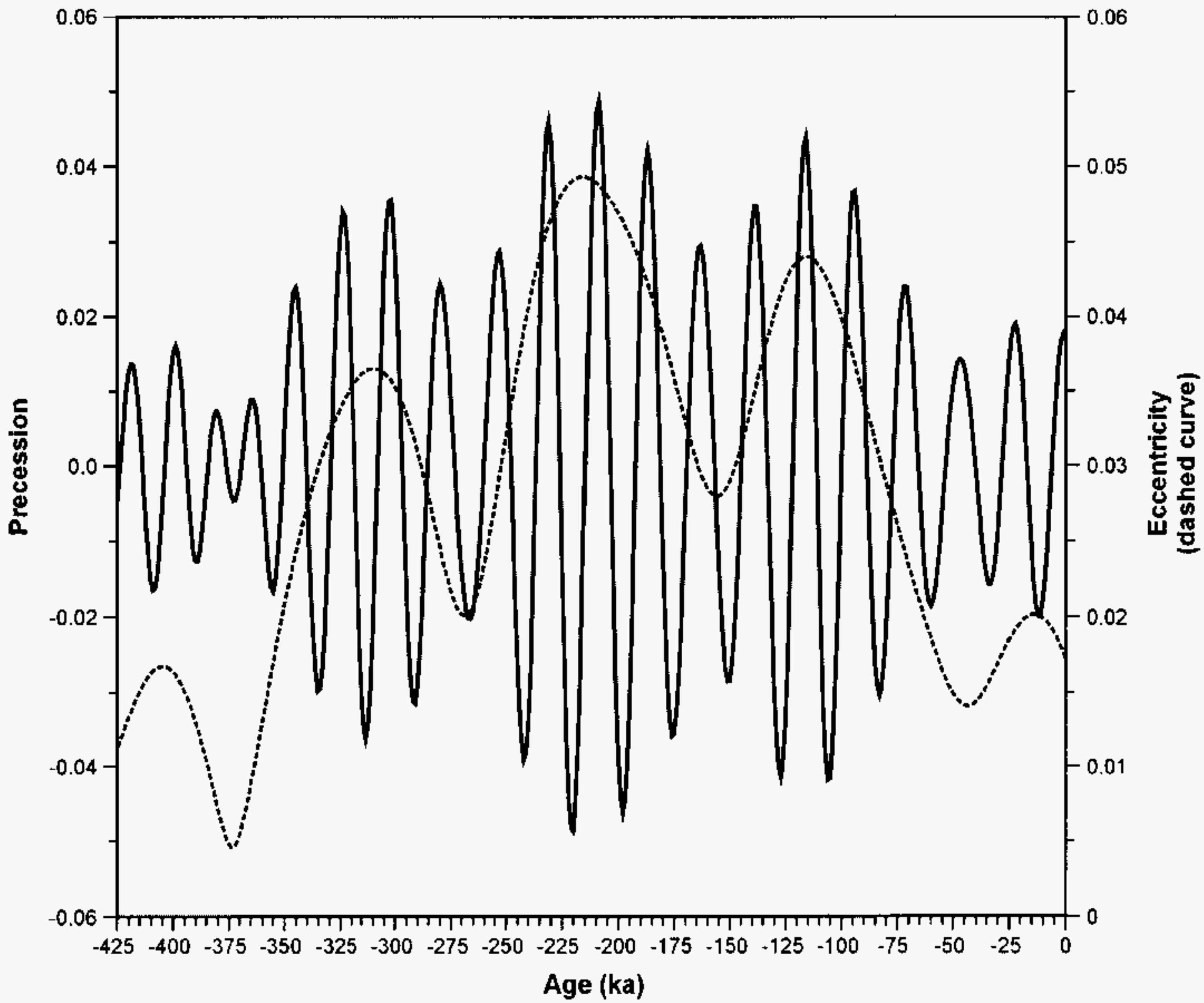
(Landwehr et al. 1997, DTN: GS000200005121.003) and the SPECMAP chronology (see discussion in CRWMS M&O 1998, p. 4.2-14). However, that is not at issue here, because the Devils Hole chronology of climate change is used in this analysis.



Source: modified from Imbrie and Imbrie (1986, figs. 13, 14, 16)

Figure 4 Generalized View of Precession, an Orbital Parameter related to the Timing of Earth's Long-Term Climate Change

There are three orbital parameters, each having its own periodicity: 1) eccentricity, the shape of the earth's orbit changing in a systematic way from an ellipse to circular and back to an ellipse with time, about every 100,000 years; 2) obliquity, the angle of the Earth's axis of rotation changing a few degrees with time, about every 41,000 years; and 3) precession, the wobble of the Earth's axis like that of a spinning top changing with time, about every 23,000 years. Precession, which dominates insolation (heat from the sun as measured at the top of the atmosphere) at low latitudes, is the primary parameter used here to identify the timing of climate change (Figures 4 and 5). Because of precession the summer of perihelion (the point in the orbit nearest the sun) shifts from one hemisphere to the other about every 11,500 years or so. Figure 5 shows how eccentricity amplifies or dampens the precession value. Obliquity, which influences the nature of seasonality at high latitudes and is a key component in SPECMAP, did not show any consistent relation with the Devils Hole record (Landwehr et al. 1997, DTN: GS000200005121.003), so it is not considered further.

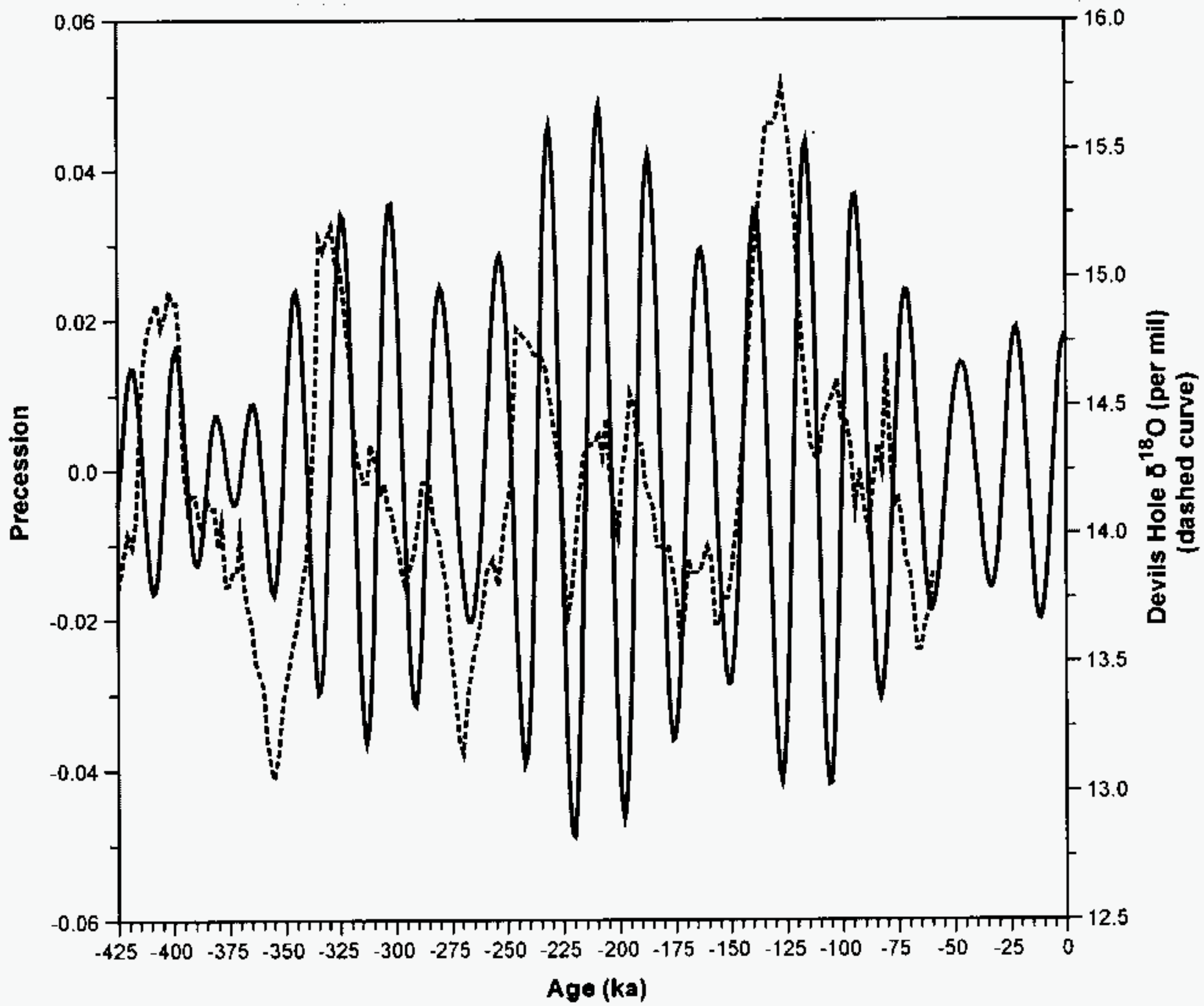


DTN: GS000200005121.001

Figure 5. Relation Between Precession and Eccentricity for the Past 425,000 Years

The orbital cycles (Berger and Loutre 1991, DTN: GS000200005121.001) are compared with the Devils Hole climate change chronology (Landwehr et al. 1997, DTN: GS000200005121.003) because Devils Hole is the only accurately and independently dated climate record on earth. Other long, dated climate records exist, but typically the chronology for those records relies on extensive interpolation between dates. So, in this analysis, the Devils Hole record forms the basis for the comparison and timing of climate change. The temporal changes in the orbital parameters are compared with the Devils Hole climate change chronology in search of an orbital clock that agrees with the times for climate change at Devils Hole and from that can be used to time future climate change. The latter is the opposite of common practice in which climate records acquire their chronology from orbital data, and that is because all earth records except Devils Hole lack a continuous internal chronology.

A general qualitative relation between Devils Hole data (Landwehr et al. 1997, DTN: GS000200005121.003) and precession (Berger and Loutre 1991, DTN: GS000200005121.001) is evident where maximal values of precession mark the ends of the Devils Hole interglacials and other warm periods (Figure 6). That qualitative relation was expanded into a formal relation between the Devils Hole $\delta^{18}O$ profile, precession, and eccentricity from direct inspection of the respective curves. The formal relation provides an orbital clock that offers a rationale for timing future climate change in terms of the Devils Hole chronology of climate change in the YM region. Imbrie, Mix, and Martinson (1993) and Shaffer et al. (1996) also have identified similarities between the Devils Hole $\delta^{18}O$ profile and orbital parameters. In the latter two studies Devils Hole data were compared to orbital parameters (the opposite of what was done in this study) to determine if the Devils Hole record reflects orbital forcing, that is, is the variation in the Devils Hole $\delta^{18}O$ profile attributable to variation in orbital parameters, and if so, is the variation in the Devils Hole $\delta^{18}O$ profile evidence for the assumption that changes in orbital parameters cause climate change?



DTN: GS000200005121.003, GS000200005121.001

NOTE: Stable isotope data are reported relative to VSMOW.

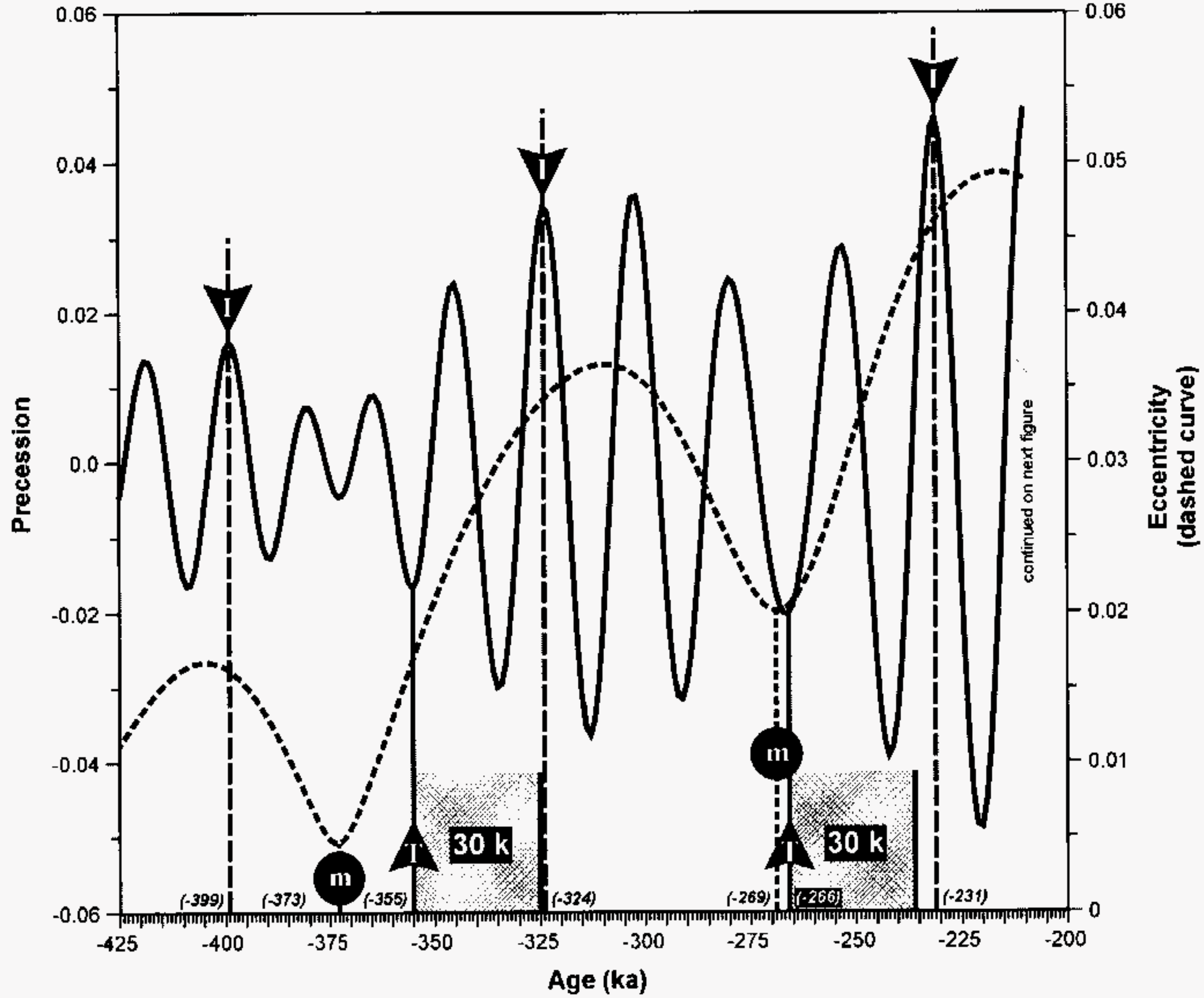
Figure 6. Relation of Precession to the Devils Hole Stable Isotope Climate Proxy Record During a Long Climate Cycle

The existence of an orbital clock, defined below, that times change in the Devils Hole record (Landwehr et al. 1997, DTN: GS000200005121.003) may not indicate climate change is caused by change in orbital parameters. Change in orbital parameters may simply be correlated with some other factor that causes climate change, such as solar output (Gauthier 1999), or may be a relatively minor factor, but one that tips the balance and drives the earth's climate system over some unknown threshold (Shaffer et al. 1996). Although the relation with timing of past climate change with changes in the earth-orbital parameters provides information about the timing of climate change, it does not imply magnitude or nature of climate change.

In order to describe the formal relation for orbital timing of climate change, the relation between Devils Hole $\delta^{18}O$ (Landwehr et al. 1997, DTN: GS000200005121.003) and precession (Berger and Loutre 1991, DTN: GS000200005121.001) shown in Figure 6 was examined. Notice that the inflection points in the Devils Hole data marking a change from a high towards a low value coming forward in time correspond to high precession values. Precession plays the dominant role in determining the nature of tropical and subtropical insolation, so a relation between the precession spectra and the Devils Hole record may imply a linkage between climate change and tropical insolation.

By comparing the Devils Hole $\delta^{18}O$ and age data (Landwehr et al. 1997, DTN: GS000200005121.003) with orbital parameter and age data (Berger and Loutre 1991, DTN: GS000200005121.001), a formal relation was found to determine which precession values are the ones that define the beginning or the end of a glacial period, so the relation could be applied in a consistent way to the orbital-parameter data in the future. The relation, starting with the end of the interglacial period around 400,000 years ago, appears to consistently identify all of the primary inflection points in the available Devils Hole record (new work at Devils Hole has extended the record from about 50,000 to about 9,000 years ago, but those data are not yet available).

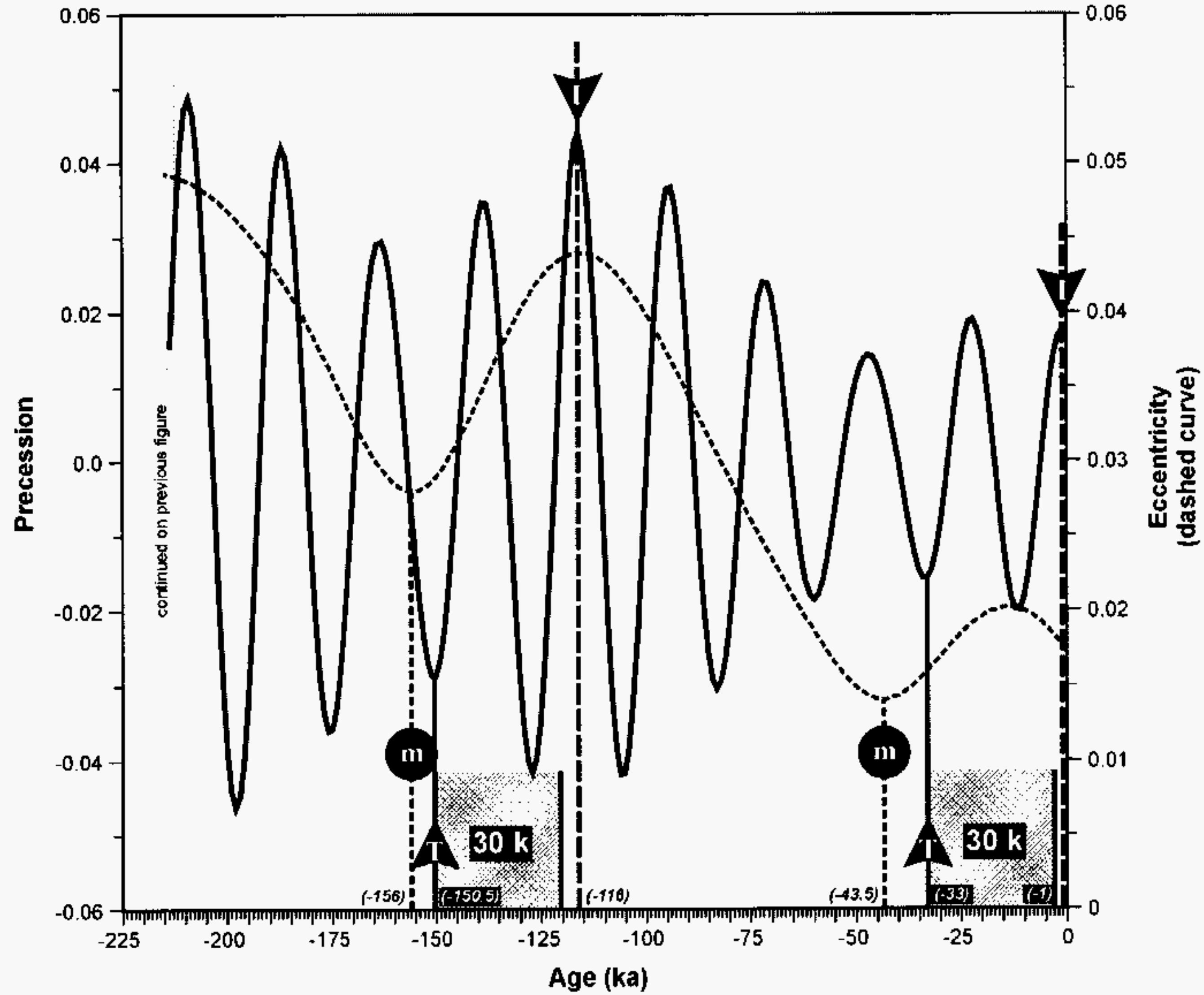
Inspection of precession plots (Figures 7a and 7b) and of the timing of precession versus Devils Hole $\delta^{18}O$ (Figure 6) shows that, in particular, a maximal positive precession (letter I in Figures 7a, 7b, and 8) marks the approximate termination for all of the interglacials defined by the Devils Hole record. By convention, a maximal positive precession is maximum precession (see Figures 4 and 5) in the Southern Hemisphere, whereas a minimal (most) negative value is maximum precession in the Northern Hemisphere.



Source: orbital data from DTN: GS000200005121.001

NOTE: I = initiation of transition to glacial climate; T = initiation of transition to interglacial climate; m = minimum eccentricity value.

Figure 7a. Proposed Relation Between the Timing of Past Climate Change and Earth-Orbital Parameters During a Long Climate Cycle; Continuation of Diagram is Given as Figure 7b

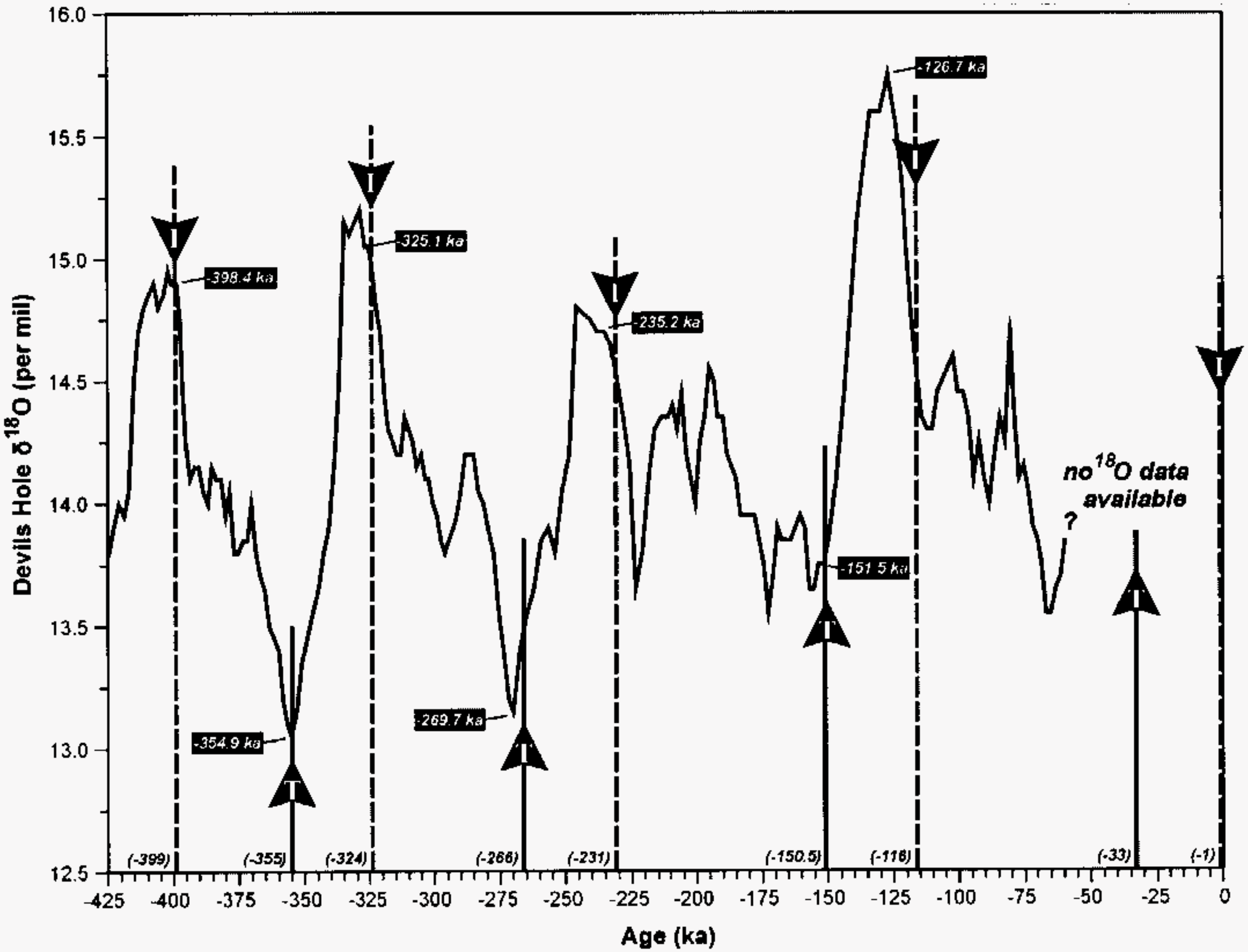


Source: orbital data from DTN: GS000200005121.001

NOTE: I = initiation of transition to glacial climate; T = initiation of transition to interglacial climate; m = minimum eccentricity value.

Figure 7b. Continued from Figure 7a; Proposed Relation Between the Timing of Past Climate Change and Earth-Orbital Parameters During a Long Climate Cycle

Termination of interglacials is here defined as the point in time where the Devils Hole $\delta^{18}O$ curve (Landwehr et al. 1997, DTN: GS000200005121.003) moves from high interglacial values towards lower values, that is, the terminal inflection point in an interglacial sequence coming forward in time, identified by the number below the letter I in Figure 8. It is less evident, but will be suggested below, that minimal precession values mark the ends of glacial periods, which are here defined as the point in time where the Devils Hole $\delta^{18}O$ record reverses its trend from low values and moves progressively towards high values, that is, the primary inflection point in the curve beyond which the values become progressively higher, identified by the number near the letter T in Figure 8. Selecting inflection points at the ends of interglacials and glacial periods to mark the beginnings and ends of (inter)glacial periods is not conventional, but better suits the purposes of this study.



Source: Devils Hole data from DTN: GS000200005121.003

NOTE: Stable isotope data are reported relative to VSMOW; I = initiation of transition to glacial climate; T = initiation of transition to interglacial climate; Ages for I and T are shown in parentheses at bottom of graph; Ages for inflection points are shown in box.

Figure 8. Relation of Data Shown in Figures 7a and 7b and the Timing of Climate Change Defined by the Devils Hole Climate Proxy Record

Final glacial inflection points (see Figure 8), that is the Devils Hole inflection point marking the point after which the Devils Hole $\delta^{18}O$ values become progressively higher (Landwehr et al. 1997, DTN: GS000200005121.003), are defined by the first minimal (Northern Hemisphere precession maximal) precession value (letter T in Figures 7a and 7b) (Berger and Loutre 1991, DTN: GS000200005121.001) following an eccentricity minimum value (letter m in Figures 7a and 7b). If a precession minimum coincides with an eccentricity minimum, which happens with the first glacial period in the 400,000-year cycle, then the next precession minimum marks the final glacial inflection point. The next (younger) interglacial inflection point, that is the inflection point in the Devils Hole record after which the $\delta^{18}O$ values become progressively lower, occurs at the first precession maximal value about 30,000 years after the preceding precessional minimum (Figures 7a and 7b). The 30,000-year value is a constant that was found by inspection to work for the entire 400,000-year sequence and has no other special significance.

The general nature of (inter)glacial climate probably does not change at the primary inflection points, but rather change towards an (inter)glacial climate begins at that point. And, climate does not necessarily move continuously towards an (inter)glacial. The Devils Hole $\delta^{18}O$ profile (Landwehr et al. 1997, DTN: GS000200005121.003) is a relatively smooth curve indicating a continuous transition toward and into (inter)glacial climates, but the Devils Hole data points integrate about 1,000 years or so (Winograd et al. 1992). Examination of a higher resolution curve such as the deuterium record of the last 420,000 years from Antarctica (Petit et al. 1999) shows a pattern of numerous small magnitude climate reversals that occur on decade and century time scales. In fact, the Devils Hole $\delta^{18}O$ record shows a reversal at about 220,000 years ago that is seemingly small in magnitude and only persists for a couple of thousand years. So these "primary" inflection points in the Devils Hole record identified with the precession methodology should not be thought of as absolute timings of climate change because climate reversals towards (inter)glacials may well occur following the inflection point.

The timing of (inter)glacial bounding precession maximal and minimal values (Berger and Loutre 1991, DTN: GS000200005121.001) are shown on the Devils Hole $\delta^{18}O$ curve (Figure 8) (Landwehr et al. 1997, DTN: GS000200005121.003). The correspondence between the precession-based and Devils Hole-based sets of values is nearly identical in most cases and off by 10,700 years in one case. Although the primary inflection points signal the beginning of change to the next climate state, there is a substantial amount of time following each primary inflection point until the next climate state is reached. For example, an interglacial climate, as defined by the Devils Hole $\delta^{18}O$ values reaching a plateau following a glacial period, takes from about 20,000 to 25,000 years after the glacial primary inflection point.

The differences between the timing of the precession-based ages (Berger and Loutre 1991, DTN: GS000200005121.001) and the ages of the Devils Hole $\delta^{18}O$ inflection points (Landwehr et al. 1997, DTN: GS000200005121.003) could be caused by several factors. The differences may reflect the age uncertainty in the Devils Hole dates, even though that uncertainty is usually small. The difference could be due to the methodology of selecting a precession value that marks the Devils Hole $\delta^{18}O$ inflection points, if precession values represent a fortuitous correlation with climate change. Or the differences could be a function of regional climate, where a Devils Hole primary inflection point precedes or follows global change.

The largest discrepancy between the Devils Hole $\delta^{18}O$ record (Landwehr et al. 1997, DTN: GS000200005121.003) and precession (Berger and Loutre 1991, DTN: GS000200005121.001) occurs at the end of interglacial stage 5e, which at Devils Hole is 126,700 years ago (Figure 8). The penultimate interglacial, stage 5e, was warmer than the present interglacial, as sea level was higher than today (Muhs and Szabo 1994). The $\delta^{18}O$ values from the Devils Hole record for this interglacial period are higher than for the other interglacials. As noted above, high $\delta^{18}O$ values for precipitation in the recharge area imply limited rain out along the path taken by vapor from the source to the recharge area. Thus the primary inflection point at the end of the interglacial stage 5e in the Devils Hole $\delta^{18}O$ data may reflect a change in the vapor path, but not the actual end of that interglacial period. Szabo et al. (1994) place the end of interglacial stage 5e at about 114,000 years ago. The precessional timing for the end of this stage is 116,000 years ago (Figure 8) and thus at a similar relative age difference as observed for earlier interglacial primary inflection points. If the Szabo et al. (1994) timing is used, all of the precession ages and the available Devils Hole inflection point ages are within 2,500 years or less of each other, a good agreement for the two sets of data.

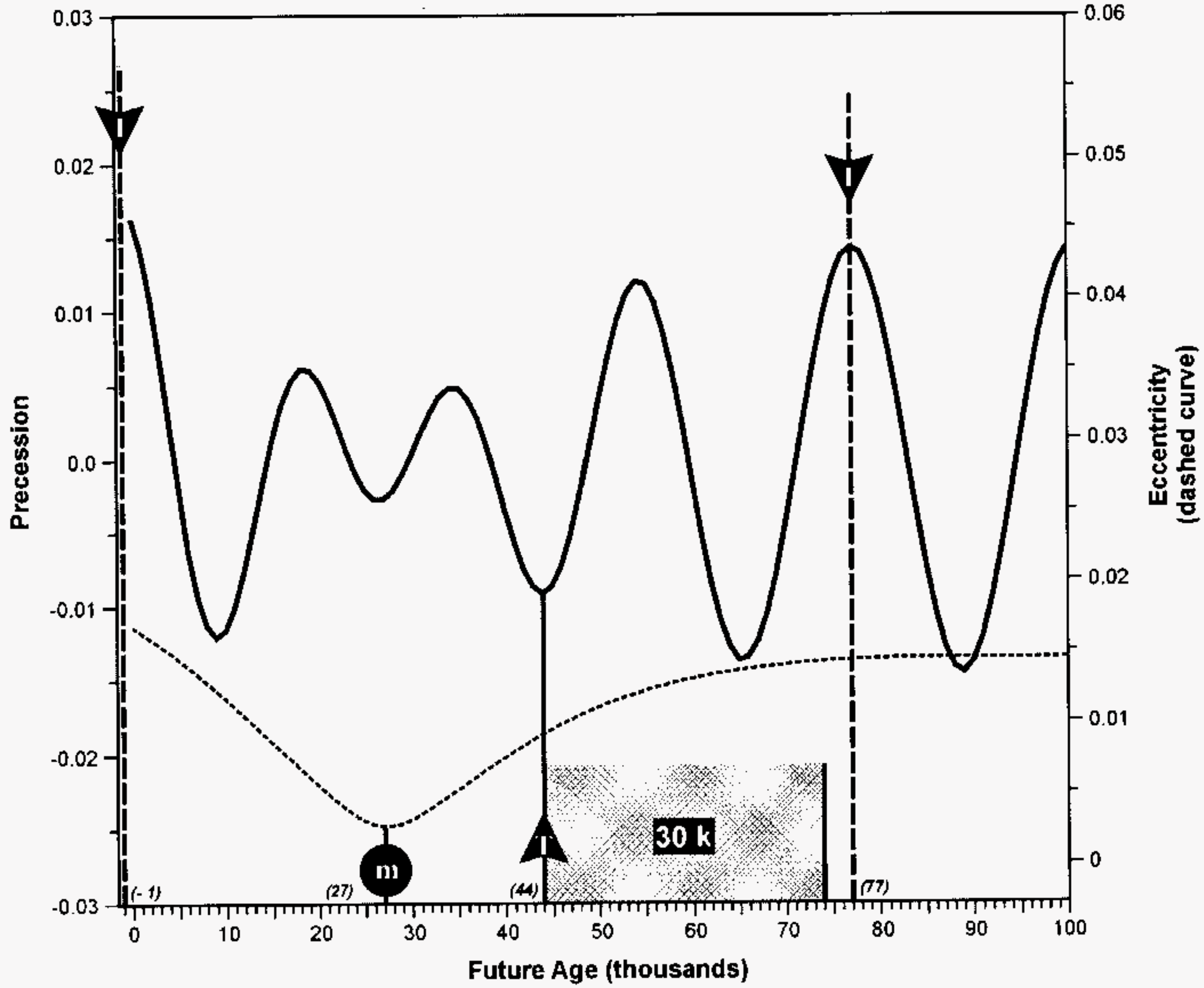
The value of the proposed orbital clock for forecasting the timing of future climate change (Figures 7a, 7b, and 8) can be viewed from another perspective. If it were 400,000 years in the past, at the beginning of the last orbital cycle rather than the present, would the forecast for the "future", as shown in Figure 8, be viewed as an accurate forecast for the timing of climate change? Given the enormous uncertainties about how the climate system works, and about the nature of past or future climate, it appears that this forecast would be a good forecast. However, there is an aspect in this forecast that needs to be addressed and its cause or implication is unknown.

The precessional method (Berger and Loutre 1991, DTN: GS000200005121.001) for identifying the primary inflection points within the Devils Hole record (Landwehr et al. 1997, DTN: GS000200005121.003) indicates there is a primary glacial inflection point at about 33,000 years ago, thus indicating climate change toward warmer conditions. Because the younger part of the Devils Hole record is not available, it is not known if the minimal precession value at 33,000 years ago corresponds with an inflection point in the Devils Hole record. If the Devils Hole record responds in the same manner about 33,000 years ago as it has in earlier parts of the record, then it should show an inflection point within a couple of thousand years of 33,000 years ago.

Winograd et al. (1996) discuss the younger part of the Devils Hole record and describe a sharp warming trend beginning at about 28,000 years ago as well as other evidence for warmth in this time frame. The earlier T events in Figure 8 have higher $\delta^{18}O$ values about 5,000 years later (33,000 minus 28,000 years) and because higher $\delta^{18}O$ values imply greater warmth, warmth at Devils Hole at 28,000 years ago is consistent with the older parts of the record. Thompson et al. (1997) also present evidence for warmth in the late 30,000-year time frame and other evidence for warmth at this time is common in the literature. Thus as with other periods marked with a T in Figure 8, the one at 33,000 years ago appears to precede a warming period, but unlike the other T periods, not a continuous warming period.

Following the warm period from about 32,000 through about 25,000 years ago, there was an extensive growth and advance of a continental glacier from about 24,000 to 18,000 years ago, with ice maximum around 21,000 years ago (Thompson et al. 1997). The climate characteristics in the vicinity of Yucca Mountain reflect a glacial climate (Thompson et al. 1999c, Forester et al. 1999). In terms of the precession methodology (Berger and Loutre 1991, DTN: GS000200005121.001) and its relation to the Devils Hole $\delta^{18}O$ record (Landwehr et al. 1997, DTN: GS000200005121.003) this represents a significant reversal in the pattern displayed in the transition periods from full-glacial climates toward the interglacial climates observed in all earlier transitions in the past 400,000-year cycle. And presumably this glaciation and its portrayal in the Devils Hole $\delta^{18}O$ record are much greater than the reversal at about 220,000 years ago. By contrast the present interglacial, the Holocene, begins about 10,000 years ago, 23,000 years after the 33,000-years-ago precession maximum in the Northern Hemisphere. The latter timing is consistent with timing for the beginning of earlier interglacials following the primary glacial inflection point. Thus, the last glaciation maximum about 21,000 years ago, which is not predicted by the precession methodology, may simply be an example of a climate variation, a feature that is typical of the last glacial cycle in the long orbital cycle, or an inconsistency in the precession orbital clock methodology.

The precession methodology is applied to the next 100,000 years in Figure 9 (DTN: GS000200005121.002). The timing of possible climate change toward and away from a glacial period is the same as for the change beginning about 400,000 years ago (Figures 7a, 7b, and 8). The duration between the initiation of climate change (I) at 399,000 years ago toward a glacial, and then away (T) from the glacial is 44,000 years (Berger and Loutre 1991, DTN: GS000200005121.001). In Figure 9, the timing from a move towards the glacial period (I at 1,000 years ago) to the move away (T at 44,000 years ago) is 45,000 years. As shown in Figure 8, the timing for the move towards and away is much longer for the remaining three glacial periods in the 400,000-year cycle, with durations of 58,000 years, 80,500 years, and 83,000 years.



Source: orbital data from DTN: GS000200005121.002

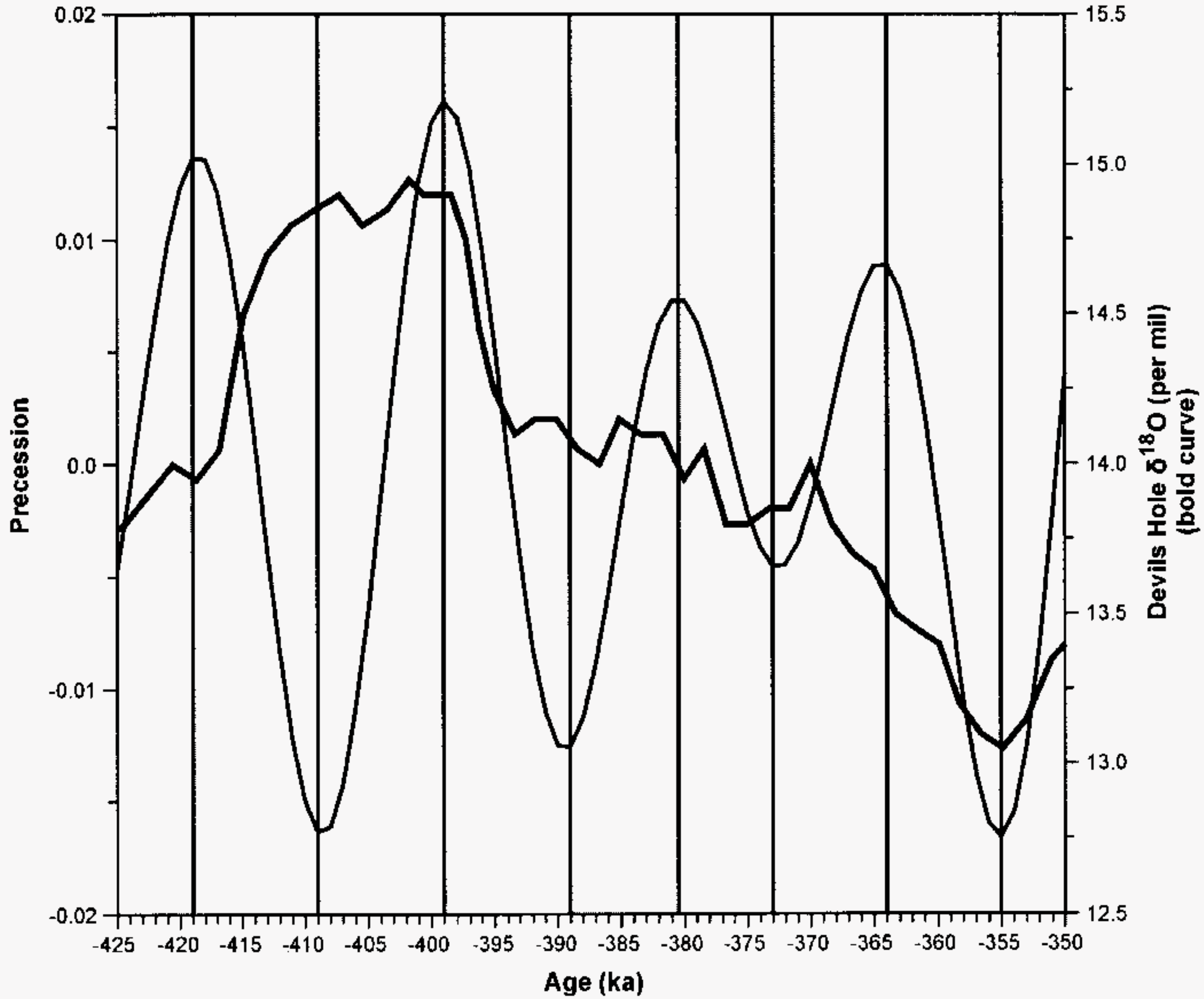
NOTE: I = initiation of transition to glacial climate; T = initiation of transition to interglacial climate; m = minimum eccentricity value.

Figure 9. Proposed Timing of Future Climate Change During the Next 100,000 Years

The discussion above indicates that a precession-based orbital clock, calibrated with the Devils Hole chronology, provides a basis to time climate change from the interglacials toward glacials and from glacials towards interglacial climates. This clock times the beginnings and ends of the major climate events during the last 400,000-year cycle and provides a potential clock for such events in the future.

Climate change, however, does not move steadily from interglacials to glacials and back again, but instead climate change is a complex array of intermediate climates between interglacial and glacial extremes. The intermediate climates may be truly intermediate in nature or they may be warmer and wetter or drier than the interglacials and colder and wetter or drier than the glacials. Understanding the timing of intermediate climates could be important, if they were to occur in the next 10,000 years. So the question becomes do changes in precession provide insight into climate change on shorter intervals of time.

To investigate identifying and forecasting climate change for shorter intervals of time than is discussed above, Figure 10 shows the relation between precession (Berger and Loutre 1991, DTN: GS000200005121.001) and the Devils Hole record (Landwehr et al. 1997, DTN: GS000200005121.003) from 425,000 to 350,000 years ago. The rationale for the selection of this interval will be discussed in more detail below, where it will be suggested that the interval from about 399,000 years to 389,000 years ago in the Devils Hole chronology is the analog for future climate. The minor lows and highs in the Devils Hole $\delta^{18}O$ data approximately, but not perfectly, correspond to the rises and falls in the precession values. This pattern is maintained for the entire Devils Hole record (Figure 6). Specifically, the change in precession from a maximal value to 399,000 years ago (maximum precession in the Southern Hemisphere) to a minimum value at about 390,000 years ago (maximum precession in the Northern Hemisphere) coincides with a change from a high $\delta^{18}O$ value (end of the interglacial) to a lower $\delta^{18}O$ value, presumably indicating a change toward a wetter and or cooler climate (Figure 10). The Devils Hole $\delta^{18}O$ record continues to rise and fall in approximate synchroneity with precession, eventually moving to a low value at 355,000 years ago reflecting the full glacial climate. The intriguing and puzzling aspect about the correspondence between precession and the Devils Hole $\delta^{18}O$ record is that in some cases there is a tendency for low values of $\delta^{18}O$ to correspond with minimal precession values, which represent insolation maxima in the Northern Hemisphere summer, and so correspond with processes that, from the isotope data, indicate cooler and or wetter conditions in the recharge area. Perhaps this implies there is no causal relation between precession and the Devils Hole $\delta^{18}O$ record or perhaps it means the response of the climate system follows or leads precession. Or perhaps it means maximal precession in the Northern Hemisphere, and consequently maximum summer insolation in the Northern Hemisphere, are linked somehow to the genesis of moisture necessary for the initiation of a glacial period, and if so that would seem to indicate that tropical climate drives climate change. Whether or not these or other factors are involved, these data indicate the timing of the minor inflection points in the Devils Hole record are at least approximately correlated with precession. Consequently, the timing of future subcycles in precession should also approximately time climate change.



DTN: GS000200005121.003, GS000200005121.001

NOTE: Stable isotope data are reported relative to VSMOW.

Figure 10. Relation Between Precession and the Timing of Climate Change in Part of the Devils Hole Record from 425,000 to 350,000 Years Ago

Inspection of the precession curve in Figure 9 (DTN: GS000200005121.002) shows that it is similar to the precession curve in Figure 10 (Berger and Loutre 1991, DTN: GS000200005121.001). Presuming the future precession curve times climate change and marks the multitude of intermediate climates that exist between interglacial and glacial climates, then such intermediate climates will characterize southern Nevada climate for approximately the next 30,000 years. Then around 30,000 years from now climate will move into the full glacial climate and will have moved out of the full glacial by about 50,000 years from now.

6.5 THE NATURE OF PAST AND FUTURE CLIMATE

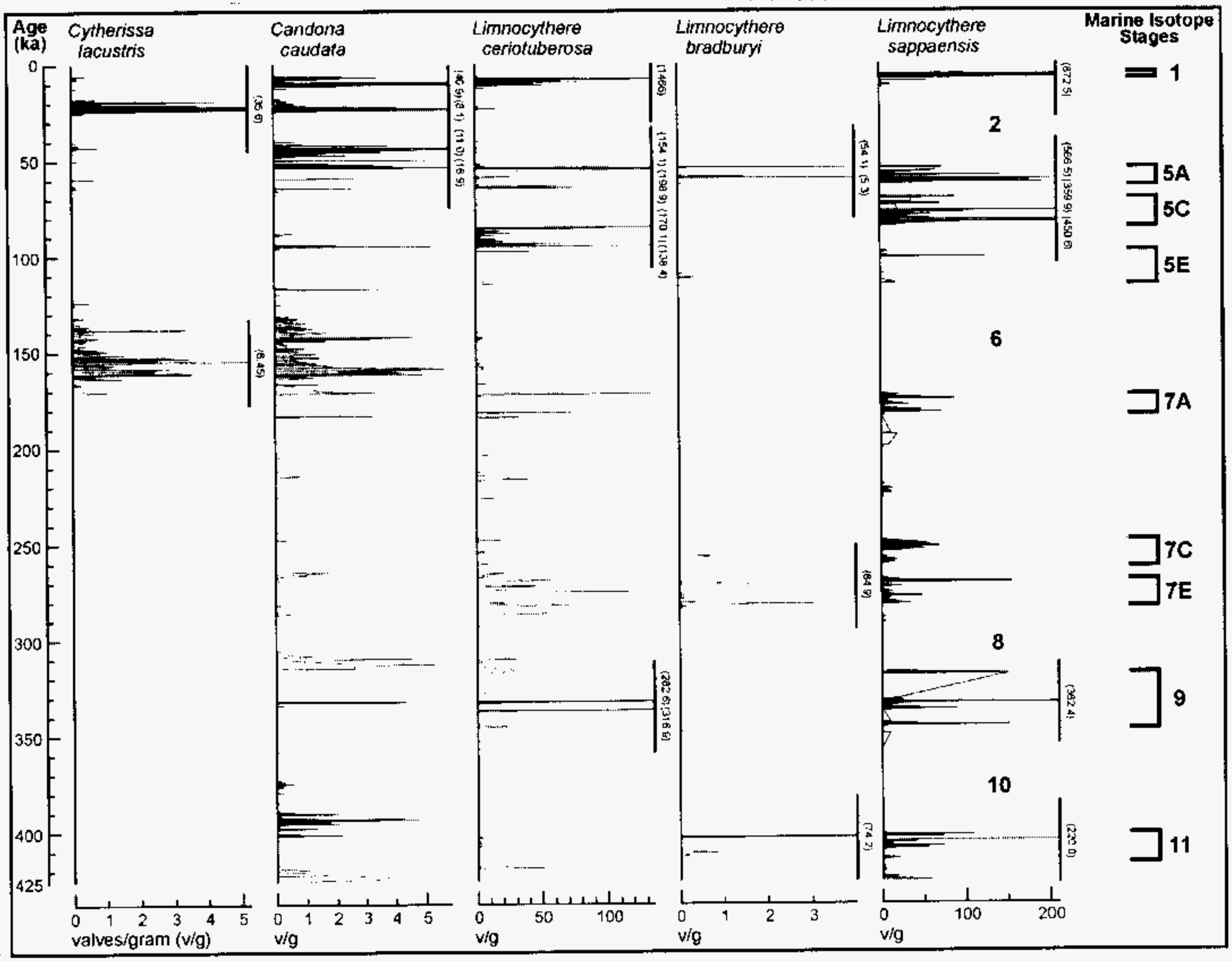
The third assumption in this analysis is that a general relation exists between the nature of climate characteristics of past glacial and interglacial climates and the sequence of those climates in the long 400,000-year earth-orbital cycle. This is the most difficult assumption to deal with, because support for it depends on the interpretation of paleoenvironments from the penultimate 400,000-year cycle and data from that cycle are limited. If the temperature and precipitation characteristics of past glacial and interglacial climate couplets differ from each other in a systematic way through a particular 400,000-year cycle, but the sequence of climate couplets in adjacent 400,000-year cycles are similar, then this relation provides a criterion for the selection of particular past climates as an analog for future climates in the next 10,000 years or perhaps longer at YM. If this assumption is not accepted, then the future climate bounding estimates would depend on a conservative estimate of climate or in other words on the extreme temperature (very cold) and precipitation (very wet) values from the previous 400,000-year cycle instead of values within the extremes.

Using this relation, the glacial and interglacial climates of the last 400,000-year orbital cycle, divided into marine isotope stages (MISs) as shown in Figure 3, will serve as sequential analogs for future climates during the next 400,000 years. Although a strict repetition of climate characteristics is not expected or implied from the available data, the general characteristics (the greatest effective moisture within the next 400,000 years) of future precipitation and temperature for a particular interglacial/glacial couplet will be similar to the corresponding MIS couplet in the past 400,000-year sequence. Because of tectonic change and other long-term climate forcing functions, climate change on the million-year time scale should change in a non-cyclic way, and the sequential nature of climate characteristics in non-adjacent 400,000-year orbital cycles may be dissimilar from each other.

6.5.1 Basis for and General Climate History of the Last 400,000 Years

Comparison of climate series from different 400,000-year cycles requires that climates from the last 400,000-year cycle be known in enough detail to serve as a basic reference for comparison of climates in older 400,000-year cycles. If the hypothesis of repetition of climates in sequence is accepted, the long YM regional climate sequence also provides the future climate analog for the next 10,000 years. Although the Devils Hole stable isotope record (Figure 3) (Landwehr et al. 1997, DTN: GS000200005121.003) provides the best-dated record for sequence study, it does not provide a means of determining the magnitude, that is the nature, of climate events. Therefore, another record, the microfossil record from cores drilled at Owens Lake, California, is used instead to reconstruct a climate history for the last long orbital cycle.

The primary data source for this discussion is the Owens Lake micropaleontological record of diatoms and ostracodes (DTN: GS970708315121.001; GS991008315121.002; GS970708315121.002; GS991008315121.001), and this discussion will focus on the ostracodes, as their story is similar to the diatoms. Diatom data will be used when necessary to support the ostracode story. A composite stratigraphic distribution of ostracodes from cores taken in the Owens Lake Basin is shown in Figure 11. The relation between the ostracode species assemblages and the Owens Lake hydrology and, from that, climate, is discussed in Forester et al. (1999) and CRWMS M&O (1998, p. 4.2-16 to 4.2-22), among others, and those discussions will only be briefly repeated here.



DTN: GS970708315121.002, GS991008315121.001, GS000208315121.002

NOTE: Interglacial marine isotope stages (odd numbers) shown in right column, inferred glacial marine isotope stages (even numbers) shown under *L. sappaensis* column. Bars centered on data spikes indicate data points beyond the scale of the graph, values to right of bars are data values at spike apex.

Figure 11. Owens Lake Ostracode Species Stratigraphic Distribution

The Owens Lake Basin is located on the eastern side of the Sierra Nevada Mountain Range (Figure 1). During the winter season the polar air masses expand (see discussion in Section 6.2), resulting in an alignment of the storm track with the Sierra Nevada Mountains. The persistence and strength of the storm track is a key factor in determining Sierran snowpack and in turn the snowpack determines the amount of runoff available for surface-water flow, that is, flow above base flow in the Owens River.

During an interglacial climate, surface-flow is typically seasonal, but during glacial climates surface-flow probably persisted throughout the year or when it did not, evaporation in the Owens Basin was greatly reduced from present-day, due to colder air temperatures. The modern-day high evaporation in the Owens Basin, estimated to be about 1,500 mm relative to 140 mm average local precipitation (Smith 1976), would support a saline Owens Lake, if surface and base flow were not diverted to Los Angeles. Thus, under natural conditions present-day annual flow is not sufficient to fill and spill Owens Lake. When the Owens River flow was greater and or evaporation was lower (low MAT) during glacial and glacial-transition climates, the lake did fill and spill, and was filled with freshwater. Primarily because of its location, the Owens Lake climate signal is dominated by winter precipitation and summer evaporation. Summer precipitation is typically limited, because tropical cyclonic activity does not usually extend into the Owens Basin from the southeast. Kay (1982), among others, has documented higher levels of summer precipitation associated with tropical storms. There is some indication from the fossil record, discussed below, that summer precipitation was an important contributor to Owens Lake hydrology in the past.

A relation between total dissolved solids (TDS) in the lake water, flow in the Owens River, and level of evaporation in the Owens Basin exists. Further, flow in the Owens River and level of evaporation in the Owens Basin are directly related to climate. When the Polar Lows were resident in the region, as during some glacial periods, Sierran snowpack and hence surface-water flow was greatly increased, and evaporation in the basin was lower (both actual MAP and effective moisture, which is MAP minus evaporation, were high). If Arctic High air were resident in the region, then evaporation in the Owens Basin must have been much lower than today, due to very cold temperatures, so surface-flow likely was at some intermediate level relative to interglacial and the high-MAP, Polar-Low-dominated climates, so effective moisture also would have been high and the lake would spill.

Ostracode and diatom species environmental tolerances provide a way to interpret the relative TDS of the Owens paleolake, and the relative temperature of its water. The TDS and water-temperature information is then interpreted in climate terms. Thus, the stratigraphic profiles of microfossil species provide a way to interpret regional climate history from their implied paleoenvironments, and hence insight into glacial and interglacial climate change, and a means to compare past climates with each other. Further, North American lacustrine ostracode species biogeography is known well enough to use it to understand the general nature of climate change in Owens Lake rather than just paleoenvironmental change. Unlike common plant species (Thompson et al. 1999a; 1999c) however, the biogeographic distributions of lacustrine ostracodes are not mapped, so can not be quantified in climate terms. Thus, particular climate parameters are not as readily derived from ostracode assemblage biogeographic data as from plant biogeographic data. Nonetheless, the occurrence of various ostracode species does provide a paleogeographic sense (polar, tropical, or temperate) of the nature of past climates.

Actual climate parameters, however, do not have to be generated from the microfossil species profiles to reconstruct long-term climate, as long as the characteristics of, for example, a given glacial or interglacial climate can be properly evaluated relative to others. The relative climate reconstruction is then compared, that is calibrated, with two absolute climate control points: 1) modern meteorological data and 2) the reconstruction of the last glacial climate based on plant macrofossils recovered from packrat middens throughout the region (Thompson et al. 1999c). Thus the knowledge of ostracode and diatom TDS tolerances, ostracode relative water-temperature preferences, and ostracode species biogeography provide a means of directly comparing general or relative nature of the past glacial and interglacial climates during the last 400,000 years.

A composite stratigraphic distribution of common lacustrine ostracode species from the Owens Lake record for about the last 425,000 years is shown in Figure 11 (DTN: GS970708315121.002, GS991008315121.001). The chronologies are based on a mass sediment-accumulation model, calibrated by radiocarbon ages at the top of the core, and the Bishop Ash at the base of the core (see discussions in Forester et al. 1999, CRWMS M&O 1998, p. 4.2-19 to 4.2-20). In this basin, as in most basins, sediment accumulation rates are not expected to be constant over long periods of time, so a chronology derived from an age model should be viewed as an age estimate, at best. Thus in the absence of direct dating, other means must be used to date the sediments from the cores. One such means is to identify the interglacial and glacial stratigraphic environmental signature from the Owens Lake record and then correlate that signature with the Devils Hole record. The Owens Lake chronology shown in Figure 11 is provided here for reference only and is not used in the analysis documented in this AMR.

Forester et al. (1999) and CRWMS M&O (1998, p. 4.2-18 to 4.2-22) discuss the relation between diatom and ostracode species, Owens paleolake chemistry, and climate. Briefly, during interglacial climates, when, at least on a seasonal basis, Owens River base flow is common, the lake becomes both saline and alkaline, that is, its solute chemistry is characterized by a high alk/calcium ratio. Alk is total alkalinity expressed as an equivalent amount of calcium carbonate ($CaCO_3$).

Limnocythere sappaensis requires the high alk/Ca water associated with base flow in the Owens River to survive (Forester 1983) and such waters characterize the warm climate episodes at Owens Lake (Menking et al. 1997). Each abundant *L. sappaensis* zone is identified with an interglacial (warm climate) MIS number starting with 1 and counting backwards in time (Figure 11) (DTN: GS970708315121.002, GS991008315121.001) (see Winograd et al. 1997, for further explanation of MISs). Warm climate episodes also include the warm periods within glacials such as MIS substages 5C and 5A. Further, MIS 9, like 7 and 5, has warm and cool substages, but the substages are not differentiated here due to loss of core. The *L. sappaensis* MIS 1 interval (Figure 11) is only a subset of the true MIS 1, which extends from present-day to about 10,000 years ago, so the other *L. sappaensis* intervals also may be subsets of the respective MIS stages they are thought to identify. Assuming the Owens Lake sedimentary record (Smith and

Bischoff 1997) is reasonably complete, then the *L. sappaensis* stratigraphic profile identifies all sustained warm climates, in other words, those with low effective moisture.

Comparing the same MIS intervals in the Devils Hole $\delta^{18}O$ record (Figure 3) (Landwehr et al. 1997, DTN: GS000200005121.003) and the Owens Lake ostracode record (Figure 11) (DTN: GS970708315121.002, GS991008315121.001) indicates that the sediment mass-accumulation age model does not provide a good chronology at Owens Lake, because the Owens Lake and Devils Hole chronologies do not correlate. So, first the proposed MIS intervals shown in Figure 11 must be evaluated. If abundant *L. sappaensis* intervals represent saline lakes when the Owens River is at base flow and hence warm, dry climates, then the times between such intervals should contain evidence of surface flow, both freshwater and cold conditions; with Owens Lake filling and spilling under a polar, cold air mass. That is, if the ostracode profiles shown in Figure 11 represent the glacial and interglacial climates for the past approximately 400,000 years, then there should be an alternating ostracode assemblage reflecting fill and spill cold lakes followed by another assemblage reflecting closed saline lakes and so on.

Cytherissa lacustris and *Candona caudata* are ostracodes that require low salinity water in order to grow and reproduce (CRWMS M&O 1998, p. 4.2-20 to 4.2-21), so their presence in this record (DTN: GS970708315121.002, GS991008315121.001) implies a fill and spill lake (Figure 11). *Limnocythere ceriotuberosa* is common in lakes receiving seasonal surface flow followed by a base-flow phase, so its presence implies greater surface flow than is typical today, but less than that during the periods when *C. lacustris* and *C. caudata* are common. The stratigraphic record in Figure 11 shows that all of the intervals between those identified by *L. sappaensis* variously contain *C. lacustris* and *C. caudata* with common occurrences of *L. ceriotuberosa.* Thus the expected sequence of taxa representing fill and spill, freshwater, cold lakes through closed, saline lakes is present in the record. This implies the record is complete, and moreover, is comparable with the sequence of glacial and interglacial cycles recorded by other records reflecting global climate change such as the Devils Hole $\delta^{18}O$ record.

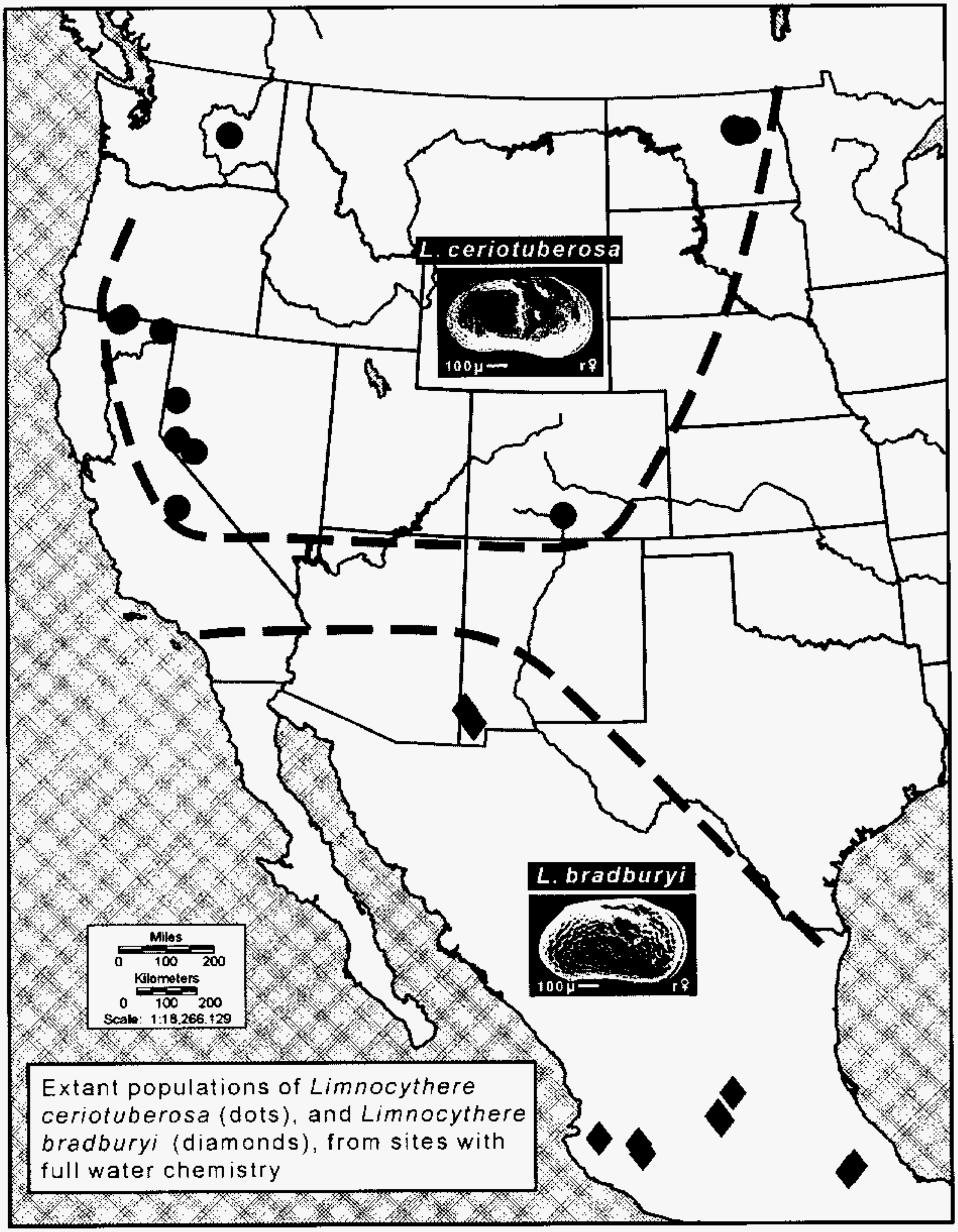
The inferences about timing and stratigraphy from the distribution of *Limnocythere sappaensis* and other ostracodes (DTN: GS970708315121.002) are in part supported by a recent revision of the Owens Lake chronology (Litwin et al. 1999). Using a high-resolution pollen stratigraphy generated in both Searles Lake, California and in Owens Lake, Litwin et al. (1999) correlate an alpha spectrometric uranium series chronology from Searles Lake to Owens Lake. They did not date the Holocene in Searles Lake, but their pollen stratigraphy for MIS 5A, 5C, and 5E agrees with the *L. sappaensis* chronology proposed here. The ostracodes and pollen data do not correlate as well in the older part of the core where the pollen analyses were based on lower resolution pollen analysis (Litwin 1999). More recent, but unpublished higher resolution analyses have changed the pollen correlation chronology (Litwin 1999), but its effect on the ostracode chronology is not yet known, but should be taken into consideration for any future revision of the climate AMR.

Assuming the Owens Lake sedimentary record (Smith and Bischoff 1997) is reasonably complete from the discussion above, the ostracode record provides the following insights into the regional climate history. The ostracode species stratigraphic profile shown in Figure 11 (DTN: GS970708315121.002, GS991008315121.001) shows that *Cytherissa lacustris* is common for about 2,000 years centered on 20,000 years ago (Owens Lake chronology), which is within MIS 2 (the last full-glacial period), and again between about 120,000 to 170,000 years ago (Owens Lake chronology), which is within MIS 6 (the penultimate glacial period). *C. lacustris* also occurs at a single horizon at about 310,000 years ago (Owens Lake chronology), which is within MIS 8. *C. lacustris* was not found in sediments attributed to MIS 10, even though a large number of samples were examined from this interval. *Candona caudata* is also common through the same horizons as *C. lacustris* and at many horizons within glacial intervals where *C. lacustris* does not occur.

Cytherissa lacustris is a taxon that lives in small to large lakes in the Boreal Forest and Arctic Circle (Delorme 1970), where the climate is dominated by polar air masses. *C. lacustris* is known only from a few large lakes south of Canada and Alaska, such as the Great Lakes. It is absent from deep, high mountain lakes in the Sierra Nevada Mountains. The distribution of modern-day *C. lacustris* supports the interpretation that it requires cold and fresh (highest TDS occurrence about 300 milligrams per liter, mg/L, Delorme 1989) water to survive. *Candona caudata* lives in Canada and Alaska, but also is common in many locations in the continental 48 states. The southernmost known distribution for *C. caudata* is in the Pahranagat Lakes, Nevada, and the known upper TDS limit is about 3,000 mg/L (Bradbury et al. 1989). Thus both *C. lacustris* and *C. caudata* imply fresh fill and spill lakes, and hence wetter than modern climates, but the *C. lacustris* intervals also imply a colder and perhaps fresher lake than the *C. caudata* intervals without *C. lacustris*.

The stratigraphic profiles of *Cytherissa lacustris* and *Candona caudata* (Figure 11) (DTN: GS970708315121.002, GS991008315121.001) indicate that glacial period MIS 10 was the warmest glacial period, followed by MIS 8, and MIS 6 was the coldest glacial period. The abundance of *C. caudata* during the warm glacial periods implies MAP was high in order to maintain a fresh and spilling lake, although the lake need not be as fresh as it was during the *C. lacustris* intervals, so the *C. caudata* lakes may imply lower effective moisture levels. Significantly, during the coldest glacial, a fresh and spilling lake could be maintained largely by low evaporation with only modest gains in MAP above modern levels, so a relatively low MAP, but a high effective moisture level. Thus the cold glacials do not require, but do not preclude, large increases in MAP to create and sustain a freshwater lake.

The ostracode *Limnocythere ceriotuberosa* commonly lives in saline to freshwater lakes in the U.S. and on the central Canadian prairies where its habitat is influenced seasonally by polar and westerly air masses (Figure 12). It is often found in lakes with seasonal changes in TDS, resulting from a seasonal shift from excess surface flow to base flow. In Owens Lake, *L. ceriotuberosa* likely reflects a lake that fills and spills in some years, but is typically at some intermediate depth between the *C. lacustris* and *C. caudata* continuously spilling lakes, and the low-level base-flow-supported saline lakes of *Limnocythere sappaensis* (DTN: GS970708315121.002, GS991008315121.001). Periods when *L. ceriotuberosa* was common in the Owens Lake stratigraphic profile imply intermediate lakes between those produced by full-glacial climates and those supported by interglacial climates, and thus indicate intermediate climates. Intermediate climates might be somewhat wetter or cooler than modern day or a combination of both, but not as wet or cold as the full-glacial climates.



Source: modified from Smith and Forester (1994, fig. 1)
NOTE: One µ equals 10^{-6} meter, "r" indicates right-hand valve, "♀" indicates female.

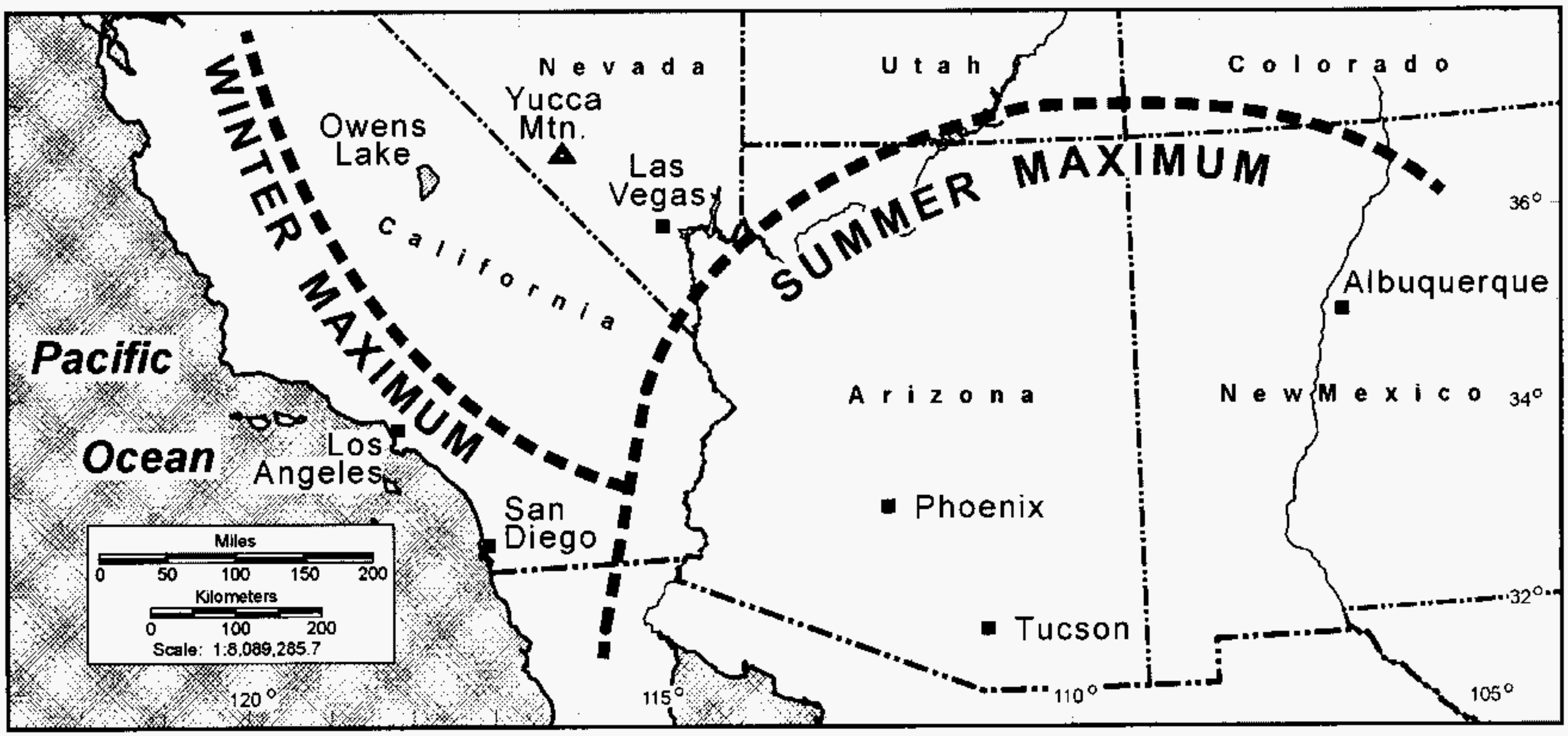
Figure 12. Modern-Day Biogeographic Distribution of Two Ostracode Species found in the Owens Lake Fossil Record Illustrating a Relation Between Biogeography and General Features of Climate (see Figure 2)

The past warm, evaporative, low-MAP climates are represented by *Limnocythere sappaensis* as discussed above. The occurrence of this taxon in the Owens Lake record (DTN: GS970708315121.002, GS991008315121.001) indicates a saline lake supported largely by base flow, and hence a modern-day-like climate or a drier/warmer climate than modern day. It does not, however, allow for a climate that is much wetter/cooler than today, because a wetter/cooler climate would result in an influx of dilute high-elevation water that is lethal to *L. sappaensis*. As shown in Figure 11, numerous *L. sappaensis* climates existed in the region during the past 425,000 years.

An interesting subclimate associated with the *L. sappaensis* climates is indicated by the presence of *Limnocythere bradburyi*. Today, the biogeographic distribution of *L. bradburyi* is centered in central Mexico (Forester 1985) where its habitat is influenced seasonally by the subtropical easterlies or the subtropical highs (Figure 12). The northern biogeographic limit, in shallow-water environments, is the January frost line in the southwestern U.S., indicating it is cold-water sensitive (Smith and Forester 1994). Other areas in the southwest that are warm enough are too dry to sustain shallow lakes long enough for *L. bradburyi* to complete its life cycle. However, past climates that were warmer and wetter than today, including those where monsoon flow through the southwest was enhanced, would sustain shallow, warm lakes promoting a northward range expansion of this species. The fossil distribution of this taxon extends into northern Nevada (Forester 1985; Forester 1987; Bradbury et al. 1989) and elsewhere and appears to have done so during many past warmer and wetter climate episodes.

Limnocythere bradburyi would not live in Owens Lake during times of higher surface flow, when such conditions resulted from resident polar air masses, which would result in a cold lake. If *L. bradburyi* could live in cold water, then its present distribution would be more northerly, as it was in the past. The sporadic occurrences of *L. bradburyi* in the Owens Lake record (Figure 11) (DTN: GS970708315121.002, GS991008315121.001) are always associated with *Limnocythere sappaensis* lakes, which reflect warmer climates. It does not occur throughout the *L. sappaensis* intervals, because the salinity tolerance of *L. sappaensis* is higher and its temperature tolerance lower than that of *L. bradburyi*.

The modern-day northern extent of the southwestern monsoon, showing the area dominated by summer precipitation (Muhs 1999), is south of the Owens Basin and YM (Figure 13). However, given a modest and uniform expansion of the modern summer rain regime, both YM and the Owens Basin would be included. The inclusion of the Owens Basin should change the basin's hydrology to reflect a summer, rather than winter precipitation regime, which would be atypical for the basin. A dilution of a warm climate saline lake and/or a shift to year round warm waters due to an overall expansion of the tropical system and contraction of the polar system, would provide an environment like those where *Limnocythere bradburyi* lives today (Forester 1985; Smith and Forester, 1994). The rarity of *L. bradburyi* in the fossil record (DTN: GS970708315121.002, GS991008315121.001) at Owens Lake during the last 425,000 years reflects the rarity of tropical regime dominance over winter regimes in the region.



Source: modified from Muhs (1999)

Figure 13. Generalized Depiction of the Present-Day Average Distribution of the Southwestern Monsoon

The ostracode species stratigraphic profiles (Figure 11) (DTN: GS970708315121.002, GS991008315121.001) provide relative climate scenarios based on inferences about the linkage between climate and paleolimnology in the Owens Lake Basin for the past 400,000 years. In order to assign approximate values of MAT and MAP to the relative climate scenario, the relative scheme must be "quantified" by comparing it to quantified climate estimates. Two climates were selected to calibrate the nature of all of the climates recorded in the Owens Lake record from the relative climate scenario: the modern-day climate and the reconstructed climate for MIS 2 (Thompson et al. 1999c). Climate parameters for both are estimated for an elevation equivalent to the top of YM.

The modern-day climate is characterized by: 1) Hot, dry, very evaporative summers due to the residence of the Subtropical Highs, 2) low levels of MAP due to both the summer air masses and to a location east of the Sierra Nevada Mountains, and 3) occasionally wet but typically dry and relatively warm winters. Modern-day MAP and MAT as estimated by Thompson et al. (1999c) for YM are about 125 mm and 13.5°C respectively. These values are lower than those commonly used by the YM project, but are derived from a longer set of historical meteorological data and are interpolated to Yucca Mountain from area rather than project stations. The Thompson et al. (1999c) numbers are closer to the Nevada region 3 and 4 averages, which represent the last 100 years, rather than just the last two decades. The modern-day warm interglacial climate at YM is assumed to be typical of all of the *Limnocythere sappaensis* records found in the Owens Lake climate record (DTN: GS970708315121.002, GS991008315121.001). By proximity, as climate is a regional and not a local phenomenon, the existence of warm evaporative climates at Owens Lake implies that such climates also exist at YM.

The last full-glacial climate (MIS 2) at YM was characterized by: 1) Cold, wet (snowy) winters due to the residence of either Polar Lows or Arctic Highs, creating high effective moisture, and 2) cool, dry summers resulting from both the presence of cool, westerly flows and the absence of Subtropical Highs in the region. The MIS 2 full-glacial climate estimates at YM for MAP is about 266 to 321 mm and for MAT is about 7.9° to 8.5° C (Thompson et al. 1999c). These estimates are derived from a study of the plant macrofossils found in packrat middens in the YM region.

The values given above provide climate numbers that can be applied to the relative climate scheme developed from the microfossil record in the Owens Lake sediments. So, for example, MIS 10 was wetter and warmer than MIS 2 and MIS 6. MIS 6 was colder than MIS 2, but probably had an MAP similar to MIS 2 to possibly higher than MIS 2. So MIS 10 may have had an MAP that was much greater than about 300 mm and an MAT than was higher than about 8 degrees Celsius (°C). MIS 6 by comparison was colder than 8°C and had an MAP of about 300 mm or higher. The *Limnocythere ceriotuberosa* intermediate climates were typically drier and warmer than MIS 2, but wetter and cooler than the modern-day values. So the *L. ceriotuberosa* intervals had an MAP that was greater than 125 mm, but less than about 275 mm and an MAT above 8 °C but below about 13 °C. The *Limnocythere bradburyi* climates were wetter and slightly warmer than the modern-day climates.

Lastly, the stratigraphic distance between the various ostracode species assemblages in the Owens Lake core are small, implying the interpreted climate changes occurred rapidly. Using the Owens Lake chronology, the timing of climate change is often occurring in decades to centuries and rarely in millennia. Such rapid changes in climate, however, are not generally from the driest and warmest to the wettest and coldest climates, but rather are transitioning through many intermediate climate states.

6.5.2 Repetition of Past Climates

The assumption discussed in this section is that a general relation exists between the characteristics of past glacial and interglacial climates and the sequence of those climates in the long 400,000-year orbital cycle. Because the characteristics of past glacial and interglacial climates differ from each other and appear to do so in a systematic way, this relation provides a criterion for selection of a particular past climate as an analog for future climate.

The ostracode fossil record from Owens Lake cores (DTN: GS970708315121.002, GS991008315121.001) provides the basis to make a number of general observations about paleoclimate. Some of these observations for the past 400,000 years include:

1. The third glacial period in the sequence (MIS 6) was the coldest of the glacial climates and had the highest level of effective moisture, but not necessarily the highest MAP,
2. The first glacial period in the sequence (MIS 10) was the warmest, and perhaps the wettest of the glacial climates, but probably had a moderate level of effective moisture relative to higher effective moisture in the colder glacial periods in the sequence,
3. There were numerous interglacial and related warm climate periods such as MIS stages 5A and 5C, when the climate was warm and dry with low effective moisture,
4. The warm, dry climate periods were occasionally punctuated by warm and wet, but low effective moisture, tropical-dominated climates,
5. There were extensive periods when climate characteristics were intermediate in nature between full-glacial high effective moisture and interglacial warm-climate low effective moisture periods, and
6. The rate of change between the various climates was rapid, apparently occurring on a decade to century time scale.

The Owens Lake ostracode hydrologic/climatic record (DTN: GS970708315121.002, GS991008315121.001), as partially summarized in 1 through 6 above, indicates that the regional climate history for the past 400,000 years was a complex array of climates. Each of the glacial climates MIS 10, 8, 6, 4/2 was different from the others and became colder as the sequence progressed reaching the coldest and most persistent glacial climate with MIS 6. MIS 6 was followed by a complex set of climates ranging from the wet and warm interglacial MIS 5E to the cold and relatively short-lived glacial climates, MIS 4 and 2.

In terms of an orbital clock, today the climate system resides at the beginning of a new 400,000-year cycle. If the cycle repeats, then the transition climate at the beginning of the last 400,000-year cycle (MIS 11 to MIS 10) may be a more probable analog for future climate than some other interglacial to glacial transition. Evidence in support of this idea comes from comparing the last cycle (400,000 years ago to present), hereafter referred to as the younger long climate cycle (YLCC), to the 400,000-year cycle before the last one, so 800,000 to 400,000 years ago, hereafter referred to as the older long climate cycle (OLCC).

In comparing the relation between the OLCC and the YLCC, the southwestern regional climate records from the OLCC are limited, and existing records are often poorly dated or not interpreted in the detail that would be preferable for this study. Further, long-term climate forcing functions, primarily tectonic, are probably not "constant" in this time frame and hence may contribute to climates in the OLCC time frame in a different way or with different magnitude than those from the YLCC or those in the future. Nonetheless, some information is available from the region, including Death Valley, and, more generally from the global marine records. A number of studies interpret climate from regional records that are dated or believed to be dated between 800,000 and 400,000 years ago, for example, see Smith (1984); Jannik et al. (1991); Whitney and Harrington (1993); Reheis et al. (1993); Reheis (1999); Knott (1999); and Oviatt et al. (1999). A general discussion is given in Smith (1991a; 1991b).

Because the older climate records, those from the OLCC or even older, are poorly dated, comparison of paleoenvironmental events from a record at one site to events at another site is difficult if not speculative. Thus the level of past climate detail, such as the six observations given above about the YLCC in the Owens Lake Basin, is not available from the older records. However, aspects of the events seen in the younger part of the Owens Lake record can be identified in the older records. During the YLCC the coldest and highest effective moisture climate was interpreted, based on the ostracode and other records, as the third glacial (MIS 6) in the YLCC. Support for the interpretation, for example, comes from the MIS 6 lake in Death Valley that was at least 175 m deep, but only about 70 m deep during MIS 2 (Ku et al. 1998).

If the OLCC and YLCC are similar, the third glacial period in the OLCC (MIS 16, from about 680,000 to 630,000 years ago) is expected to have had the coldest and highest level of effective moisture in that cycle. Deciphering MAT or other climate characteristics from the OLCC is not straightforward from the available data, which mostly are lake levels. Lake level, as discussed above and by Smith (1991a), may be a product of higher MAP or colder temperature or some combination of both. Estimation of the general order of climate change magnitude from the size of old lakes does, however, provide insights to compare the climate characteristics of glacial periods within and between 400,000-year cycles.

Reheis (1999, Figs. 2 and 3) presents evidence for MIS 16, the third glacial in the OLCC, being the biggest and deepest lake in several basins throughout the Great Basin. Knott (1999) identifies lake sediments deposited during MIS 16 (and perhaps a somewhat older lake) in Death Valley, but does not distinguish the possible size of the MIS 16 lake from others in the OLCC. Jannik et al. (1991) suggest a large lake existed in the Searles Basin during MIS 16 that was large enough toward the end of MIS 16 to overflow to the Panamint Basin. They also suggest an MIS 18 (about 725,000 to 705,000 years ago) lake may have overflowed to the Panamint Basin and that both of the latter lakes may have overflowed from the Panamint Basin to Death Valley. Similarly, Reheis (1999, Fig. 3) presents some evidence for a large lake during MIS 18. Oviatt et al. (1999) reinterpret the timing and occurrence of lakes in the Great Salt Lake Basin. They present chronological and environmental evidence from a core for a lake in that basin during MIS 16 and MIS 12 (about 490,000 to 415,000 years ago), but no others during the OLCC. Reheis (1999, Fig. 3) also presents evidence for a large lake during MIS 12, but not as large as the one during MIS 16.

The MIS 16 lakes identified by Reheis (1999) are much larger and deeper than those from the same basins during MIS 6. Although shoreline elevations are not available, the opposite appears to be true for the lakes in the Great Salt Lake Basin (Oviatt et al. 1999). The differences in size between the MIS 16 and 6 lakes could be a result of various combinations of temperature and precipitation or simply a different average position of the polar jet stream due to spatial and height differences in the two continental ice sheets. The important aspect of this information for this discussion is that the apparent biggest lakes in the OLCC and YLCC occur during the third glacial in each cycle. The third glacial in each cycle would then seem to have had the highest effective moisture; whether that was generated largely due to cold temperatures, high precipitation, or both, is not known.

Similarly, Reheis (1999, Fig. 3) suggests MIS 12 lakes also were large, but not as large as those during MIS 16. MIS 12 is in the same position in the OLCC as is MIS 2 in the YLCC, the last (4^{th}) glacial cycle. Ku et al. (1998) show that the MIS 2 lake in Death Valley was large, but smaller than the MIS 6 lakes. Jannik et al. (1991) suggest that the Owens drainage lakes filled and flowed into Death Valley during parts of MIS 16, 12, and 6, among others, but not during MIS 2. The absolute size of a lake in a particular basin is a function of many climate and non-climate factors, but what is important here is that in a given basin, the behavior of a sequence of lakes during the OLCC, that is, the lakes characterizing MIS 20, 18, 16, and 14/12, appears to be similar to the behavior of a sequence of lakes during the YLCC, that is MIS 10, 8, 6, and 4/2.

Finally, the marine isotope record (Reheis 1999, Fig. 3) provides a general proxy for ice volume, although ocean temperature may also play an important and perhaps unknown role in this record. Marine isotopic profiles during the OLCC generally are similar to those during the YLCC. The largest ice sheets are those from MIS 16, 12, 6, and 2. As continental ice sheets expand in area and become higher in elevation they force the polar air masses to the south. So large ice sheets should result in cold and or wet climates in the vicinity of YM. Large ice sheets also result in climates in the YM area with cooler summers than today, thus enhancing effective moisture. Conversely, MISs 20, 18, 14, 10, 8, and 4 apparently had smaller or lower (?) ice sheets, potentially allowing for warmer, and thus lower effective moisture climates in the YM region, as perhaps the smaller lakes associated with those periods imply.

The records of paleoclimate are often incomplete, poorly dated, and are interpreted differently by different workers. The information above, however, implies that there is some repetition between the types of climate in the OLCC and the YLCC. This provides the basis to suggest that the nature of the next glacial cycle at the beginning of the next 400,000-year cycle may be more like the glacials at the beginnings of the long climate cycles than other glacials within the long climate cycles. If so, then the transition from MIS 11 to MIS 10 provides a past analog for forecasting future climate change, and hence the basis used here to establish a potential climate scenario for the next 10,000 years.

Although not based on paleoclimate data, the orbital parameters, especially precession and eccentricity, show strong similarity at the beginning of the YLCC and from now forward in time for the next 100,000 years, which is the beginning of a new 400,000-year cycle (Berger and Loutre 1991, DTN: GS000200005121.001; and GS000200005121.002) (compare Figures 7 and 9). As has been discussed above, there is no certainty in whether or not orbital parameters that time climate change also drive climate change. If orbital parameters drive climate change, do they also determine the nature or magnitude of climate change? If the answer to the last question is yes, then position within the long orbital cycles also determines the nature of climate and thus the beginning of the YLCC is the analog for future climate during the next 10,000 years.

6.6 A FUTURE CLIMATE ANALOG FOR THE NEXT 10,000 YEARS

On the basis of the assumptions discussed above that 1) climate is cyclic, 2) climate can be timed with an orbital clock, 3) climate sequences repeat themselves in a predictable way, and 4) tectonics or other long-term climate-forcing functions that could result in non-cyclic future climate behavior are constant on the time scales of interest here, the MIS 11/10 transition was selected as the analog for future climate for the next 10,000 years. The timing of and nature of climate change for the next 10,000 years are discussed below.

6.6.1 Timing of Climate Change for the Next 10,000 Years

Forecasting the timing of future climate change simply requires the identification of a past climate sequence that is believed to be part of a cycle that will repeat itself in the future. Thus, a past climate time series analog is identified and projected into the future. Forecasting is very different from predicting. Predicting integrates all factors affecting Earth's climate into a time-series numerical model that is then run for the particular future times under predetermined boundary conditions. Specifically, climate models require particular boundary conditions to operate properly. Boundary conditions would include ocean surface temperatures at some future point in time and of course if we knew with any certainty what future boundary conditions were then we would also know something about future climate and not need to do any modeling. Furthermore, climate models and the computers they run on can not produce output for long periods of time, such as 10,000 years. Typical output might be five years of data following long computer run times. Present-day science does not know with certainty why climate changes, or know how to numerically describe the change in climate system in a time series, nor is there any agreement about future boundary conditions. Consequently, the discussion below will focus on forecasting future climate.

First a point representing the equivalent to the present day is identified in the YLCC series (a past/present point). Then the next 10,000 years of paleoclimate reconstruction from the past/present point becomes the future climate forecast. The orbital clock that was derived from the Devils Hole chronology (Section 6.4 above) provides the means to approximately identify the past/present point in the Owens Lake record. The graph (Figures 7a and 7b) shows the linkage of the present-day position in the orbital clock (I=1,000 years ago) and the equivalent point during MIS 11 (I=399,000 years ago). The orbital-clock relation is readily transferred to Devils Hole through their respective chronologies (see also Figure 8).

A precession maximum in the Southern Hemisphere, used to time the beginning of climate change from an interglacial towards a glacial climate, occurred 399,000 years ago during MIS 11 (Berger and Loutre 1991, DTN: GS000200005121.001). The first data point in the Devils Hole record (Landwehr et al. 1997, DTN: GS000200005121.003) indicating climate change away from the MIS 11 interglacial climate occurs at 397,300 years ago (ignoring the Devils Hole age standard deviation) or 1,700 years after the precession maximum. A precession maximum in the Southern Hemisphere during the present interglacial climate occurred 1,000 years ago (Figure 7b). Using the MIS 11/10 timing indicates the beginning of climate change away from the present interglacial may be about 700 years in the future. Therefore, what will the climate of the next 700 years and beyond be like and what will be the timing of those future changes in climate?

Placement of a past/present point in the Owens Lake sedimentary record requires that the sedimentary chronology be placed in the context of the Devils Hole chronology. The Owens Lake chronology, as discussed above in Section 6.5, is based on a sediment mass-accumulation curve. Figure 11 shows a possible correlation of the Owens Lake sedimentary record (DTN: GS970708315121.002, GS991008315121.001) to the MIS periods. By correlation with the chronology of the Devils Hole $\delta^{18}O$ record (Landwehr et al. 1997, DTN: GS000200005121.003), the Owens Lake MIS periods are given an absolute chronology. Applying the Devils Hole chronology to the Owens Lake record indicates the sediment accumulation ages at Owens Lake are variously too old or too young or about correct in a few instances such as the MIS 11/10 interval. This implies the mass-accumulation rate clock variously runs too fast or too slow, and occasionally is on time. Nonetheless, the correlation between the Owens Lake record and Devils Hole does place the approximate position of the transition between MIS 11/10 in the Owens Lake record in Devils Hole terms.

Placement of the Owens Lake sedimentary record in the Devils Hole chronology, unfortunately, only approximates where the past/present point belongs. In order to further refine the Owens Lake age estimates, the ostracode and diatom data (DTN: GS970708315121.002, GS991008315121.001, GS970708315121.001, GS991008315121.002) in the Owens Lake record are used to identify environmental change during and from the MIS 11 interglacial, and then from the sequence of environmental change, to estimate where the past/present point belongs. Inspection of the stratigraphic distribution of ostracode species in Figure 11 shows a sequence of ostracode species from about 425,000 years ago (Owens Lake chronology) to about 405,000 years ago starting with *Candona caudata*, followed by *Limnocythere ceriotuberosa*, and ending with *L. sappaensis*. The interpretation of this ostracode sequence (Section 6.5) indicates a transition from a full and spilling lake during a glacial or glacial-transition climate (*C. caudata*) to an intermediate climate between glacial and interglacial (*L. ceriotuberosa*), to an interglacial climate (*L. sappaensis*). Similar ostracode sequences occur at the ends of other glacials including the last one (Figure 11).

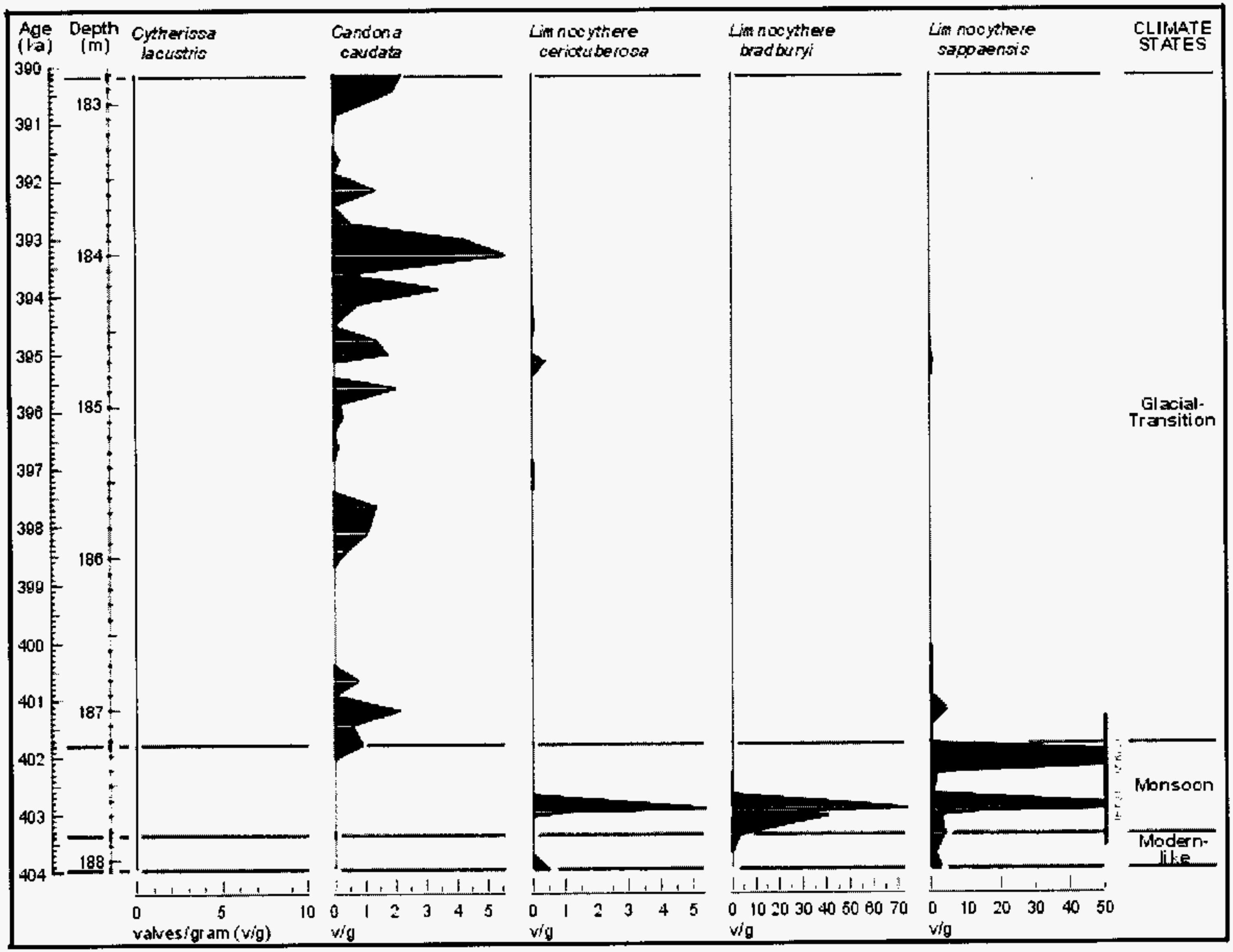
During MIS 11 the abundance peaks of *Limnocythere sappaensis* at about 405,000 years ago (Owens Lake chronology) are followed by abundant *Limnocythere bradburyi* at about 403,000 years ago (Owens Lake chronology) (also present around 410,000 years ago, Owens Lake chronology) (DTN: GS970708315121.002, GS991008315121.001). *L. bradburyi* does not occur in the Owens Lake record at the transition into the present interglacial, but was very common in several basins from the southwest, such as the San Agustin Basin (Markgraf et al. 1984). The appearance of *L. bradburyi* indicates a period of intense summer monsoon activity (Section 6.5).

Various saline benthic diatoms co-occur with *Limnocythere sappaensis* (DTN: GS970708315121.002, GS991008315121.001, GS970708315121.001, GS991008315121.002) from its first appearance in MIS 11 until about 405,000 years ago (Owens Lake chronology). From about 405,000 to 403,000 years ago (Owens Lake chronology) the sediments are barren of diatoms. Because diatoms are made of opal and opal dissolves in alkaline water, the absence of diatoms and the presence of a saline, alkaline ostracode implies the latter interval of time was one where Owens Lake was both very saline and very alkaline. When *L. bradburyi* appears at 403,000 years ago (Owens Lake chronology) it co-occurs with saline benthic and planktic diatoms, implying a saline lake, but one that is both fresher than the one without diatoms, and also one that is deeper. A fresher and deeper lake, if derived from snowpack, should have cold climate ostracodes, such as *L. ceriotuberosa* without *L. bradburyi,* as is typical of much of the

Owens Lake record. The presence of planktic saline diatoms, and *L. bradburyi* imply a significant summer rain input to the lake, perhaps with limited or no winter-precipitation-derived surface-water flow.

The Holocene lake core (MIS 1) contains abundant *Limnocythere sappaensis* through about 4,000 or 5,000 years ago radiocarbon time, followed by a core containing salt and few to no ostracodes (Smith and Bischoff 1997). Recent historic records also report the existence of a saline, alkaline lake before the Owens River was diverted to Los Angeles. The climate associated with MIS 11 therefore is similar to that of MIS 1, but there are also differences. MIS 1 in particular has no *L. bradburyi* at its beginning, and *L. ceriotuberosa* is much more common in MIS 1, implying it was cooler and perhaps wetter than MIS 11.

Presuming that climate is cyclic, then the past/present day point in the MIS 11 sequence at Owens Lake is above the large *L. sappaensis* abundance peak (labeled 220.0), but below the *L. bradburyi* peaks (DTN: GS970708315121.002, GS991008315121.001). The argument is that the large *L. sappaensis* abundance peak in MIS 11 reflects a mid-stage warm, dry climate and the enhanced monsoon reflecting the *L. bradburyi* abundance peak has yet to occur in MIS 1. Because the present interglacial is nearing its end, the modern climate state should be close to the proposed monsoon. Accordingly, the past/present point was placed closer to the monsoon climate indicator than to the interglacial climate indicator, at an Owens Lake chronology age of 403,970 years ago (see Figure 14). Comparison of the diatom record from MIS 11 and 1 (DTN: GS970708315121.001, GS991008315121.002) leads to a similar conclusion as that derived from the ostracode data.



DTN: GS970708315121.002, GS991008315121.001, GS000208315121.002

Figure 14. Stratigraphic Distribution of Ostracodes in Part of the Owens Lake Record Used for the Future Climate Analog

From the past/present point at Owens Lake, the timing of the climate change intervals is forecast on the basis of the abundance intervals for the ostracode species (DTN: GS970708315121.002, GS991008315121.001). The time between the sample in the *L. sappaensis* abundance peak 403,970 years ago and the first appearance of *L. bradburyi* is about 600 years in Owens Lake time, the length of modern-like climate remaining before the enhanced monsoon climate begins (Table 2). In turn, the length of the *L. bradburyi* interval of monsoon climate is about 1,400 years in Owens Lake time (this includes the interval above *L. bradburyi* containing abundant *L. sappaensis*) (Figure 14). The monsoon interval is followed by more than 8,000 years of glacial-transition climate represented by the *Candona caudata* interval, thus completing the 10,000 years for the future climate analog (Figure 14).

Table 2. Meteorological stations selected to represent future climate states at Yucca Mountain, Nevada

Climate State	Duration	Representative Meteorological Stations	Locations Of Meteorological Stations	
Modern Interglacial Climate	400 to 600 years	Site and regional meteorological stations	Yucca Mountain region	
Monsoon Climate	900 to 1,400 Years	Average Upper Bound:	North Latitude	West Longitude
		Nogales, Arizona	31° 21'	110° 55'
		Hobbs, New Mexico	32° 42'	103° 08'
		Average Lower Bound:		
		Site and regional meteorological stations	Yucca Mountain region	
Glacial Transition Climate	8,000 to 8,700 Years	Average Upper Bound:	North Latitude	West Longitude
		Spokane, Washington	47° 38'	117° 32'
		Rosalia, Washington	47° 14'	117° 22'
		St. John, Washington	47° 06'	117° 35'
		Average Lower Bound:	North Latitude	West Longitude
		Beowawe, Nevada	40° 35' 25"	116° 28' 29"
		Delta, Utah	39° 20' 22"	112° 35' 45"

The timing of the climate episodes noted above are based on the Owens Lake sediment mass-accumulation curve that was derived for the entire core. As discussed above the mass-accumulation curve gives an average chronology at best and in many places in the core the average accumulation rate of sediment may not be a good indicator of elapsed time. The average sediment-accumulation rate is about 40 cm per 1,000 years (Smith and Bischoff, 1997), and is the basis for the times listed in the paragraph above and in Figure 14.

The study by Litwin et al. (1999), which focuses on the upper part of the core, suggests that the sediment accumulation rates during dry climate periods are much higher than during wet climate periods. In Litwin et al. (1999) they estimate accumulation rates for interglacial, glacial, and transitions between interglacial and glacial climates. The future climate analog (MIS 11/10) deals with interglacial and glacial-transition climates. However, the part of the core that should be considered in terms of different accumulation rates is the interglacial, as the glacial-transition climates extend well beyond the 10,000-year limit discussed here. Litwin et al. (1999) estimate that interglacial climate sediment accumulation rates from MIS 1 and 5 are 60 and 66 cm per 1,000 years, respectively. These values provide an alternative accumulation rate for the interglacial periods in Owens Lake to the approximately 40 cm per 1,000 years mass-accumulation rate for the entire record.

The sediment accumulation rates for interglacial climates noted above average about 63 cm per 1,000 years. There is no way of knowing if the MIS 11 interglacial had a similar sediment accumulation rate, but given that the rates for MIS 5 and 1 are similar, it is reasonable to assume such a rate might apply to MIS 11. If the higher rate of sediment accumulation does apply, then the timing of climate change derived from it is more probable than that derived from a uniform rate of sediment accumulation. Applying a rate of 63 cm of sediment accumulation per 1,000 years to MIS 11 results in an alternative timing for the three climate states of:

1. Modern-like for about 360 years, rounded to 400 years,

2. Monsoon for about 895 years, rounded to 900 years, and

3. Glacial transition for about 8,700 years (10,000 minus 400 minus 900).

A modern-like or warmer than modern-like climate for about 1,300 years before entering a glacial-transition climate is similar to the estimate previously discussed (700 years) based on a comparison of precession and the Devils Hole record. It is also similar to Imbrie and Imbrie's estimate (1986, p. 183-184) that earth's climate should become progressively warmer for about the next 1,000 years due to an increase in solar output, and then begin to cool due to Milankovitch forcing.

Combining the above estimates for the timing of future climate change derived from the different estimates of sediment accumulation rates results in the following forecast for timing of climate changes. A modern-like climate should persist for about 400 to 600 years after present. The modern-like climate will be followed by a monsoon climate that will last from about 900 to 1,400 years after present and that climate will be followed by a glacial-transition climate that will persist through the remainder of the 10,000-year period at YM.

Other factors that may impact the timing of the three climate states include the standard deviation associated with the Devils Hole ages, the uncertainty of the exact time when the Devils Hole record implies climate is changing, the uncertainty of exactly where the past/present point is in the Owens Lake record (analog climate proxy record), and the uncertainty of climate change itself. The standard deviations about the mean of the Devils Hole ages are, by their nature, an estimate of uncertainty. That estimate was not incorporated into the analysis, in part, because the other sources of uncertainty can not be estimated and hence their relation to standard deviation is unknown.

The uncertainty of the exact time when the Devils Hole record is beginning to change implies climate has two components. The first component involves the uncertainty of knowing if the beginning of a change in the isotope values in the recharge area are directly correlated with changes in MAP and MAT or other climate parameters. There could be a lead or a lag between change in regional climate parameters and a record of recharge at Devils Hole. The second component involves the nature of the Devils Hole samples themselves. Each sample integrates a particular thickness of carbonate in a continuous sample series and represents about 1,000 years (Winograd et al. 1992). Consequently, any rapid change in the recharge recorded at Devils Hole could occur anytime within the 1,000 years.

Placement of the past/present point in the Owens Lake record is a matter of interpretation, and has an unknown level of uncertainty associated with it. Because this uncertainty could be large or small it may compound or limit the effects from obtaining time from the estimates of sediment accumulation.

The final source of uncertainty comes from the chaotic nature of the climate system itself (Stanhill 1999). The latter may be compounded with unknown effects of human activity on climate change. The climate proxy records throughout the Owens Lake cores show various degrees of variability that may well reflect decade- or century-scale variability that may or may not have significance to the timing of climate change on the multi-century or millennia time scales.

The above sources of uncertainty could sum together to create a large uncertainty or could cancel each other out so as to create a smaller uncertainty. Unlike the different estimates of sediment accumulation rates, there is no simple or objective way of assessing the nature of the above four sources of uncertainty as it might apply to the future.

6.6.2 The Nature of Future Climate Change

The nature or characteristics of future climate, but especially the annual and seasonal characteristics of precipitation and temperature, provide the input terms to the infiltration model (USGS 2000) whose output feeds the unsaturated zone flow and transport process model report (PMR). The nature of future climate, as discussed below, is forecast in terms of an upper bound and a lower bound. Upper- and lower-bound values are given here because: 1) they are needed for the models and 2) given the numerous uncertainties (Sections 6.3, 6.4, and 6.5) in the record of turning climate proxy data into climate values, establishing possible bounds is more defensible than establishing means, especially means that are applied to long periods of time. Because the infiltration model (USGS 2000) requires annual and seasonal climate values to run properly, the upper- and lower-bound values are established with meteorological stations, selected as representative of the climate. Stations with complete and long records were given priority.

The past climate history proposed as the timing for the future climate analog (Section 6.6.1) is composed of three climates, each characterized by particular species assemblages of ostracodes (DTN: GS970708315121.002, GS991008315121.001). When necessary, the ostracode assemblage interpretations are supported by interpretations of the diatom assemblages (DTN:

GS970708315121.001, GS991008315121.002). The modern-like climate interval is characterized by *Limnocythere sappaensis* and is forecast to persist for the next 400 to 600 years. The second climate interval is characterized by a mixture of *L. bradburyi* and *L. sappaensis* and is forecast to persist for about 900 to 1,400 years after the first climate interval. The third and last climate interval is characterized by *Candona caudata* as well as rare occurrences of *L. sappaensis*. The third climate interval also is characterized by the diatom *Stephanodiscus asteroides*, and diatom species belonging to *Campylodiscus* spp. and *Anomoeneis* spp., based on the data collected by J. Platt Bradbury (DTN: GS970708315121.001, GS991008315121.002), and is forecast to persist for the remainder of the 10,000-year period.

The modern-like climate interval is an interval of time when Owens Lake was supported by ground-water discharge, and an Owens River that was predominately at base flow. Summers are warm to hot and very evaporative with evaporation greatly exceeding precipitation at low elevation. Snowpack at high elevation is typically low to moderate, because the polar front does not remain fixed at a southerly position during the winter, and so does not set up a storm wave train that moves Pacific moisture over the Sierra Nevada Mountains (see discussion in Section 6.2). Consequently with low snowpack, surface-water flow in the Owens River is usually low and seasonal. Owens Lake remains saline and at a low lake level for long periods of time. Precipitation, whether as rain or snow, is typically recycled to the atmosphere by evaporation or used by the local vegetation.

The wettest years, which represent the upper-bound moisture regimes during modern-day climate, will typically be years when Pacific air flow is focused towards the high Sierra Mountains, increasing snowpack and hence the seasonal duration of surface-water flow in the Owens River and its potential to dilute or flush Owens Lake, thus diluting the salt content. Such climates also focus Pacific moisture towards southern Nevada, such as the El Nino climates that have been common during the last couple of decades. Dry years, which represent the lower-bound moisture regimes during modern-day climate, will be those years with minimal winter precipitation, typically years when the polar front remains largely north of the region and summer precipitation is dominated by subtropical high activity, but not to the degree necessary to generate a monsoon-type climate.

Meteorological data for the upper and lower bounds come from available stations in the region, including YM project and non-project data (see Figure 15, Table 2) (USGS 2000). Regional averaged meteorological data from the National Oceanic and Atmospheric Administration (NOAA) reported in Thompson et al. (1999c, Figures 16 and 17) indicate that areas largely north of YM within central Nevada have had a range of MAP from about 75 mm to one value as high as 360 mm for the period of record (about 100 years). Similarly, from the same data sets, areas largely south of YM have had a range of MAP from less than 50 mm to one value as high as 325 mm for the period of record. Notably, there are more low values than extremely high values, that is, the typical value is in the lower half of the range. By contrast, MAT in both regions falls into a smaller range of about 4 °C, or about 16 to 20 °C for the area south of YM and about 8 to 12 °C for the area north of YM (Thompson et al. 1999c, Figures 16 and 17).

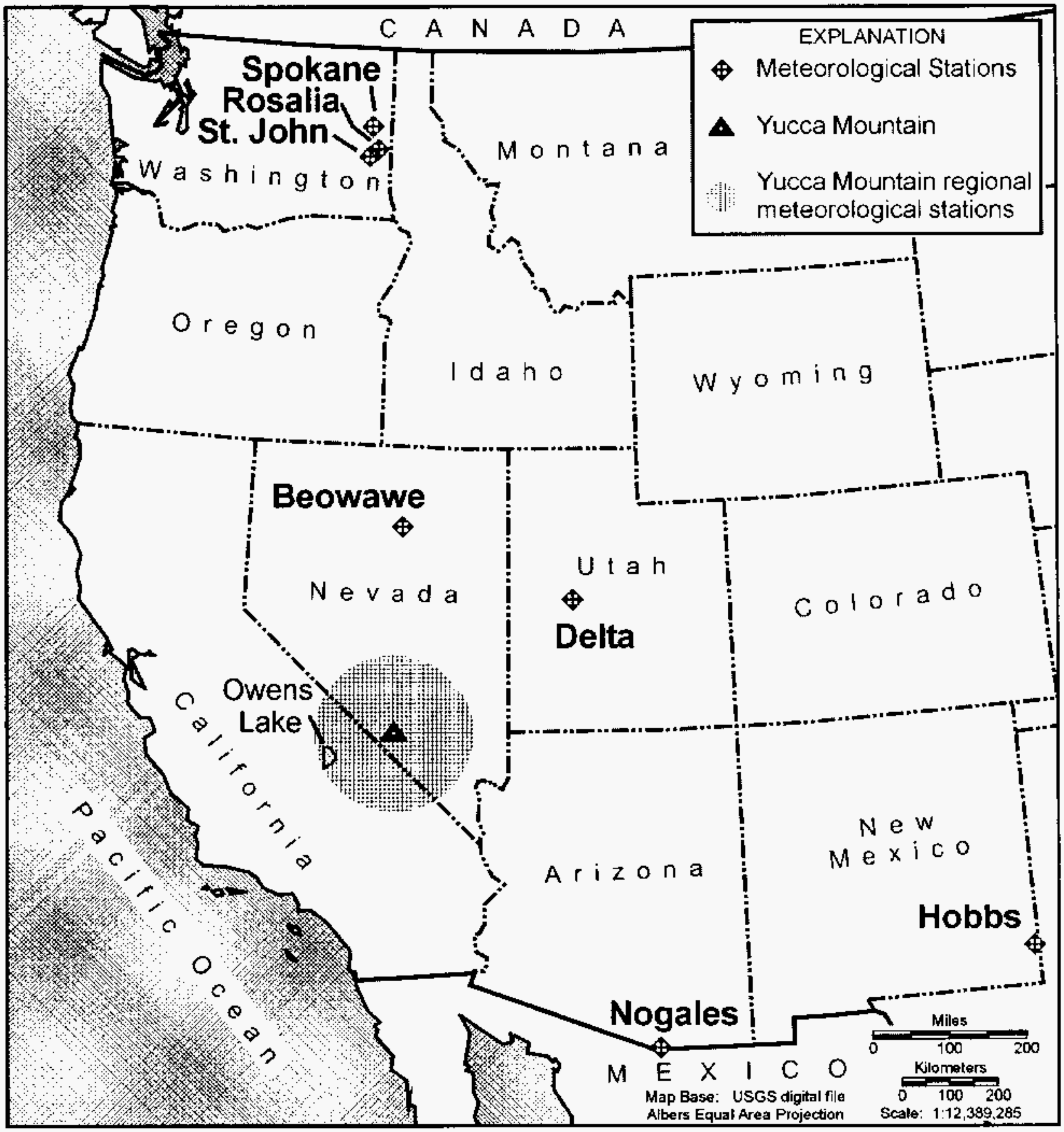


Figure 15. Meteorological Stations Selected (Table 2) to Represent Future Climate States at Yucca Mountain, Nevada

Because climate is a regional phenomenon and climate is the primary driver of hydrology, the climate that creates the environmental characteristics defined above for Owens Lake also must be more or less the climate that exists at Yucca Mountain. So a hot and dry climate at YM is consistent with a saline Owens Lake supported largely by base flow. Owens Lake hydrology therefore is a direct proxy for climate at YM.

The second climate interval, the monsoon climate, is characterized in the Owens Lake record by a mixture of *Limnocythere bradburyi* and *L. sappaensis* (DTN: GS970708315121.002, GS991008315121.001). Because *L. bradburyi* has a lower salinity tolerance than *L. sappaensis* (Forester 1983; Forester 1985) and does not appear to be tolerant of cold winters (Smith and Forester 1994), its existence in Owens Lake must imply a relatively lower TDS (less than about 10,000 mg/L) and a source water derived from something other than snow melt. Surface flow derived from snow melt itself probably is not a problem for *L. bradburyi*, but rather the cold winter climates that generate the snowpack are a problem for this species. The hydrology of Owens Lake is strongly linked to winter precipitation and hence dilute deeper lakes are due to seasonal to annual flow derived from snowpack (see Section 6.5). From Figures 12 and 13 as well as discussion in Section 6.5, an expansion and intensification of the summer rain system, that is a stronger monsoon sufficient to generate diluting surface flow in the Owens River, is the simplest way to explain the occurrence of this species. The diatoms that occur during the *L. bradburyi* interval include saline planktic species, implying the lake is deeper, and less alkaline during this period. The diatom paleoenvironment is consistent with that implied by *L. bradburyi*.

Accordingly, an analog meteorological station(s) for the *L. bradburyi* monsoon climate must be found to the south of Owens Lake today in either Mexico or the southernmost U.S. An analog from either Mexico or the southernmost U.S. would fulfill the taxon's temperature requirements and identify sites whose primary precipitation falls in the summer season. The level of precipitation has to be higher than modern-day Owens Lake MAP in order to maintain a lower salinity lake that is supported largely by summer precipitation within the modern warm evaporation regime. Summer rain and associated cloud cover would tend to lower evaporation relative to today. Historic records of MAP from Haiwee Reservoir 11 km south of Owens Lake show that summer rain dominated the annual precipitation during the years 1963, 1976, and 1977, with MAP levels amounting to 270 mm, 251 mm, and 208 mm respectively (U.S. Department of Commerce 1964; 1977; 1978). During those years flow in the Owens River was minimal, (CRWMS M&O 1998, Figure 4.2-15). So those levels of MAP were not sufficient to create the deeper and slightly saline lake that the ostracode and diatom proxies imply existed during the monsoon climate.

Considering the above climate conditions, the available meteorological data, and the region in which *Limnocythere bradburyi* occurs now, the station closest to the occurrence of the taxon in the U.S. is the one at Lordsburg, New Mexico with an MAP of 284 mm (DTN: GS000100001221.001). An MAP value of only 284 mm per year at Lordsburg is sufficient only to support an ephemeral playa and from the Haiwee Reservoir meteorological data above is less than values that resulted in limited flow in the Owens River. Sites in central Mexico where the taxon lives commonly have MAP values above 500 mm and as high as 2,000 mm (Forester 1985). Remarkably, despite the latter very high levels of MAP, the Mexican lakes in which the taxon lives are typically shallow, if not ephemeral, and slightly saline, reflecting the very high levels of evaporation. Presumably the *L. bradburyi* regions in central Mexico would be poor analogs for Owens Lake, because these lower latitude sites have a much higher solar input, thus creating a different climate-lake-evaporation regime than would have existed at Owens Lake in the past.

Selection of a monsoon climate analog site(s) must then come from the southern U.S. An upper-bound value for the monsoon climate presumably must be a higher value than any of the values from Haiwee Reservoir, and MAT must remain as high or higher than Owens Lake today. Within the region in the U.S. that experiences a strong summer monsoon and where *Limnocythere bradburyi* lives, there are two meteorological stations with long, complete records that have consistently higher levels of MAP than Haiwee Reservoir: the station at Hobbs, New Mexico and the station at Nogales, Arizona, with MAP levels of 418 mm and 414 mm, respectively (DTN: GS000100001221.001). Two stations are selected to minimize the influence of local meteorological phenomena on the input to the infiltration model (USGS 2000) (Figure 15, Table 2). The MAP at these sites may not be high enough to generate the appropriate lake in the Owens Basin, but within the available modern meteorological data, these are the best choices available. Because *Limnocythere sappaensis* exists throughout the climate interval and at some horizons is the only ostracode (DTN: GS970708315121.002, GS991008315121.001), the conditions at YM today are representative of the dry lower bound for the monsoon climate. The meteorological stations selected for the lower bound for the monsoon climate are those from the YM region today (USGS 2000).

The monsoon climate, from the analogs, is a climate where winter precipitation exists, but does not dominate MAP. The lesser importance of winter precipitation means that winter air masses are also of less importance, and thus the winter season is likely warmer than today and hence more evaporative. The annual transition from the winter season to the wet summer season would be hot and dry as is true of most seasonal transitions to a monsoon climate. Summer rain would then expand northward either due to a monsoon land-to-ocean circulation or to the northward migration of the subtropical easterlies, that is, the trades. Intense summer rain, unlike today, would be sufficient to sustain flow into Owens Lake to maintain a moderate-sized and slightly saline lake at least on a seasonal basis. Climate during this period would vary from episodes of intense summer rain to modern-like climates with relatively more winter and less summer precipitation. The intense summer rain periods would necessarily be periods with extensive cloud cover whereas summers with lesser rain and winter seasons would have limited cloud cover.

An expansion of the summer rain regime to the Owens Basin region also would have expanded well north of YM (Figure 13). Because YM would be more centrally located within such a summer rain regime it may experience upper-bound levels of MAP that are higher than those identified above from the analog meteorological stations.

The third climate, the glacial-transition climate, is characterized by the appearance of *Candona caudata* (DTN: GS970708315121.002, GS991008315121.001) as well as by the diatom *Stephanodiscus asteroides*, and diatom species belonging to *Campylodiscus* spp. and *Anomoeneis* spp. (DTN: GS970708315121.001, GS991008315121.002). The change from the monsoon climate to the glacial-transition climate is rapid, assuming no unconformities in the Owens Lake record, occurring within 100 to 200 years (Smith and Bischoff 1997). The magnitude of the climate change was as large as it was fast, shifting from a strong monsoon system dominated by summer precipitation to a winter regime with sufficient effective moisture to sustain a fresh and spilling Owens Lake.

Candona caudata lives in the Owens Lake area today as well as in many places north of Owens Lake including sites within Canada and Alaska. In the Owens Lake area it lives in the Owens River as well as in freshwater lakes at higher elevation, and thus is tolerant of the region's seasonal temperature variability, but is not tolerant of saline water that would be typical for Owens Lake today under natural conditions. *Candona caudata* only enters Owens Lake when the TDS falls and remains below about 3,000 mg/L (Bradbury et al. 1989), and that typically implies the lake is full and spilling. The presence of *Stephanodiscus asteroides*, a cool and freshwater planktic diatom (DTN: GS970708315121.001, GS991008315121.002), also implies a deep spilling lake. Conversely, the sporadic appearance of *Limnocythere sappaensis* (DTN: GS970708315121.002, GS991008315121.001) as well as the diatoms *Campylodiscus* spp. and *Anomoeneis* spp. imply there were also episodes during this climate period that were relatively warm and dry, thus demonstrating some degree of climate variability.

As described above (Section 6.5), for the lake to be full and spilling the polar front must be resident in the region during much of the winter, both lowering MAT and hence evaporation, and increasing snowpack, and hence surface flow to the lake. The genesis of greater snowpack with a resident polar air mass must also lower MAT and increase MAP at YM. The cooler climate, however, never becomes very cold with a high effective moisture as was true of the last two full-glacial periods. The ostracodes and diatoms implying warm dry climates do not persist throughout the Owens Lake record thus indicating the warmth is not seasonal summer warmth, as is true of the modern climate, but rather represents warm episodes within a generally cool and wet period. The climate during the glacial-transition period was typically a cool, usually wet winter season with warm (but not hot) to cool summers that were usually dry relative to the modern day summers.

Selecting upper- and lower-bound meteorological stations for the glacial-transition climate must identify sites with cool winter wet seasons, and warm to cool and dry summers, so areas north of the summer rain regime shown in Figure 13. Further, if possible, the analog sites should lie on the east side of large mountain ranges, and hence in the rain shadow of those ranges. The absence of *Cytherissa lacustris*, (DTN: GS970708315121.002, GS991008315121.001) the ostracode implying cold Canadian-like climate, implies the upper-bound analog lies within the contiguous U.S.

The analog station(s) presumably should be areas with some or all of the common ostracodes and diatoms found in Owens Lake (DTN: GS970708315121.002, GS991008315121.001, GS970708315121.001, GS991008315121.002), thus potentially integrating the biology, hydrology, and climate linkages that were expressed in the past at Owens Lake. The study by Thompson et al. (1999c) suggests the MAT at YM during the last full-glacial period was about 8°C and during that period *Cytherissa lacustris* was common in Owens Lake. Thus the MAT for the glacial-transition climate should be no colder than and preferably warmer than 8°C. Finally, the analog station(s) should be in the semi-arid west, because, although the glacial-transition climate is wetter and cooler than the interglacial climates, effective moisture is still negative, as is true for all of the glacial and glacial-transition climates at Owens Lake and YM.

The meteorological station(s) representing the glacial transition upper bound should be in a place with a higher MAP than periods of high Owens Lake discharge derived from winter precipitation during the historic period. One of the highest discharge years for the Owens River (CRWMS

M&O 1998, Figure 4.2-15) was in 1969 and the MAP at Haiwee, just south of Owens Lake, was 309 mm (U.S. Department of Commerce 1970). Surface flow in the Owens River is primarily influenced by snowpack in the Sierra Mountains, not by high winter MAP near Owens Lake, unlike times of high summer MAP when surface flow is dominated by summer rain. Nonetheless, high snowpack years also correspond to high MAP from winter precipitation at Owens Lake (Forester et al. 1999; CRWMS M&O 1998, p. 4.2-16 to 4.2-18). Accordingly, the upper-bound meteorological site(s) should have higher MAP than 309 mm, because even the high historic discharge levels are not sufficient to fill and spill the lake as implied by the diatoms and ostracodes. Because the fill and spill of Owens Lake is believed to be related to the seasonal, if not the annual, residence of the polar front (see Section 6.2), then the upper-bound meteorological station should logically be selected in an area where in today's climate the polar front resides through most or all of the winter season and where its average position resides most of the year.

Given all of the above qualifying conditions, the upper-bound glacial-transition meteorological site is selected in the northwestern U.S. east of the Cascades for several reasons. The region lies east of a high mountain range, and thus falls within a rain shadow as does YM. The regional MAP is winter-precipitation dominated, and is under the influence of the polar front during the winter as well as being situated near the average position of the polar front throughout the year. Furthermore, unlike localities farther north in Canada, the region does not experience extended dominance by the very cold Arctic high-pressure air, typical of the cold, full-glacial periods. A number of meteorological stations in the region have MAP values well above 300 mm (U.S. Department of Commerce 1970), which in today's temperature regime in the Owens Basin only supports a saline lake. The regional values of MAT are on the cool side, but several stations are above the 8°C values considered to be a lower limit for the glacial-transition climate (Thompson et al. 1999c). The diatoms and ostracodes common to the glacial-transition interval in Owens Lake are known to live in lakes in the region such as Sprague Lake, Washington. Thus lakes in the region contain a common biology, hydrology, and climate linkage with the paleolake in the Owens Basin.

Examination of the meteorological station data from eastern Washington (DTN: GS000100001221.001) both in the context of the above considerations and in terms of length and completeness of record provides three stations that fit all of the criteria for the upper-bound glacial-transition climate (see Figure 15, and Table 2). The stations, Spokane, Rosalia, and St. John, are all close to each other, but do not have identical records, presumably reflecting local differences in MAP and MAT. As in other cases, selecting multiple meteorological stations is intended to minimize local effects on the climate parameters used as input to the infiltration model (USGS 2000).

The meteorological stations representing the lower-bound glacial-transition climate should be in a place where MAT is higher than for the upper bound and thus most will be south of the upper-bound localities. The MAT should, however, be lower than that for the Owens Lake Basin today so that effective moisture levels are higher consistent with a fill and spill lake. The stations should have a lower MAP than the upper-bound sites, because the record from the Owens Lake Basin shows episodes when either saline diatoms or ostracodes or both are present implying less surface flow in the Owens River. The absence, however, of abundant saline taxa implies effective moisture is higher than modern day and that likely reflects cooler than modern-day MAT values rather than high MAP values. So the lower-bound meteorological sites may have

MAP values that are similar to or even lower than modern-day Owens Lake Basin. As with the upper-bound meteorological sites, the region should be winter precipitation dominated, should be north of the summer rain regime (Figure 13), and have some or all of the ostracode or diatom species found in the fossil record at Owens Lake.

Inspection of meteorological sites that fit these conditions reveals that there are few choices available. The one set of meteorological data that fits all of these criteria and also has a long and complete record is found at Delta, Utah (DTN: GS000100001221.001), and thus that site is selected as one of the lower-bound sites (Figure 15, Table 2). The site at Beowawe, Nevada (DTN: GS000100001221.001), was added as a lower-bound meteorological station, again to avoid the potential of using a single site for input into the infiltration model (USGS 2000) (Figure 15, Table 2), because its meteorological data meet most of the requirements noted above.

The upper-bound MAP values for the monsoon and the glacial-transition climates are only slightly higher than the modern high values from the region. Thompson et al. (1999c) show the NOAA data for region 3, generally north of YM, and region 4, generally south of YM. The latter data show upper-bound values in the mid-300's of mm and numerous values in the low 300's of mm. Thus selection of meteorological stations having upper-bound values in the low 400's of mm implies that the future climate states are only somewhat wetter than the modern climate. The lower-bound MAP value, selected as a future climate analog for the glacial-transition climate, is much higher than the modern lower-bound values reported for regions 3 and 4 (see Thompson et al. 1999c). Similar to the lower-bound glacial-transition value for MAP, the values of MAT for the glacial-transition analog climate are much lower than the MAT values in the YM and Owens Lake region today (Thompson et al. 1999c and DTN: GS000100001221.001). Thus the apparent principal differences between the modern-day climate and the glacial-transition climate upper and lower bounds are that the latter climates are not as dry nor as warm as modern day, that is, the biggest differences from today are in the lower-bound values, not the upper-bound values. MAT and its impact on evaporation and hence on effective moisture would seem to affect the future climate analog more than gains in MAP.

7. CONCLUSIONS

The analysis of future climate change in this AMR consists of examining the paleoclimate record in order to find a past climate sequence on which to base extrapolation of future climatic conditions in the Yucca Mountain region. Four key assumptions are discussed:

1. Climate is cyclical over 400,000-year periods and the earth is at the beginning of the next 400,000-year cycle. Climate cyclicity is important for forecasting future climate because it implies some past climate or aspects of past climate will recur in the future.
2. Climate change can be timed with an earth-orbital clock of precession and eccentricity, so the timing of future climate change can be estimated from the orbital clock. Timing climate change with a clock that can be set accurately in the future is important for forecasting climate, because it allows for an accurate assessment of future climate durations used as input by TSPA and infiltration (USGS 2000) models. Cycles of glacial and interglacial climates occur about every 100,000 years.
3. Past glacial/interglacial climates differ from each other, and the nature of particular past climates should repeat themselves in a predetermined order. Thus the analysis can focus on one particular climate sequence rather than all past climates and need not take the conservative approach of using the climates that generate the highest infiltration as being those expected in the next 10,000 years.
4. Long-term earth-based climate-forcing functions, such as tectonic change, have remained relatively constant over the past 500,000 years or so and will remain constant for the next 10,000 or more years. This is important to climate forecasting because such forcing functions change climate in non-cyclic ways, so if they were not constant the first three assumptions would be invalid.

From the discussion of the above four assumptions, which are intended to establish a defensible means for climate forecasting, the Owens Lake climate record is used to describe the climate conditions of the interval selected as the past/future climate analog. The past/future climate analog shows three distinct climates each of which are described in terms of an upper-bound and a lower-bound climate value. The upper and lower bounds of each climate are described from what are believed to be representative analog meteorological stations (Figure 15, Table 2) and the data at those stations then serve as input to the infiltration model (USGS 2000). Although other stations might have been selected as more representative of the upper and lower-bound climate conditions, it is more likely that the way the climate interpretations are used by the infiltration model impacts the amount of infiltration more than differences between particular meteorological stations would impact the amount of infiltration.

The past/future climate analog forecasts that during the next 10,000 years at YM the modern-day climate should persist for 400 to 600 years, followed by a warmer and much wetter monsoon climate for 900 to 1,400 years, followed by a cooler and wetter glacial-transition climate for the remaining 8,000 to 8,700 years. The range of ages represents uncertainty in the sediment accumulation rates in Owens Lake during the climate analog period.

The upper-bound precipitation values for the monsoon and glacial-transition climates exceed the upper bounds of the region's modern-day climate (see Thompson et al. 1999c, Figures 16 and 17) by about 100 mm. The glacial-transition climate's lower bound exceeds the modern lower-bound values by about 150 mm (see discussion Section 6.6.2). Thus the future climate based on this method of analysis is wetter, but not substantially wetter than the modern climate. Temperature, however, defines an important difference between the modern climate and the glacial-transition climate. The glacial-transition climate is cooler than the modern climate, so evaporation is substantially lower than during modern times. A lower level of evaporation means that precipitation will be more readily stored, and hence available for infiltration, than in today's climate.

Forecasting future climate was selected rather than modeling future climate because climate modeling, among many complications, requires that the future climate boundary conditions be known for input to the model. If the future climate boundary conditions were known with confidence, then there would no longer be the need to model climate or the need would be diminished. Because future boundary conditions are not known, a climate model must either use the modern-day values or estimates of the future values and in either case, the value of the output from such a model would have limited value in terms of defensibility.

Forecasting the future by using a past climate sequence to bound the future also has many uncertainties, such as 1) differences in the selection of a particular past sequence to forecast the future, 2) the chaotic nature of climate (Stanhill 1999), and 3) the possibility that human activity may change the climate system in a way that will change the cyclical patterns. Therefore, in this analysis, the rationale for a particular past climate is described, and the method is then applied to acquire possible future climate values. Nonetheless, other arguments can be made for using other past climate sequences as an analog for the next 10,000 years. Like the one presented in this AMR, these other arguments would have evidence to support them. Uncertainties associated with the potential for forecasting future climates with different past climates is a consequence of the uncertainty of future climate itself, and of the uncertainty associated with depicting future climate by extrapolation of particular past climates into the future. Because there are many past climates that may or may not repeat in the future, and because forecasting is extrapolation, the future climate forecasts given in this AMR, or any other forecast, must by their very nature have some substantial, but indeterminate, level of uncertainty associated with them. Similarly, if climate is wholly chaotic, then it might not be cyclic and so the past might not provide a basis to understand the future. Human activity might enhance chaotic behavior within the climate system. Despite all of the uncertainties, it is contended that the analysis in this AMR is reasonable, that it is based on a consistent interpretation of available data, and so is defensible. That is, defensible in the sense that the analysis is based on a body of data and a reasonable possibility rather than that the climate forecast by this analysis is much more likely to occur relative to other possible methods. There are no other uncertainties than those discussed, and there are no limitations on the use of the analysis.

Although the data sets used in this analysis are listed currently as TBV, no impacts on the analysis are expected after the TBV status is revised. Five of the data sets were developed by USGS (DTN: GS970708315121.001, GS970708315121.002, GS991008315121.001, GS991008315121.002) and are expected to have full Q status following reverification. The four remaining data sets (DTN: GS000100001221.001, GS000200005121.001, GS000200005121.002, GS000200005121.003) have been designated Accepted Data per AP-SIII.2Q. No impacts of TBVs on the analysis are expected.

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GS000200005121.003. Radiometric Dating and δ18O Data from Devils Hole, Nevada.