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Late-Glacial and Early Holocene Vegetation and Climate Change near Owens Lake, Eastern California

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Pollen and algae from Owens Lake in eastern California provide evidence for a series of climatic oscillations late in the last glaciation. Juniper woodland, which dominated the Owens Valley from 16,200 to 15,500 cal yr B.P., suggests much wetter conditions than today. Although still wetter and cooler than today, the area then became fairly warm and dry, with woodland being replaced by shrubs (mainly sagebrush) from 15,500 to 13,100 cal yr B.P. Next, Chenopodiaceae (shadscale) increased, woody species declined, and lake levels fell—all evidence for a brief (ca. 100–200 yr) drought about 13,000 cal yr B.P. The climate continued to oscillate between wet and dry from 13,000 to 11,000 cal yr B.P. After 11,000 cal yr B.P., low lake levels and the increased dominance of desert shrubs indicate the beginning of warm, dry Holocene conditions. The region's climate was unstable during the Younger Dryas but uncertainities in dating prevent identification of the Younger Dryas interval in the Owens Lake record. Comparison of the Owens Lake record with studies in the Sierra Nevada and Great Basin suggest that the climate was generally wetter between 13,000 and 11,000 cal yr B.P., with warmer summers, although no consistent pattern of climate change emerges.

Key Words: **Owens Lake; California; Great Basin; pollen; algae; climate change.**

INTRODUCTION

The transition from the last glacial maximum to the present interglaciation was punctuated by a series of brief but significant climatic oscillations identified from northern European macrofossil and pollen records (Peteet, 1995). Additional evidence from Greenland ice cores (Dansgaard *et al.*, 1982), lake sediments (Eicher *et al.*, 1981), and North Atlantic marine cores (Ruddiman and McIntyre, 1981; Lehman and Keigwin, 1992) prompted debate about the geographic extent of these phenomena and their implications for abrupt short-term climatic changes (Rind *et al.*, 1986). Recent studies have identified late-glacial climate variability from a number of sites in western North America (Engstrom *et al.*, 1990; Mathewes, 1993; Benson *et al.*, 1997; Grigg and Whitlock, 1998). Identifying the geographic distribution, timing, and local effects of late-glacial climatic oscillations is basic to understanding the mechanisms controlling global climate change.

Benson *et al.* (1997) analyzed $\delta^{18}O$ and total inorganic carbon (TIC) from Owens Lake in the western Great Basin and identified a series of wet/dry climatic oscillations that possibly match those in the GISP2 Greenland ice-core temperature record. Pollen evidence was consistent with the geochemical data, suggesting that local vegetation responded rapidly to short-term climatic change. Previous pollen records from Owens Lake have analyzed Pleistocene-age cores (Woolfenden, 1995; Litwin *et al.*, 1997). In this paper, I present a detailed analysis of pollen and algae from the Pleistocene/Holocene transition and document regional changes in vegetation and climate.

Owens Lake lies in a graben between the Sierra Nevada and Inyo-White mountains in eastern California (Fig. 1). Water diversions begun in 1913 have nearly eliminated the lake. At its maximum during the Pleistocene, the lake was 80 m deep and covered 527 km^2. The lake basin is steep-sided and flat-bottomed, so that with an initial drop in surface elevation of 10 m below the maximum level, only 7% (40 km^2) of the lake bottom is exposed. About 40–45 km^2 is exposed with each 10 m of shallowing, to depth of 40 m. Additional shallowing exposes new playa at accelerating rates.

The basin is in the rainshadow of the Sierra Nevada. Annual precipitation ranges from $>$1000 mm along the Sierra crest above 3000 m elevation to $\sim$225 mm at 2000 m elevation and 160 mm in Owens Valley (Hollett *et al.*, 1991; Keef, S., unpublished data, Los Angeles Department of Water and Power, 1999). About 60–80% of the annual precipitation is associated with storms from October through April (Hollett *et al.*, 1991).

The steep elevational and moisture gradient compresses vegetation zones into narrow bands. Shadscale dominates the valley floor (1100–1300 m), which lies within the shadscale zone (Billings, 1949), dominated by *Sarcobatus vermiculatus* (greasewood) and *Atriplex confertifolia* (shadscale) (Chenopodiaceae family), *Artemisia spinescens* (budsage) (Asteraceae family), and *Ephedra nevadensis* (Mormon tea) (taxonomy follows Hickman (1993) and Mozingo (1987). Above the shadscale zone to the south and east (1300–1550 m), vegetation is dominated by Mojave Desert species including *Larrea tridentata* (creosote bush), *Ambrosia dumosa* (burro-weed), and *Opuntia* spp. (Litwin *et al.*, 1997). To the north and west, sagebrush steppe species associated with the cooler Great Basin are dominant,

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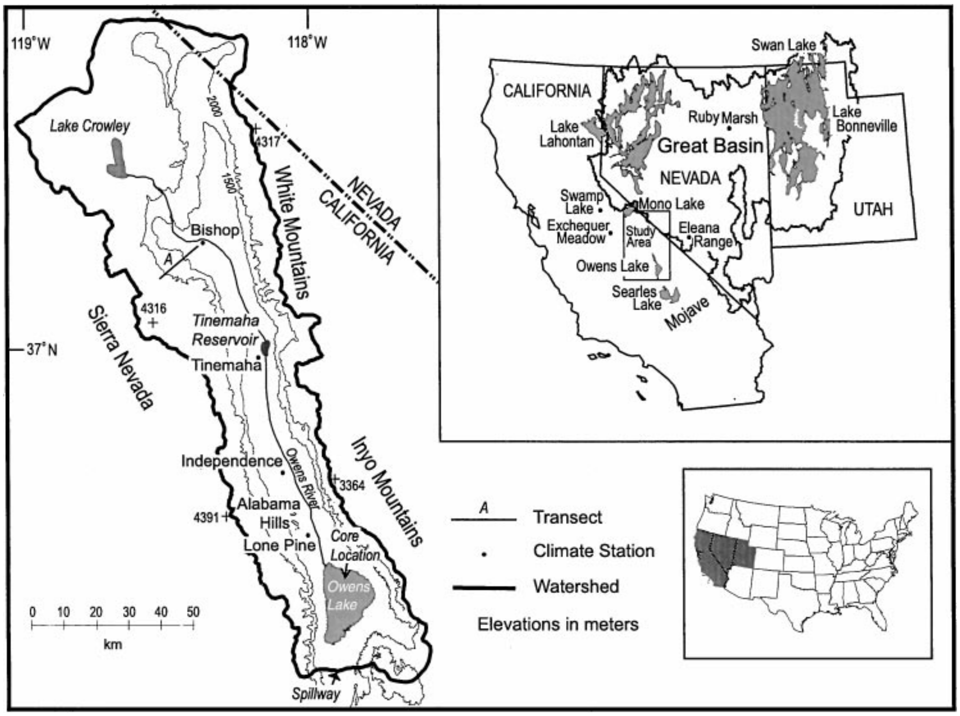

FIG. 1. Maps showing location of study area in the Owens Lake watershed and other sites referred to in this study. Transect A follows the location of surface pollen samples for this study. In the inset map, lakes shown in gray represent Pleistocene high stands.

including *Artemisia tridentata* var. *tridentata* (big sagebrush), *Purshia tridentata* (bitterbrush), and *Ephedra viridis* (Solomon and Silkworth, 1986). Conifers dominate above the sagebrush, including *Pinus monophylla* (pinyon pine) (1550–1800 m elevation); *P. jeffreyi* (Jeffrey pine), *Abies concolor* (white fir), and *A. magnifica* (red fir) (1800–2750 m elevation); and *P. balfourniana* (foxtail pine), *P. monticola* (western white pine), *P. albicaulis* (whitebark pine), and *P. flexilis* (limber pine) (2750–3600 m) (Griffin and Critchfield, 1972; Litwin *et al.*, 1997).

The Inyo-White mountains east of Owens Valley have an equally sharp zonation pattern, even though precipitation averages only 200–300 mm (Solomon and Silkworth, 1986). *Pinus monophylla* grows at low-elevation tree line at about 1900 m elevation, and *Juniperus osteosperma* (Utah juniper), which is not present on the Sierran slopes, grows above 2000 m elevation. *Pinus flexilis* and *P. longaeva* (bristlecone pine) grow at higher elevations, but none of the other Sierran pines are present.

METHODS

A 12-m-long core (OL84B) was recovered by Steve Lund in 1984 using a modified square-rod piston corer. Core description and sampling procedures are described in Benson *et al.* (1997). A series of 23 AMS radiocarbon dates of bulk sediment indicates hiatuses at 2.2 and 9.2 m (6000–4000 ^{14}C yr B.P. and 15,020–13,270 ^{14}C yr B.P.) (Benson *et al.*, in press). This study uses the core section from 3.4–9.2 m depth between the upper and lower haituses.

Thirty 2- to 5-cm-thick sediment samples were taken for pollen analysis. Pollen preparation followed standard methods (Faegri and Iversen, 1985). A known quantity of exotic spores was added to each sample to calculate pollen concentration (Stockmarr, 1971). Pollen was identified to the lowest possible taxonomic level using modern reference material and published pollen keys (Kapp, 1989; Moore and Webb, 1978). TCT (Taxodiaceae/Cupressaceae/Taxaceae) pollen was assumed to be *Juniperus* because it is the only genus of these three families common in the region. Unlike in the late-glacial pollen record from Mono Lake (Davis, 1999), no *Sequoiadendron giganteum* (giant sequoia) pollen was identified. Unidentified pollen grains were classified as "unknown" or "indeterminate" if damaged beyond recognition. Five types of colonial algae were also identified, including four species of *Pediastrum* and *Botryococcus* (Jankovská and Komárek, 1982).

At least 400 pollen grains were counted for each level. Algae were counted along with pollen. In six samples, algae were particularly abundant relative to pollen. For these samples, at least 500 algae were identified and total algae was calculated as a proportion of algae to total *Lycopodium* counted. Terrestrial pollen percentages were calculated from the sum of terrestrial pollen and spores. Aquatic pollen percentages were calculated using the total sum of pollen and spores. Pollen accumulation rates were calculated by dividing the pollen concentration by the number of years in the sample. Algae accumulation rates were similarly calculated using algae concentration divided by the years in the sample. Pollen zonation was based on a constrained single-link dendrogram program modified from Birks and Gordon (1985).

Climate reconstruction was based on modern analogs. Each fossil sample was compared with a database of 1050 modern surface samples from western North America (Davis, 1995). The squared chord distance dissimilarity coefficient was calculated for each sample with a critical value of 0.15 (Overpeck *et al.*, 1985). The calculations are based on nine upland pollen types representative of the area.

Many of the samples in the database are from sites with significant summer precipitation. In general, the western Great Basin recieves very little summer precipitation. To test the appropriateness of the database for use in this study, I compared the database with surface samples from Owens Valley. I collected five surface samples from sites near climate stations and along an elevational gradient (Fig. 1). For dry sites, at least 20 pinches of soil were taken along a transect of 100 m (Adam and Mehringer, 1975; Thompson, 1984). For lakes, at least 10 samples were collected from surface sediments along the shoreline at >0.5 m depth. At each site, dominant plants were identified. Each sample was thoroughly mixed, then prepared and counted like the fossil material.

The database successfully identified analogs that matched the local precipitation and temperature data. However, more surface samples are needed from low-elevation summer-dry sites such as the Owens Valley. Many of the taxa commonly found in pollen analyses have wide ecological tolerance, with species adapted to summer rainfall or summer drought. Similar pollen spectra may be composed of different species with different climatic requirements. Therefore, more complete surface sampling is required in the western Great Basin to improve the accuracy of climate reconstructions for this region. For the purposes of this paper, the emphasis is on the trends identified in the climate reconstruction rather than the specific values.

Wigand (1987) has shown that the ratio of *Artemisia* to Chenopodiaceae pollen (A/C ratio) provides a relative measure of available moisture. Shadscale, primarily Chenopodiaceae, dominates valley bottoms of the western Great Basin, where annual precipitation averages 115 mm. *Artemisia* typically dominates slopes and fans above the valley floor, where annual precipitation averages 220 mm. (Billings, 1949). Byrne *et al.* (1979) noted that Chenopodiaceae pollen increases during dry periods as saltbush species colonize new playa surfaces. I calculated the A/C ratio to provide a qualitative measure of aridity.

RESULTS

Owens Lake Core Chronology

An age–depth model was constructed from 13 AMS radiocarbon dates on bulk sediment (Table 1). Although the dates were not corrected for hard-water effects, other Great Basin lakes, such as Pyramid Lake, have a reservoir age (Lin *et al.*, 1998), and a shift of up to 600 yr may be appropriate for the OL84B chronology (Benson, L., personal communication, 2000). Radiocarbon ages were converted to calibrated years (cal yr B.P.) using the CALIB v4 program (Stuiver and Reimer, 1993) with the INTCAL98 data set (Stuiver *et al.*, 1998a). Samples incorporated ~50 to 60 yr of sediment, so the calibration curve was smoothed using a weighted moving average of 60 yr. A straight line was fit between sections of constant sedimentation to construct the age–depth model (Fig. 2). Radiocarbon dates cited from other records were similarly calibrated.

TABLE 1
Radiocarbon Ages from Owens Lake Core OL84B

Sample (Figs. 3, 4)	Depth (m)	Age (^{14}C yr B.P.)	Lab. no.	Age (cal yr B.P.) used in age model and 2σ range
a	3.36	6900 ± 60	CAMS 22386[a]	7690 (7840–7620)
b	3.36	7140 ± 60	CAMS 20024[a]	7950 (8030–7840)
c	4.79	9170 ± 60	CAMS 20025[a]	10,250 (10,500–10,210)
d	5.58	9520 ± 60	CAMS 20026[a]	10,730 (11,110–10,590)
e	5.58	9540 ± 60	CAMS 22388[a]	10,900 (11,130–10,590)
f	6.32	9680 ± 60	CAMS 20027[a]	11,160 (11,200–10,770)
g	7.00	10,050 ± 50	CAMS 59870[b]	11,460 (11,920–11,270)
h	7.25	10,870 ± 50	CAMS 59871[b]	12,920 (13,000–12,670)
i	7.80	11,520 ± 60	CAMS 20028[a]	13,460 (13,800–13,200)
j	8.20	12,230 ± 50	CAMS 59872[b]	14,150 (15,280–14,100)
k	8.53	12,650 ± 70	CAMS 20218[a]	15,290 (15,550–14,350)
l	9.07	13,360 ± 70	CAMS 20219[a]	16,100 (16,440–15,760)
m	9.13	13,270 ± 70	CAMS 21541[a]	15,980 (16,320-15,650)

[a] Dates from Benson *et al.* (in press).
[b] Unpublished dates provided by Michaele Kashgarian, CAMS.

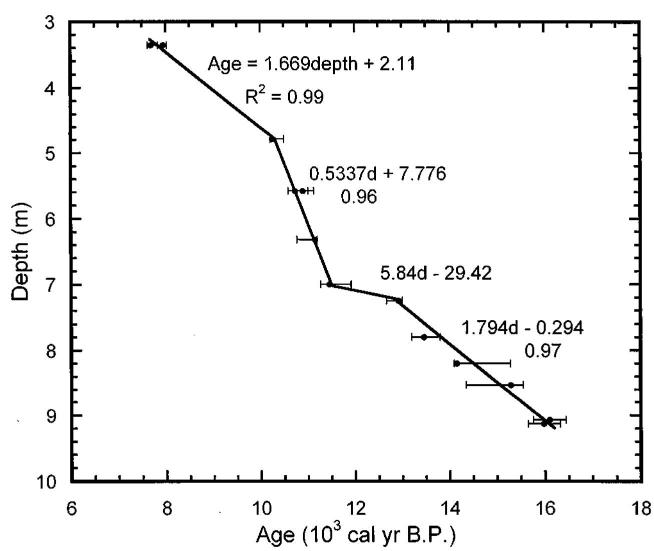

FIG. 2. Age vs depth curve and regression equations for Owens Lake. Error bars show the two-sigma ranges. Calibrated ages used in the model are listed in Table 1.

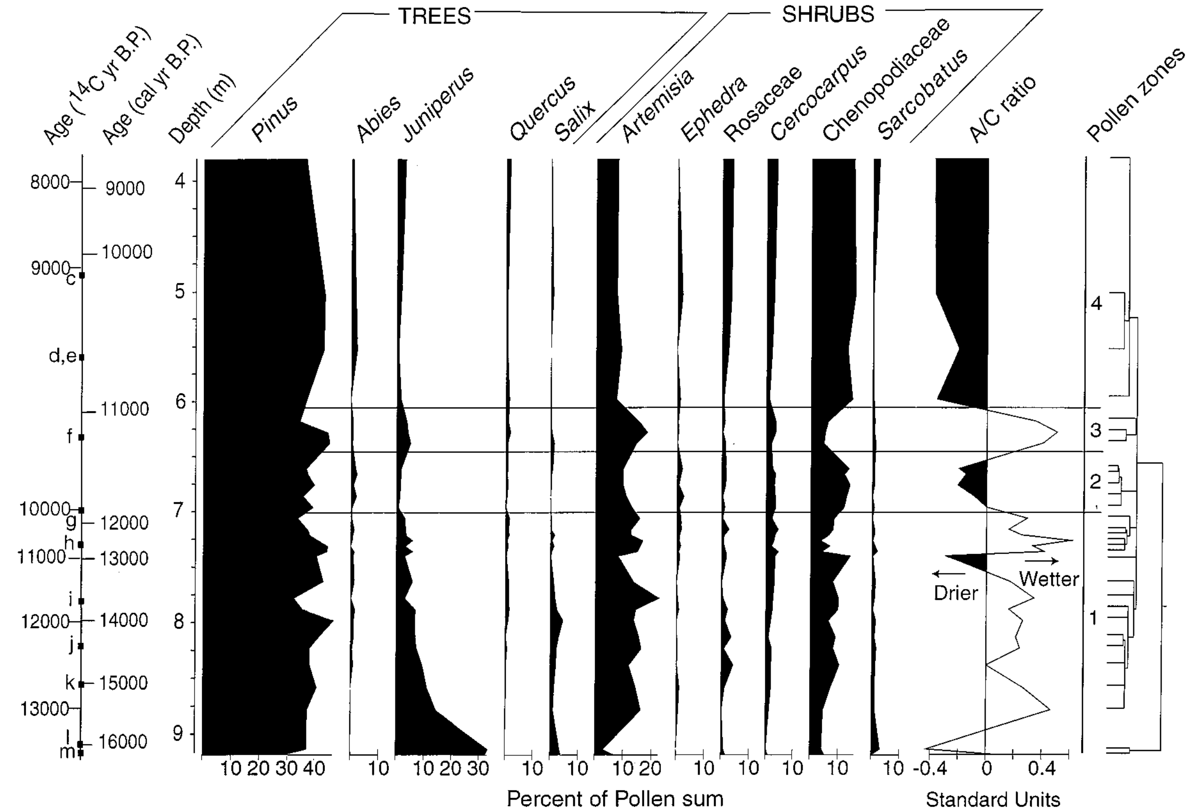

FIG. 3. Pollen percentage diagram of selected tree and shrub taxa. The ratio of *Artemisia*/Chenopodiaceae + *Sarcobatus* (A/C ratio) is calculated as $(a - c)/(a + c)$, where a represents *Artemisia* and c represents Chenopodiaceae + *Sarcobatus*. Positive values represent increased *Artemisia* (wetter climate), and negative values represent increased Chenopodiaceae (drier climate). Black squares (c–m) mark locations of ^{14}C dates in the core (Table 1).

Pollen Stratigraphy

Four pollen zones were defined from the dendrogram (Figs. 3 and 4). Pollen accumulation rates support the percentage data throughout the record. *Pinus* is the most common pollen type, averaging 37% of the pollen sum. Although pines grow above 1550 m on the eastern slope of the Sierra Nevada, atmospheric pollen transport studies show that they contribute 26 to 62% of the pollen sum in the valley (Solomon and Silkworth, 1986). The percentage of *Pinus* pollen present in the Owens Lake record is consistent with that expected from long-distance transport.

Zone 1 (16,200–11,750 cal yr B.P.; 13,500–10,200 ^{14}C yr B.P.) pollen is initially dominated by *Juniperus* (>30%). The percentage of *Salix* is relatively high (4%), indicating the presence of shoreline trees, riparian corridors, or both. After 15,500 cal yr B.P., *Juniperus* declines steadily and *Artemisia* and Chenopodiaceae become the dominant terrestrial pollen types. *Artemisia* (15%) is generally twice as abundant as Chenopodiaceae (8%). The percentage of *Ambrosia* remains relatively low, averaging 4%. *Typha* and Cyperaceae, common to shallow freshwater environments, as well as Poaceae, increase to their maximum (4–5%) between 12,700 and 11,750 cal yr B.P.

The predominant algae include *Pediastrum simplex* and *Botryococcus* spp., with *P. kawraiskyi* common after 12,950 cal yr B.P. Whereas the autecology of *Pediastrum* and *Botryococcus* are not well known, other studies in the Great Basin have found *P. kawraiskyi* in saline water (Wigand, P., personal communication, 1999). *Pediastrum kawraiskyi* is now present in Owens Lake, as well as in less saline lakes. *Pediastrum boryanum* and *P. simplex* appear to have wide ecological amplitude, although today *P. simplex* can be found in warm, weakly eutrophic waters (Jankovská and Komárek, 1982).

The deposit at 739 cm depth is different from the rest of the zone in nearly every respect. Chenopodiaceae (15%) is twice as abundant as *Artemisia* (8%), *Ambrosia* increases to 8%, and Cyperaceae and *Typha* decline. Among aquatic algae, *P. boryanum* becomes dominant along with *P. kawraiskyi*, and *P. simplex* declines.

In Zone 2 (11,750–11,200 cal yr B.P.; 10,200–9800 ^{14}C yr B.P.) desert taxa such as Chenopodiaceae and *Ambrosia* increase while steppe and woodland taxa, including *Artemisia* and *Juniperus*, decline. *Salix*, *Typha*, and Cyperaceae also decline in abundance, and *P. boryanum* replaces *P. simplex*. A short wet phase marks Zone 3 (11,200–11,000 cal yr B.P.; 9800–9550 ^{14}C yr B.P.), with a return of woodland taxa. *Juniperus* increases to 4% and macrofossil evidence from the Alabama Hills immediately west of Lone Pine confirms that *J. osteosperma* was still locally present (Koehler and Anderson, 1995). *Artemisia* is two

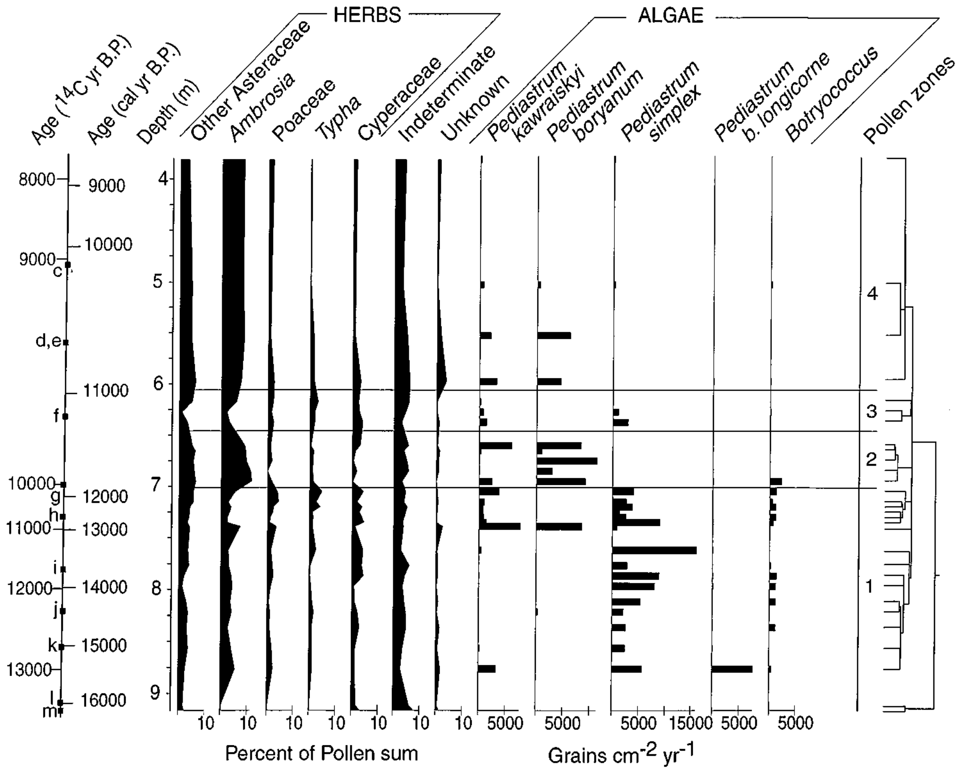

FIG. 4. Diagram of selected terrestrial herbaceous pollen and aquatic algae. Pollen is expressed as a percentage of the total pollen sum. Algae is expressed as accumulation rate. Black squares (c–m) mark locations of ^{14}C dates in the core (Table 1).

to three times as abundant as Chenopodiaceae, and Cyperaceae and *Typha* show modest increases while *Ambrosia* declines. *Pediastrum simplex* returns and *P. boryanum* is absent, although total algae accumulation is low.

Zone 4 (11,000–7850 cal yr B.P.; 9550–7000 ^{14}C yr B.P.) represents the shift to Holocene conditions. Chenopodiaceae (18%) reaches its highest values for the record and is more than twice as abundant as *Artemisia* (8%). *Ambrosia* increases to 8%. *Juniperus* declines, and macrofossil evidence indicates that by 9700 cal yr B.P. *J. osteosperma* became locally extinct (Koehler and Anderson, 1995).

INTERPRETATION AND COMPARISON WITH OTHER RECORDS

Transition from Full-Glacial to Late-Glacial Time

The abundance of *Juniperus* pollen (>30%) at 16,000 cal yr B.P. agrees with other Pleistocene pollen records from Owens Lake (Litwin *et al.*, 1997) and suggests that juniper woodland covered the floor of Owens Valley toward the end of the last glacial maximum (Fig. 4, Zone 1). *J. osteosperma* needles were abundant in packrat middens in the Alabama Hills throughout late-glacial time (Koehler and Anderson, 1995). Today, *J. osteosperma* is found only above 2000 m elevation in the White-Inyo mountains, where annual precipitation is >250 mm per year (Jennings and Elliot-Fisk, 1993). The climate reconstruction based on modern pollen analogs (Fig. 5) indicates a mean annual temperature of 9.4°C, about 4° to 5°C cooler than the present mean of stations in the Owens Valley. These estimates are similar to those of Smith and Anderson (1992) for Swamp Lake, Yosemite in the central Sierra Nevada (3.7°C cooler in January and 3.0°C cooler in July), and those of McCarten and Van Devender (1988) for the northern edge of the Mojave Desert (3.2°C cooler in January and 4.0°C cooler in July).

Modern analogs for the pollen spectra between 16,200 and 15,000 cal yr B.P. imply a mean annual precipitation of 308–370 mm (Fig. 5). Annual precipitation is 160 mm in Bishop, but it increases greatly with elevation. The reconstructed estimate potentially represents a >80% increase in effective moisture. Although this is much higher than Spaulding's (1985) suggestion of a 35–40% increase in southern Nevada, continued cool, wet climate is consistent with pollen data from Yosemite that show an altitudinal lowering of 1000 m for *Tsuga mertensiana* (mountain hemlock) (Smith and Anderson, 1992). The δ^{18}O data from Owens Lake (Benson *et al.*, 1996) and Mono Lake (Benson *et al.*, 1998), and ages of tufa from Searles Lake (Lin *et al.*, 1998) and Lake Lahontan (Benson, 1993), indicate high lake stands about 16,500 cal yr B.P. (14,000–13,500 yr B.P.) and provide additional evidence for a very wet climate in the western Great Basin at this time.

Only the final stages of the last pluvial period are recorded in the OL84B core between 8.8 and 9.2 m depth. By 15,000 cal yr

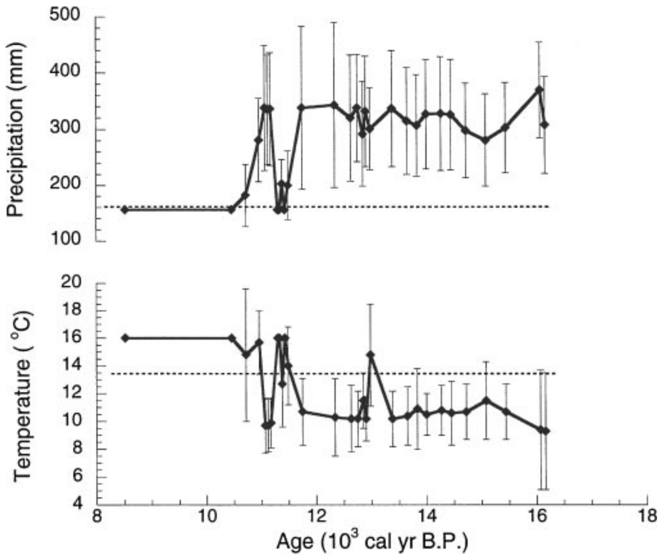

FIG. 5. Climate reconstruction for Owens Lake based on comparison between fossil pollen in Owens Lake core OL84B and modern pollen analogs from 1050 sites throughout the arid west of North America. Plotted values are the averages for the best analogs (squared chord distance <0.15). Error bars show one standard deviation. Points without error bars have only one analog. Dashed lines represent the modern mean annual temperature and precipitation for Bishop, California.

B.P. shrubs, primarily *Artemisia* and Chenopodiaceae, began to replace juniper woodland, which is evidence for a warming and drying trend under conditions still cooler and wetter than today (Fig. 5). *Artemisia* pollen twice as abundant as Chenopodiaceae suggests that sagebrush steppe dominated the valley. Owens Lake overflowed intermittently between 15,000 and 13,000 cal yr B.P. (Benson *et al.*, 1997). The first appearance in Owens Valley of Mojave Desert species, including *Coleogyne ramosissima* (blackbrush) and *Opuntia echinocarpa* (cholla), provides further evidence of warming trend after 16,000 cal yr B.P. (Koehler and Anderson, 1995).

A shift about 13,900 cal yr B.P from cool, wet conditions to possibly a more seasonal climate with cool, wet winters and warmer summers is recorded in the Sierra Nevada by an increase in *Quercus* (oak) and *Abies* (fir) and a decrease in *Tsuga* (mountion hemlock) (Smith and Anderson, 1992). In the Eleana Range of southern Nevada, macrofossil evidence indicates $>80\%$ similarity (Sorensen's index) between fossil and modern flora by 13,700 cal yr B.P.; the climate at that time was warm and dry, although still wetter and cooler than today (Spaulding, 1985). The appearance of *J. osteosperma* and *Pseudotsuga mensezii var*. *scopulorum* (Rocky mountain douglas fir) in the eastern Great Basin provides further evidence of warmer conditions by 13,900 cal yr B.P. (Thompson, 1988).

The generally wet conditions at Owens Lake were briefly interrupted by drought about 13,000 cal yr B.P. The δ^{18}O and TIC data suggest that the lake did not spill for at least a century (Benson *et al.*, 1997). A 5% increase in Chenopodiaceae pollen suggests expansion of shadscale onto a large exposure of playa. Marsh and riparian species declined, and dominant algae changed as well (Figs. 3 and 4). All this evidence implies a dry climate.

Younger Dryas and Transition to the Holocene

Several studies from western North America have identified late-glacial climatic oscillations roughly synchronous with the Younger Dryas (YD) interval, which lasted from 12,900 to 11,600 cal yr. B.P. (Stuiver *et al.*, 1995). Pollen studies from coastal locations in Alaska (Engstrom *et al.*, 1990) and British Columbia (Mathewes, 1993) found evidence for cooler, wetter climate between 13,000 and 11,200 cal yr B.P. Sites in western Oregon registered a weak Younger Dryas oscillation associated with cooler conditions. However, at these sites the vegetation shift to *Pinus* dominance may also be associated with increased summer drought caused by high July insolation values (Grigg and Whitlock, 1998).

Sediment records from the Santa Barbara Basin and the Gulf of California suggest increased oxygenation of intermediate waters in the North Pacific between 12,970 and 11,200 cal yr B.P. (Kennet and Ingram, 1995). The authors suggest that cooling in the North Atlantic may have been transmitted through the atmosphere to the North Pacific, affecting upwelling and resulting in well-oxygenated waters along the Pacific coast. Results for sensitivity experiments with general circulation models support this suggestion (Mikolajewicz *et al.*, 1997). The model results show an eastward shift in the Aleutian low and a strong northward component in winds along California. Cooling was inferred to be greatest north of 50°N and minimal along the California coast.

Two radiocarbon dates bracket the YD interval in the OL84B core (Table 1), but the potential radiocarbon reservoir age could make these dates as much as 600 yr younger. A plateau in the ^{14}C calibration curve (Stuiver *et al.* 1998a; Stuiver *et al.*, 1998b) also complicates comparison of time series for this period. Whereas the age control on the OL84B core is not sufficient to clearly define the YD for direct comparison with other sites, the Owens Lake record does show a series of abrupt climatic oscillations between 13,000 and 11,000 cal yr B.P., some of which may correlate with YD.

The abrupt drought about 13,000 cal yr B.P. was followed by a cool, wet period between 12,900 and 11,750 cal yr B.P., when *Artemisia* was dominant and the lake overflowed. Increases in *Typha* and Cyperaceae support evidence for a freshwater lake and more effective moisture. An increase in Poaceae suggests greater effective moisture in late spring and summer. *Pediastrum simplex* is abundant, which is consistent with earlier times when the lake was overflowing.

This wet phase was followed by a warm dry climate that persisted for about 550 yr (Figs. 3 and 4, Zone 2). A probable soil horizon suggests a very shallow, intermittent lake and an extensive playa surface (Benson *et al.*, 1997). Desert shrubs, primarily shadscale (Chenopodiaceae) and *Ambrosia*, increased and the dominant algae shifted from *P. simplex* to *P. boryanum*. The analog pollen spectra for this zone show mean temperature and precipitation similar to the modern climate and suggest that winter precipitation was probably similar to that of today. A final cool, wet period about 200 yr long occurred about 11,000 cal yr B.P. (Figs. 3 and 4, Zone 3). It is marked by a return of open *Juniperus* woodland and an increase in *Artemisia*. The δ^{18}O evidence suggests that the lake overflowed (Benson *et al.*, 1997). Winter precipitation must have increased to fill the basin during this period.

Although other studies from the western Great Basin and southern Sierra Nevada also record climatic variability between 13,000 and 11,000 cal yr B.P., there is no clear correlation among these records, and none shows the same series of oscillations found in the Owens Lake record. Lake Bonneville experienced a modest transgression between 12,950 and 12,250 cal yr B.P., forming the Gilbert Shoreline (Oviatt *et al.*, 1992). Ruby marshes deepened between 12,850 and 12,400 cal yr B.P. (Thompson, 1992). Although Mono Lake shows some variability in the pollen record between 12,900 and 11,400 cal yr B.P., the climate inferred from it is similar to that of the Holocene (Davis, 1999). In southern Nevada, increased effective moisture is inferred between 12,500 and 10,900 cal yr B.P. from the abundant formation of black mats, organic-rich layers associated with spring discharge. However, wet conditions are not limited to this period; mats began to form as early as 13,900 cal yr B.P. and continued to form until at least 9000 cal yr B.P. (Quade *et al.*, 1998). In the Sierra Nevada, a mixed coniferous forest persisted in Yosemite between 13,000 and 11,400 cal yr B.P., suggesting cooler wetter winters, and possibly warmer summers (Smith and Anderson, 1992). At Exchequer Meadow, south of Yosemite, the presence of *Sequoiadendron* near its modern upper elevational limit suggests warmer temperatures at 12,800 cal yr B.P. (Davis and Moratto, 1988). Pollen evidence from Swan Lake at the northern edge of the Great Basin suggests a transition from cold to warm climate between 12,900 and 12,000 cal yr B.P. (Bright, 1966). Taken together, these records suggest a generally wetter climate with some warming, possibly during summer, although no consistent pattern of climate change emerges.

The oscillations between wet and dry climates seen in the Owens Lake record indicate that the amount of precipitation received in the watershed varied greatly in late-glacial time. The North American ice sheets were still large enough to influence atmospheric circulation patterns at this time (Peltier, 1994). Enhanced ventilation of deep water in the northeastern Pacific Ocean about 11,600 cal yr B.P. (Lund and Mix, 1998) may also have affected circulation patterns. Summer insolation reached a maximum between 11,000 and 10,000 cal yr B.P., resulting in higher summer temperatures and probably increased seasonality (Grigg and Whitlock, 1998).

After 11,000 cal yr B.P., low lake levels (Benson *et al.*, 1997) and the increased dominance of desert shrubs (Fig. 3) indicate the beginning of warm, dry Holocene conditions. A warm, dry early Holocene is consistent with evidence from local packrat midden studies (Koehler and Anderson, 1995; Jennings and Elliot-Fisk, 1993) and pollen studies from the Great Basin (Thompson, 1988) and Sierra Nevada (Smith and Anderson, 1992; Davis *et al.*, 1985; Davis and Moratto, 1985).

CONCLUSIONS

Climate in Owens Valley ca. 16,000 cal yr B.P. was much cooler and wetter than today (>80% increase in effective moisture), with dense juniper woodland covering the valley floor. Beginning about 15,000 cal yr B.P. warming and drying began, although the climate was still cooler and wetter than today, and the valley was soon dominated by sagebrush steppe. At 13,000 cal yr B.P. a brief (100–200 yr) drought lowered the lake and allowed expansion of shadscale onto the playa. Cool wet conditions prevailed from 12,900–11,750 cal yr B.P., followed by a ca. 550-yr period of very dry climate, and then a brief ($\sim$200 yr) wet period. By the early Holocene, the climate was warm and dry and the modern vegetation became established, with shadscale dominant in the valley.

Pollen and algal data from this study, and δ^{18}O and TIC from Benson *et al.*, (1997), record abrupt wet and dry oscillations between 13,000 and 11,000 cal yr B.P. These oscillations may be associated with shifts in the winter circulation patterns caused by changes in the North American ice sheets, or by ventilation of deep ocean water in the northeastern Pacific Ocean. Summer insolation maxima may have resulted in higher summer temperatures and increased seasonality. Within the uncertainties of dating, the YD interval at Owens Lake may correlate with cool, wet conditions (end of Zone 1) or warm, dry conditions (Zone 2). Comparing the Owens Lake data with other regional studies does not produce a consistent record of climate change during lateglacial time. Additional well-dated studies from the region are needed to develop a coherent model of climate change.

Identification of several *Pediastrum* to species level shows that the dominant algae changed with changing lake levels. Autecological research of these and other algae commonly recovered in lake sediments would provide another valuable proxy for interpreting climate from paleolimnologic records.

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