High-Resolution Record of Climate Change in the Owens Lake Basin, California, for the Period 52,500 to 12,500 YBP

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Abstract: High-resolution ^{18}O and total inorganic carbon (TIC) studies of cored sediments from the Owens Lake Basin, California, indicate that Owens Lake was hydrologically open (overflowing) most of the time between 52,500 and 12,500 ^{14}C YBP. Desiccation of Owens Lake occurred between <15,500 and 13,700 ^{14}C YBP. Poor correspondence of ^{18}O and TIC variability in the time intervals 52,500 to 40,000 and 26,000 to <15,500 ^{14}C YBP indicates the occurrence of glaciation in the Sierra Nevada. Comparison of the Owens Lake δ^{18}O record and the lithic record of North Atlantic core V2381 indicates some degree of association. However, there does not appear to be any clear and simple relationship between iceberg discharge in the North Atlantic and variation in the hydrologic balance of Owens Lake. Numerous millennial-scale oscillations in the hydrologic balance of the Owens Lake surface-water system are absent from North Atlantic lithic and temperature records. The lack of a strong correspondence between North Atlantic climate records and the Owens Lake δ^{18}O record has two possible explanations: (1) the sequence of large and abrupt climate change indicated in North Atlantic records is not global in scope and is largely confined to the North Atlantic and surrounding areas, or (2) Owens Lake is located in a part of the Great Basin that is relatively insensitive to the effects of climate perturbations recorded in the North Atlantic region.

Introduction

Evidence for rapid oscillations in air and water temperatures during the last glacial period has been recognized in ice-core records from Greenland (Dansgaard *et al* 1993; Grootes *et al* 1993; Taylor *et al* 1993) and in sediment cores from the North Atlantic (Heinrich 1988; Bond *et al* 1992; Bond and Lotti 1995). The most recent Dansgaard-Oeschger cold event, the Younger Dryas, has also been documented in pollen records from western Europe, Maritime Canada, and southern New England and may be represented in pollen records from the Pacific Northwest (Wright 1989; Peteet 1995 and references therein). Layers of lithic fragments have been found in sediment cores from the North Atlantic. The thickest and most widespread of these layers (Heinrich layers) are rich in ice-rafted carbonate-rich debris and appear to be linked to the dynamics of the Laurentide ice sheet via iceberg discharge into the North Atlantic (Bond et *al* 1992; Bond and Lotti 1995; Broecker 1994; Andrews and Tedesco 1992; Broecker *et al* 1992; Andrews *et al* 1993). Five of the last six Heinrich events occurred at the end of progressive decreases in sea surface temperature and were followed by rapid increases in temperature (Bond *et al* 1993). Thus, Dansgaard-Oeschger cycles and lithic events are

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thought to be associated with major oscillations in atmospheric and sea-surface temperatures.

The causes and global extent of these climatic perturbations are not clear. Several authors have attempted to link proxy records of climate change from central China, the southeastern and western United States, the Chilean Andes, and New Zealand with Dansgaard-Oeschger cycles or Heinrich events (Porter and Ahisheng 1995; Grimm *et al* 1993; Allen and Anderson 1993; Phillips *et al* 1994; Clark and Bartlein 1995; Lowell *et al* 1995). Many of these studies lacked the resolution or age control to demonstrate unequivocally that climatic perturbations in the study areas were synchronous with North Atlantic climatic oscillations. In this paper, we compare a well-dated high-resolution proxy record of variation in the hydrologic balance of Owens Lake, California, with the timing of North Atlantic lithic events to examine whether abrupt changes in the hydrologic balance of a western Great Basin lake were synchronous with abrupt climatic oscillations in the North Atlantic region.

Climate and Hydrology of the Owens Lake Basin

Owens Lake is in the western part of the Great Basin at the southern end of Owens Valley, which lies between the central Sierra Nevada on the west and the Inyo-White mountain ranges on the east (Figure 1). During the historical period, Owens Lake was a hydrologically closed (endorheic) system. Consumptive use of water from the Owens River system began about 1870 (Lee 1912). At the time the Los Angeles aqueduct was completed in 1913, Owens Lake was about 10 meters deep (surface elevation about 1091 meters) and had a surface area of about 260 km^2. By about 1930, the lake had desiccated as the result of diversion of surface flow to the Los Angeles aqueduct (LADWP 1976).

Cool-season precipitation from North Pacific sources is dominant throughout the central Sierra Nevada. The paths of westerlies bringing moisture-laden air from the Pacific Ocean is an important determinant of the hydrologic balance of Owens Lake. The progression of maximum precipitation along the western flank of the Sierra Nevada is associated with southward movement of the mean position of the polar jet stream (Riehl *et al* 1954; Horn and Bryson 1960; Pyke 1972). A tendency for precipitation maxima to concentrate near the axis of the jet stream and for precipitation to decrease rapidly south of the axis and less rapidly north of the axis has been observed (Starrett 1949). During July and August, the westerlies weaken, and Pacific storm tracks move north of the Sierra Nevada. During this warm season, the Owens Valley receives only a small amount of moisture in the form of convective storms that originate in the Gulf of California. Because of the orographic effect of the Sierra Nevada, about 99% of the runoff reaching the Owens Basin originates in this mountain range (Hollett *et al* 1991).

Rock Types in Owens Lake Catchment Areas

The Sierra Nevada west of Owens Valley is composed of granitic and metamorphic rocks, and the Inyo-White mountains to the east are mostly composed of granites and sedimentary rocks (Hollett *et al* 1991 and references therein). Carbonate, in the form of calcitic marble, makes up fs20 % of Sierra Nevada bedrock in the Owens River drainage (Bateman 1965). Historically, little dissolved carbonate entered the Owens River from the arid Inyo-White drainage. In addition, the western drainage of

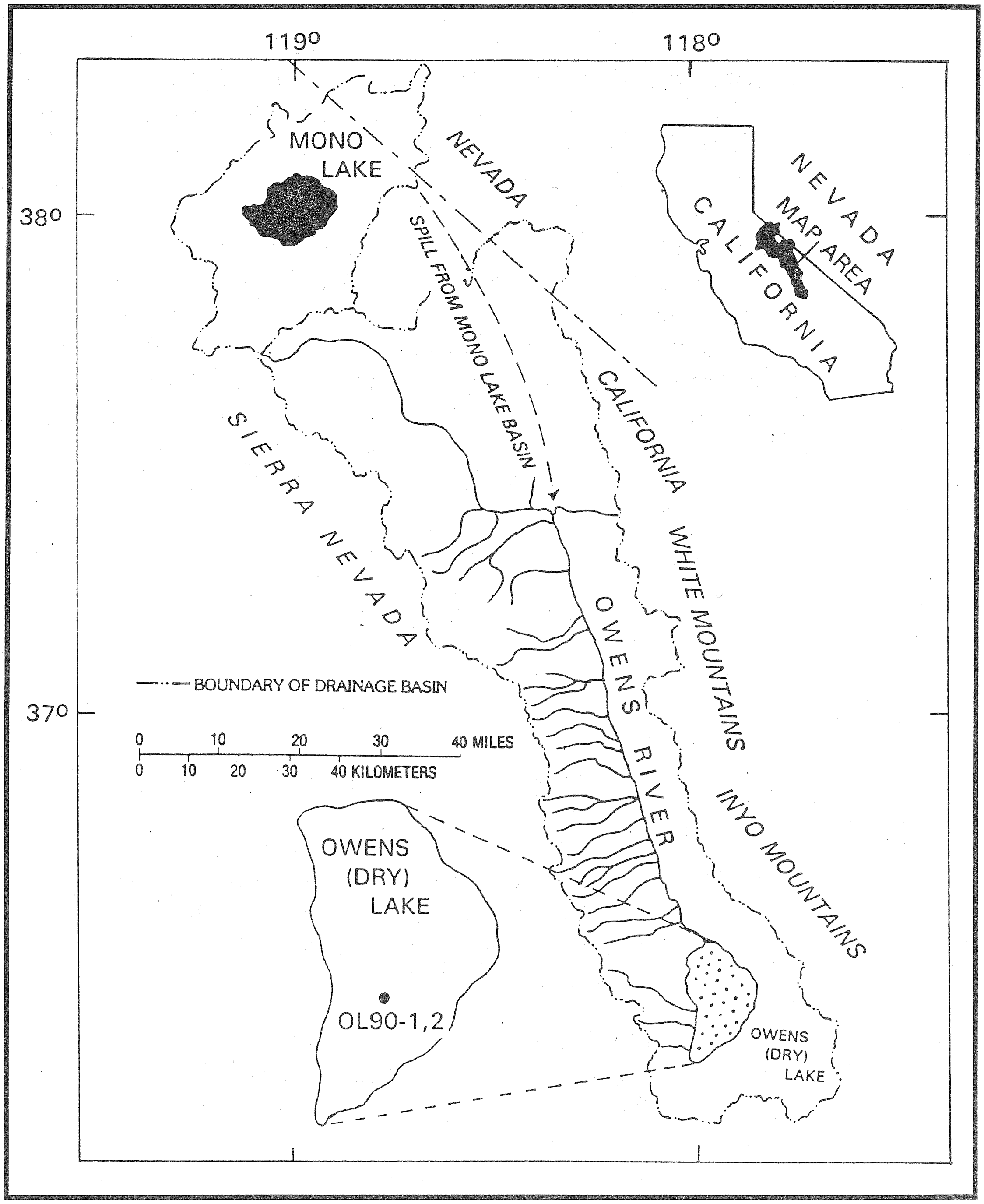

Figure 1 Location map of the Mono and Owens Lake basins.
Mono Lake is not thought to have spilled to the Owens Lake basin during the past 100,000 years.

the Inyo-White mountains appears to have remained unglaciated during the Wisconsin period (A.R. Gillespie and F.M. Phillips, personal communication, 1996). This suggests that little or no detrital carbonate was transported from the Sierra Nevada and Inyo-White mountains to the Owens Lake basin during past glaciations and that the Owens River contained little dissolved carbonate derived from the dissolution of carbonate bedrock.

Methods

In 1990, sediment cores OL90-1 (28.20 m) and OL90-2 (32.75 m) were obtained from the Owens Lake basin (Figure 1) using a truck-mounted split-spoon corer. The cores were stored in a refrigerated facility after collection. Age control for OL90-2 is based on 26 AMS ^{14}C determinations made on the total organic carbon (TOC) fraction of cored sediment (Figure 2). AMS radiocarbon dates were determined at the Lawerence Livermore National Laboratory Center for Accelerator Mass Spectrometry on bulk organic matter. Small aliquots of sediment (20-50 mg) were rinsed several times in an ultrasonic bath with deionized water to remove salts and also with 0.1N HCl to remove soluble carbonate from the sediment. The samples were then dried at 50°C in a vacuum oven. The procedure used for oxidation of bulk organic matter in pretreated sediment and subsequent reduction of CO_2 to filamentous graphite for AMS assay is described in Vogel *et al* 1987. Because carbonates make up <1% of the Sierra Nevada catchment area, we believe that the $^{14}C/C$ ratio of Owens River water approached the $^{14}C/C$ ratio of atmosphere CO_2 in the past; *ie*, the reservoir effect was small.

An age model for OL90-2 was obtained by fitting a second degree polynomial to the ^{14}C age-depth data (Figure 2). The ^{14}C chronology for OL90-1 was first obtained by correlating magnetic susceptibility peaks in OL90-1 and OL90-2 (Figure 3) and then using a correlation plot (Figure 4) to calculate an equivalent OL90-2 depth for OL90-1 samples. The ^{14}C age-depth polynomial for OL90-2 was then applied to OL90-1 samples. The Laschamp geomagnetic excursion, which has a K-Ar age of 46,600 ± 2400 cal YBP (Levi *et al* 1990 and references therein), was found at a depth of 28.0 meters in OL90-1 (Steve Lund, unpublished data). Our age model yields a ^{14}C age of 44,900 YBP at this depth. This is equivalent to a calendar age of 48,800 YBP (Edouard Bard, unpublished data).

About 650 sediment samples from the two cores were analyzed for $\delta^{18}O$ and TIC. Because carbonate makes <1% of the Sierra Nevada catchment area, we believe that detrital carbonates did not make up a significant part of the carbonate used in stable isotope analyses. The cores were sampled continuously except for the 5.36- to 16.00-meter interval of OL90-2. In this sediment interval, 1 centimeter was skipped between 2-centimeter-long samples. Each sediment sample (which integrates between 20 and 100 years of record) was suspended in 40 milliliters of distilled-deionized water, centrifuged at 15,000 rpm, and the salty supernatant decanted. This procedure was repeated until conductivity of the supernatant was less than 3 times tap water. The samples were then freeze-dried and homogenized.

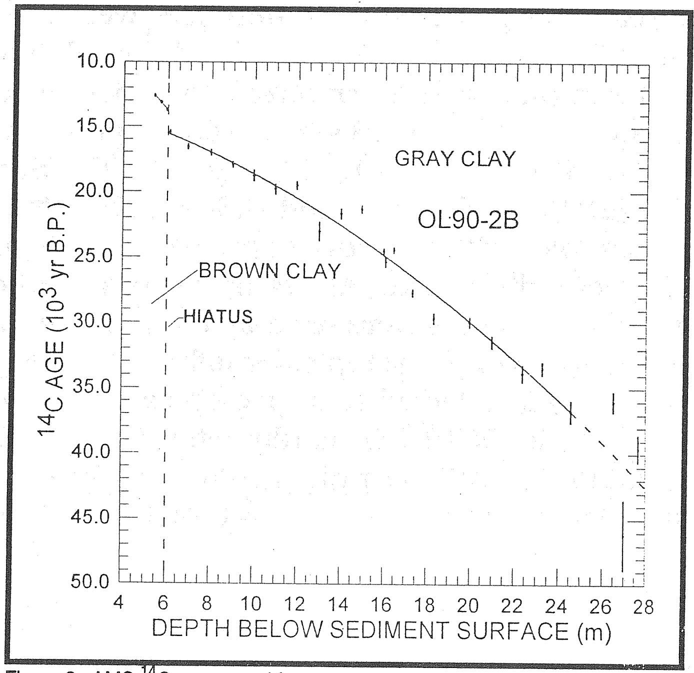

Figure 2. AMS ^{14}C age control for core OL90-2. The ^{14}C age polynomial was not fit to samples from depths greater than 25 meters.

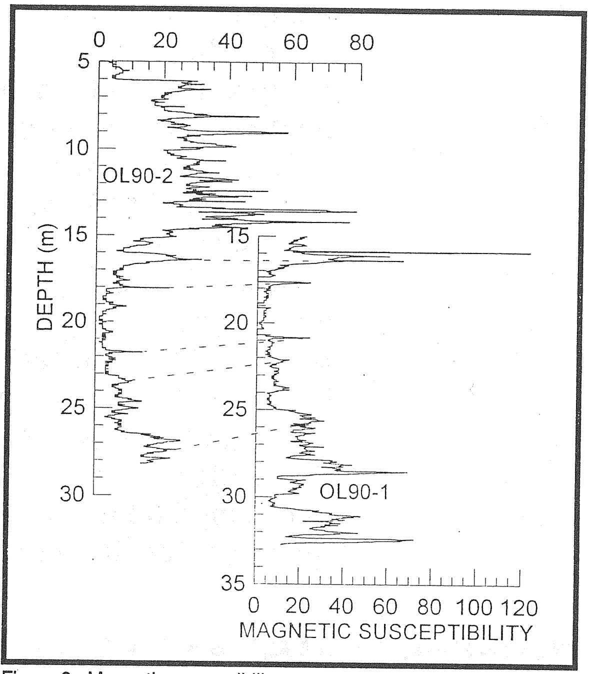

Figure 3. Magnetic susceptibility records for cores OL90-2 and OL90-1. Dashed lines indicate method of peak-to-peak correlation between these two records.

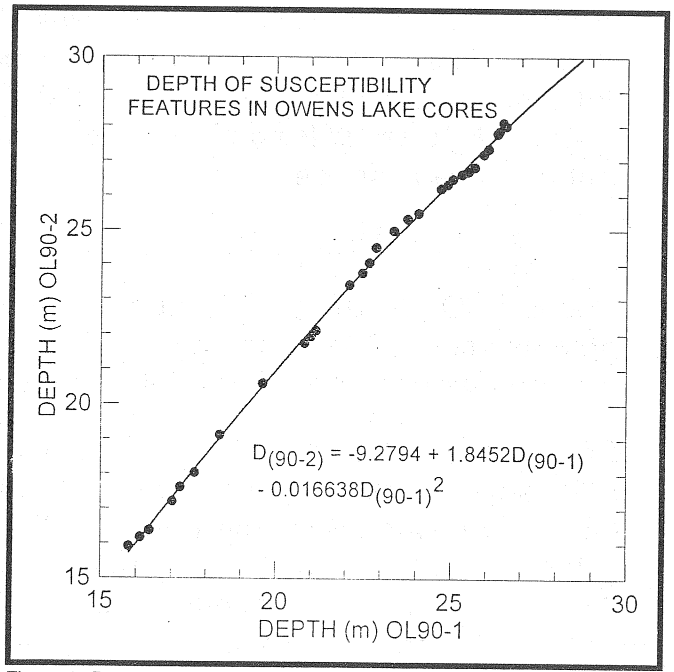

Figure 4. Depth-depth polynomial fit to susceptibility features in cores OL90-2 and OL90-1.

The ^{18}O values of the TIC were obtained in the following manner. Bulk samples were roasted in *vacuo* at 380°±10°C for 1 hour. Each sample was reacted individually for 10 minutes at 75°C. Evolved CO_2 was purified on a Kiel Automated Carbonate Extraction Device[1], introduced directly into a Finnigan MAT 251 triple collecting mass spectrometer, and analyzed for stable carbon and oxygen isotopes. Isotopic ratios of the samples were compared to a standard reference gas, and the differences were reported in standard delta notation (Craig 1957) vs. VPDB and VSMOW. Isotopic compositions of analyzed samples were normalized to a best-fit curve derived from repeated analyses of three NBS standards. Reported precisions were ±0.07‰ for $\delta^{13}C$ and ±0.10‰ for $\delta^{18}O$. Sample reproducibilities were 0.22±0.29‰ for $\delta^{13}C$ and 0.34±0.37‰ for $\delta^{18}O$ (103 samples). Data from samples with transducer pressures <150 µ and sample voltages <0.5 V were discarded. All samples that indicated anomalously high or low isotopic values were rewashed and rerun. A low isotope (^{18}O:^{16}O) ratio is referred to as isotopically light (more negative $\delta^{8}O$ value); a high isotope ratio is referred to as isotopically heavy. TIC was measured using a UIC Model 5012 CO_2 coulometer. Sample reproducibility was 0.015±0.012%C (27 samples). TIC analyses were performed on OL90-2 samples between 5.36 and 14.0 meters before and after the desalting process.

Variation in δ18O and TIC with Change in Hydrologic State and Balance

In terms of hydrologic state, a lake is either closed (endorheic) or open (overflowing). When Owens Lake is closed, the isotopic value of lake water at any instant represents a balance between isotopically light water entering the lake as inflow and on-lake precipitation ($\delta^{18}O_{d+p}$) and isotopically light water leaving the lake as evaporation. When hydrologic and isotopic steady states are achieved,

$$\delta^{18}O_L = \delta^{18}O_{d+p} - 10^3 \ln \alpha_{w->v}$$

where $\delta^{18}O_L$ is the $\delta^{18}O$ value of lake water and $10^3\ln \alpha_{w->v}$ is the time-averaged ^{18}O fractionation factor between liquid water (w) and water vapor (v) (Benson and White 1994; Benson *et al* 1996).

Data for $\delta^{18}O_{d+p}$ and $10^3\ln \alpha_{w->v}$ are not available for the existing Owens Lake surface water system; however, values of these two variables exist for surface water systems north of Owens Lake; for example, the $\delta^{18}O$ values of streams that flow into Mono Lake average about −16‰ (unpublished data of W.P. Patterson and C.N. Drummond); and $10^3\ln \alpha_{w->v} \approx -14$‰ for waters evaporating from Pyramid Lake, Nevada (Benson and White 1994). Therefore, $\delta^{18}O_L \approx -2$‰ during hydrologic closure, when

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[1] Use of tradenames in this paper does not imply endorsement by the U.S. Geological Survey.

hydrologic and isotopic steady states are achieved. This value is an approximation, valid only for the present-day climate, because the fractionation factor ($10^3 \ln \alpha_{w->v}$) is a function of relative humidity, the fraction of advected air in the boundary layer that overlies the lake, and the $\delta^{18}O$ value of advected air (Benson and White 1994). Values of these parameters in the late Wisconsin differed from present-day values. The above calculation indicates, however, that when a hydrologically closed Great Basin lake approaches an isotopic steady state, it becomes enriched in the heavy isotopes of oxygen.

When inflow (discharge) and on-lake precipitation (V_{d+p}) exceed evaporation (V_e), lake level rises and $\delta^{18}O_L$ decreases; when $V_e > V_{d+p}$, lake level declines and $\delta^{18}O_L$ increases until an isotopic steady state is achieved. The rate of change of $\delta^{18}O_L$ is a function of the rate of change in lake volume (V_L); the greater the rate of change in V_L, the greater the excursion in $\delta^{18}O_L$. Only large and rapid shifts in the hydrologic balance are recorded in the $\delta^{18}O$ values of carbonates precipitated from open waters of Owens. When Owens Lake overflowed, $\delta^{18}OL$ was primarily a function of the outflow:inflow (V_o:V_{d+p}) ratio (Benson *et al* 1996). Decrease in $\delta^{18}O_L$ accompanied increase in V_o:V_{d+p}. When the residence time of water in the Owens Lake basin approached zero, the value of $\delta^{18}O_L$ approached $\delta^{18}O_{d+p}$; *ie*, when $V_o \rightarrow V_{d+p}$, $\delta^{18}O_L \rightarrow \delta^{18}O_{d+p}$.

When the influx of detrital sediments is relatively constant, variation in the percentage of TIC tends to mirror variation in the $\delta^{18}O$ concentration of the TIC fraction. In a hydrologically-closed Na-HCO_3-dominated lake, all Ca that enters the lake precipitates as $CaCO_3$. When the lake overflows, however, some of the dissolved Ca in lake water is carried out of the basin by overflow; the greater the V_o:V_{d+p} ratio, the greater the loss of Ca. Therefore, if the flux of detrital sediments is relatively constant, high TIC amounts will parallel heavy $\delta^{18}O$ values and *vice versa*.

Results and Discussion

Variation in the Effective Wetness[2] of the Owens Lake Basin

The overall $\delta^{18}O$ record (Figure 5) indicates that Owens Lake overflowed much of the time between 52,500 and 12,500 ^{14}C YBP. High-frequency oscillations in $\delta^{18}O$ during this time are interpreted to indicate variations in the V_o:V_{d+p} ratio or brief oscillations in hydrologic state (closed ↔ open). The highest overflow rates appear to have occurred between 13,200 and 12,500 ^{14}C YBP. Large amounts of TIC and heavy $\delta^{18}O$ values between

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[2] Effective wetness is a measure of change in the hydrologic balance of a lake. For a hydrologically closed lake, effective wetness is defined as the ratio of the surface area of a lake at time *t* divided by the mean historical surface area. For an overflowing lake, the theoretical surface areas at time *t* can be calculated by dividing the inflow volume by the evaporation rate. For Owens Lake to overflow, the effective wetness must be ≥ 2.4.

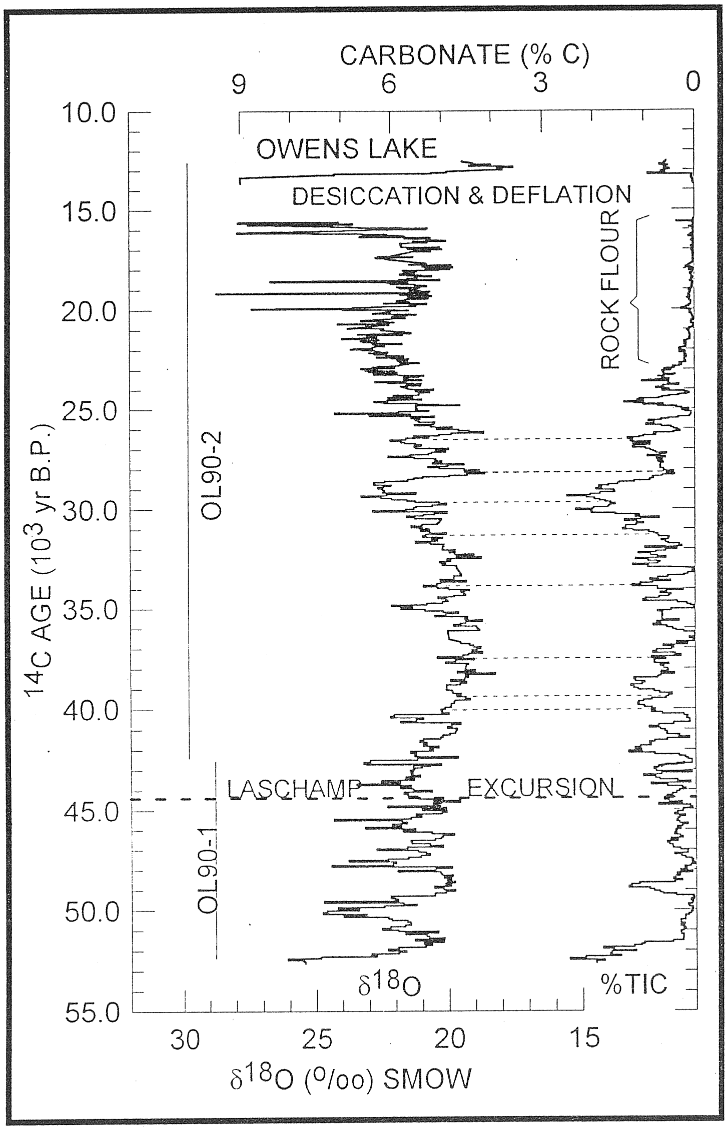

Figure 5. Oxygen-18 and total inorganic carbon records in cores OL90-2 and OL90-1 for the period 51,500 to 12,500 ^{14}C YBP. Thin dashed lines indicate correlations between both records between 40,000 and 26,000 ^{14}C YBP. The Laschamp excursion, which in France has been dated at 46,600±2400 cal YBP, was found at a depth equivalent to 44,900 ^{14}C YBP in core OL90-1.

31,000 and 29,000 ^{14}C YBP indicate a time of relatively low overflow and a greater frequency of closed-basin conditions[3].

Discontinuities in the depth-age distribution of Owens Lake sediments (Figure 2) indicate the existence of a sediment hiatus between <15,500 and 13,600 ^{14}C YBP. Sediments at the base of the hiatus are characterized by several features that indicate the occurrence of desiccation and deflation in the Owens Lake basin, including: (1) ≤1 centimeter of topography, (2) a 1- to 3-millimeter-thick lag deposit of coarse micaceous sand and frosted quartz grains, and (3) mudcracks. Soluble carbonate salts below this hiatus (Figure 6) document the former existence of a Na-CO_3 brine that diffused into the bottom of Owens Lake prior to its desiccation. Thus, the ^{14}C and salt data indicate that Owens Lake desiccated between <15,500 and 13,600 ^{14}C YBP and that deflation removed an unknown thickness of sediment from the dry lake bed.

First and second order variations in TIC and $\delta^{18}O$ can be associated for the period 40,000 to 26,000 ^{14}C YBP. The lack of association of TIC and $\delta^{18}O$ variability between 52,500 and 40,000 ^{14}C YBP and between 26,000 and 15,500 ^{14}C YBP indicates dilution and masking of the TIC signal by detrital sediments. We believe the detrital sediments were produced by glaciers located along the east flank of the Sierra Nevada; *ie*, in the summer months, glacially derived rock flour was transported to the Owens Lake basin by meltwater. The youngest rock flour event probably represents material derived from the Tioga and possibly Tenaya glaciations (Dorn *et al* 1987; Bursik and Gillespie 1993 and references therein). The oldest rock flour event may be a late stage of the Younger Tahoe glaciation (Blackwelder 1931; Phillips *et al* 1990).

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[3] Overflow during even the wettest of climates may have been seasonal. During winter, tunnels at the base of the glacier through which snowmelt and rock flour were transported would have frozen shut. The only water escaping the glacier during the winter season would have been water produced by subglacial melting.

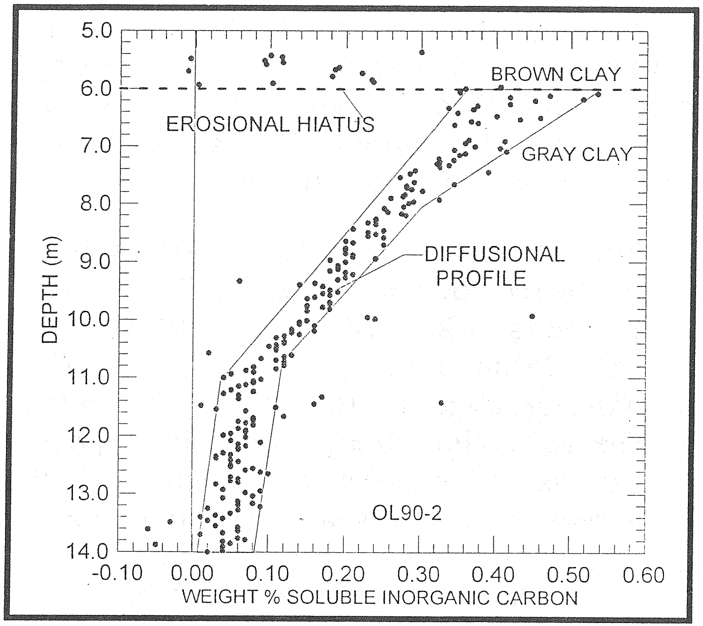

Figure 6. Weight % soluble inorganic carbon below hiatus in core OL90-2. Top of diffusion profile has been removed by deflation.

Values of $\delta^{18}O$ during the interglacial period (40,000 to 26,000 ^{14}C YBP) are generally lighter than during periods of glaciation, indicating that the intervening interglacial period was wetter than the glacial periods that preceded and followed the interglacial. Lack of intense glaciation between 40,000 to 26,000 ^{14}C YBP suggests that warm-season temperatures were high enough to melt and evaporate winter snow accumulations.

Comparison of the Owens Lake $\delta^{18}O$ Record with the V2381 Lithic Record

Bond *et al* (1993) have correlated proxy air temperature records (Dansgaard-Oeschger events) from the Summit ice core with proxy sea surface temperature records from North Atlantic sediment cores. The North Atlantic cores also contain intervals rich in ice-rafted lithic fragments, released from icebergs that had been discharged from the Laurentide ice sheet. The lithic intervals with the highest accumulation rates are called Heinrich events (Heinrich 1988). In their correlation, Bond *et al* (1993) demonstrated a link between iceberg discharge from the Laurentide ice sheet (evidenced by lithic layers) and variation in air and water temperature in the North Atlantic region; *ie*, five of the last six Heinrich events occurred at the end of progressive decreases in sea surface temperature and were followed by rapid increases in temperature.

The trajectory of the polar jet stream played a key role in the hydrologic balance of the Owens Lake basin during the Wisconsin glacial cycle. The presence of an ice sheet across Canada greatly affected the position and intensity of westerly flow, forcing the jet stream southward throughout the year (Kutzbach and Guetter 1986; Kutzbach 1987; Kutzbach *et al* 1993). During the Wisconsin glaciation, the Laurentide ice sheet underwent gradual expansion and contraction in response to external factors such as solar forcing, and it also may have experienced abrupt decreases in size resulting from its own internal dynamics (MacAyeal 1993). Some of the changes in the size and shape of the ice sheet may have been accompanied by a rapid shift of mean position of the polar jet stream over the Great Basin and a concomitant change in the hydrologic balance of Great Basin lakes, including Owens. If the cold-warm oscillations documented in the North Atlantic sediment and ice records were linked to changes in ice-sheet size, we might expect changes in the hydrologic balance of Great Basin lakes to correlate with North Atlantic records of climate change.

To determine if the abrupt and large changes in climate recorded in North Atlantic ice and sediment cores affected the climate of the Great Basin, we attempted to correlate the Owens Lake hydrologic-balance proxy record ($\delta^{18}O$) with a North Atlantic lithic record from core V2381 (Figure 7; numbered warm Dansgaard-Oeschger events are also indicated). The lithic record, instead of the left-coiling *Neogloboquadrina pachyderma* proxy-temperature record, was chosen for comparison with the Owens Lake $\delta^{18}O$ record for two reasons: (1) the sea surface temperature record (based on the relative abundance of *N. pachyderma*) is not sensitive to extremely cold water temperatures, and (2) the lithic record may indirectly reflect changes in the size of the Laurentide ice sheet.

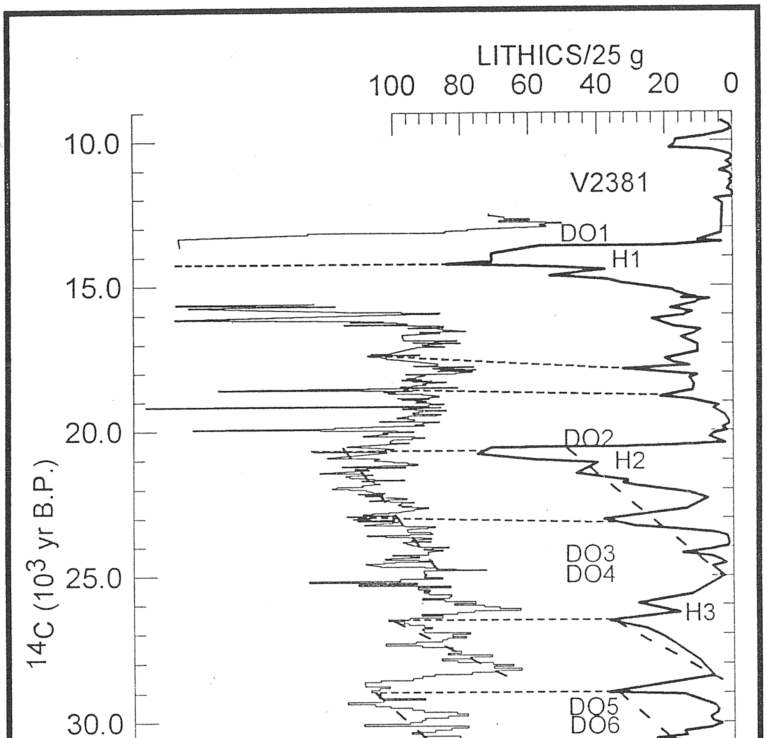

Figure 7. Oxygen-18 values of TIC fraction in Owens Lake cores compared with lithic record from North Atlantic core V2381.
H1-H4 indicate Heinrich events; DO1-DO11 indicate Dansgaard-Oescheger warm events. Thin dashed lines indicate attempts to associate lithic maxima with $\delta^{18}O$ minima; heavy dashed lines indicate trends in both records.

We were able associate trends of increasing iceberg discharge with decreases in effective wetness of the Owens Lake basin; for example, a generally decreasing trend in effective wetness corresponds to a period that features a series of successively larger lithic events bounded by Heinrich events H3 and H2. It also is possible to associate some of the major lithic events with decreases in effective wetness; for example, Owens Lake desiccated at the time of H1 (Figure 7). To the extent that these associations are correct, the data suggest that release of icebergs to the North Atlantic reduced the size of the Laurentide ice sheet, thereby allowing the mean position of the polar jet stream to shift northward over the Great Basin. However, there does not appear to be any clear or simple relationship between iceberg discharge in the North Atlantic and variation in the hydrologic balance of Owens Lake. There are numerous millennial-scale oscillations in the hydrologic balance of the Owens Lake surface water system that are absent from North Atlantic lithic and temperature records (Figure 7).

The lack of a strong correspondence between North Atlantic climate records and the Owens Lake $\delta^{18}O$ record has two possible explanations: (1) the sequence of large and abrupt climate change indicated in North Atlantic records is not global in scope and is largely confined to the North Atlantic and downwind regions, or (2) the Owens Lake basin is in a region that is relatively insensitive to climate perturbations recorded in the North Atlantic region. For example, it may be that when the polar jet stream shifted northward in response to a reduction in ice-sheet size, its mean path remained south of the Owens Lake basin.

Conclusions

Between 52,500 and 12,500 ^{14}C YBP, the climate of the Owens Lake basin was often ≥2.4 times effectively wetter than during the historical period. Glaciers occupied the Sierra Nevada during the first third (52,500 to 40,000 ^{14}C YBP) and most of the last third (26,000 to <15,500 ^{14}C YBP) of this wet period. The lack of Sierran glaciers during the middle third (40,000 to 26,000 ^{14}C YBP) indicates that summers were relatively long and/or warm. A desiccation of Owens Lake that occurred between <15,500 and 13,700 ^{14}C YBP was followed by an extremely wet period (13,300 to <12,500 ^{14}C YBP).

Comparison of the Owens Lake $\delta^{18}O$ record and the lithic record of North Atlantic core V2381 indicates some degree of association. However, there does not appear to be any clear or simple relationship between climate records from the North Atlantic and a proxy hydrologic-balance record from the Owens Lake basin.

Acknowledgments

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