Pollen Analysis of a Late-Glacial and Holocene Sediment Core from Mono Lake, Mono County, California

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Pollen analysis of a 752-cm core from Mono Lake, Mono County, California indicates generally high lake levels 11,600–7000 ^{14}C yr B.P., moderate lake levels until ca. 4000 ^{14}C yr B.P., and fluctuating levels to the present. Drying events, with lake levels near or below the historic minimum are dated ca. 8800, 4000, 2400, and 1100 ^{14}C yr B.P. Chronologic control is provided by six radiocarbon dates and six volcanic ashes. The rate of upland vegetation change is greatest 11,000, 4000, and 1130 ^{14}C yr B.P. *Juniperus* and *Sequoaidendron* pollen declines 11,000 yr B.P., marking the transition from late-glacial juniper woodland to Holocene steppe. High values (5–20%) of *Sequoaidendron* pollen are unique to this study and may indicate the presence of these trees east of the Sierra crest. The pollen-based reconstructions of climate are generally cooler and wetter than today, with relatively dry but cool climate during the early Holocene. The contrast between higher lake levels and more arid vegetation during the early Holocene can be explained by insolation-driven seasonality. Greater summer insolation produced summer drought, but lower winter insolation led to greater snowpack, greater spring runoff, and higher lake levels. Increased *Artemisia* and other Compositae pollen percentages mark the establishment of modern vegetation ca. 2000 ^{14}C yr B.P. During the late Holocene, the pollen-based reconstructions of climate generally match the Mono Lake fluctuations proposed by Stine (1990), but fewer fluctuations are recorded. © 1999 University of Washington.

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INTRODUCTION

Mono lake is a large (150 km^2) hypersaline lake (Mason, 1967) at the heart of a closed basin in eastern California and western Nevada (Fig. 1). The region is characterized by great topographic relief (3980–1950 m) and geologic heterogeneity. The Sierra Nevada to the west is comprised of granitic and metamorphic rocks, but most of the basin is covered with Holocene volcanic deposits, alluvium, Pleistocene lake deposits, and glacial outwash and till.

In historic time, lake level has fluctuated from 1960 to 1942 m, and generally has been falling during the last 70 yr. Mean water depth is 19 m and the maximum depth is 51 m southwest of Paoha Island (Scholl *et al.,* 1967). A pycnocline

develops at ca. 13 m depth in open water; salinity increases from 82 g l^{-1} to 92 g l^{-1} at that depth. Sodium is the major cation (28 g l^{-1}), and chlorine (17.5 g l^{-1}), carbonate (15.75 g l^{-1}), sulfate (9.8 g l^{-1}), and potassium (1.4 g l^{-1}), are the other major ions.

The chief aquatic animals are brine shrimp (*Artemia monica*) and brine flies (*Ephydra hians*), which live on green algae (*Nannochloris, Ctenocladus cricinnatus*), diatoms (*Nitzschia frustulum*), and cyanobacteria (Mono Basin Ecosystem Study Committee, 1987). Fish and cladocera presently do not live in the lake.

Meteorology and Hydrology

Three-fourths of the annual precipitation falls as snow in the western Mono Basin, but the proportion of summer rainfall increases eastward (Vorster, 1985). Total annual precipitation ranges from 127 cm at the Sierra Crest to less than 16 cm east of Mono Lake. Near the lake, soil moisture is below the wilting point (moisture deficit) from April to October (Kruse, 1990). Mean monthly temperature on the valley floor ranges from 0°C in January to 20°C in July.

Surface runoff originates almost entirely in the Sierra Nevada during spring snow melt. But flow is year round in several of the streams entering the west side of the lake (Fig. 1). Surface flow from other watersheds may contribute minor groundwater recharge to the lake (Kruse, 1990).

Paleoenvironmental Studies

Mono Lake has been the topic of paleoenvironmental investigation since I.C. Russell (1889) described its Pleistocene shorelines and glacial moraines. Detailed reconstructions of late-Quaternary and Holocene lake levels have been made by Putnam (1950), Lajoie (1968), and Stine (1990). The Pleistocene shoreline at 2134 m (Fig. 1) formed while the lake overflowed into the Owens River system through an outlet east of the lake.

Lajoie (1968) concludes that Mono Lake last overflowed 13,000 ^{14}C yr B.P., with rapid desiccation interrupted about 11,000 ^{14}C yr B.P. The high-stand is approximately contemporaneous with the final (Tioga 4) Sierra Nevada glacial ad-
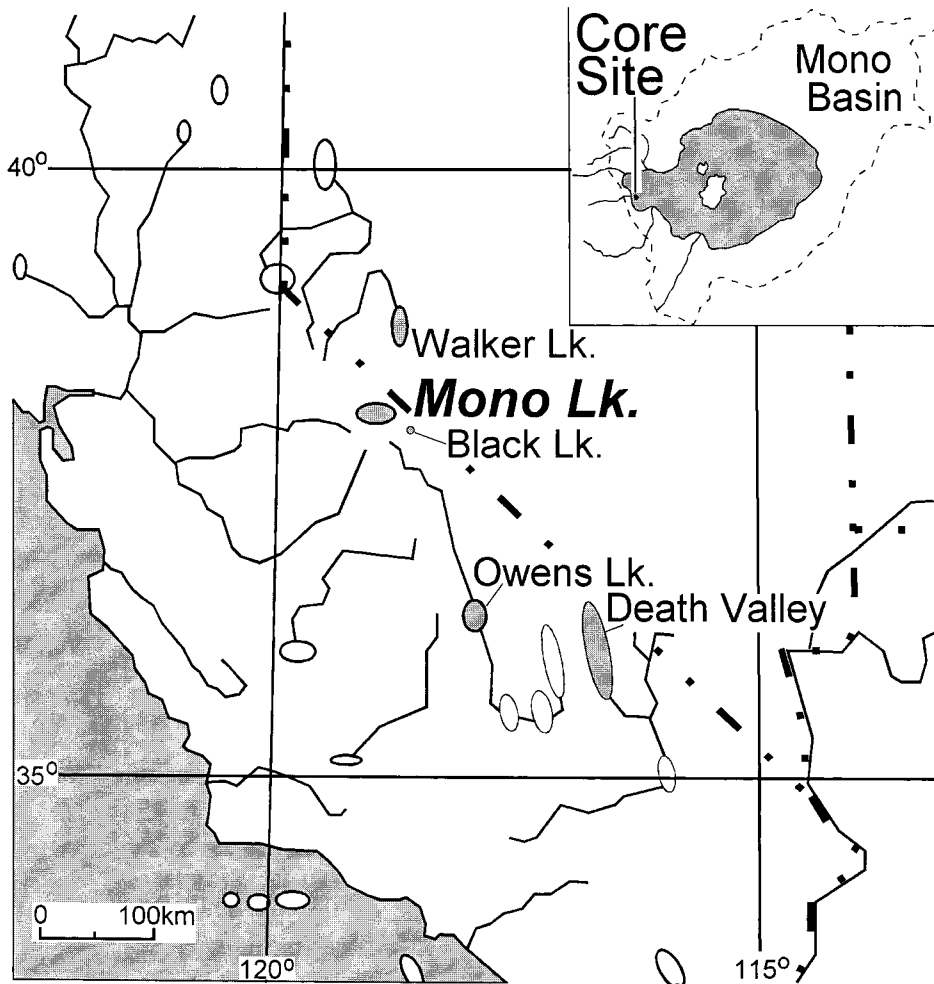
FIG. 1. Map showing location of Mono Lake and the 1986 core site.

vance (Phillips *et al.,* 1996). Stine (1990) proposes an intermediate lake level (1980 m) ca. 3800 ca. yr B.P. with lowstands ca. 1800, 1000, 720, 550, 380, and 190 ca. yr B.P. The 1800 and 1000 ca. yr B.P. minima are below the historic lowstand (1942 m; Stine, 1990).

Reconstruction of late-Pleistocene climate and vegetation for the region include palynological studies of Black Lake (Batchelder, 1970; Fig. 1), Walker Lake (Bradbury *et al.,* 1989), and Owens Lake (Woolfenden, 1996; Litwin *et al.,* 1997). The most complete Black Lake core (Batchelder, 1970) dates to 11,350 ^{14}C yr B.P., and contains five volcanic ashes. The pollen assemblage is dominated by *Pinus* (pine) and Cyperaceae (sedge). Peak percentages of *Ambrosia* and Chenopodiaceae-*Amaranthus* indicate low effective moisture during the early Holocene (11,350–5230 ^{14}C yr B.P.), with maximum aridity 6000–7000 ^{14}C yr B.P. A similar chronology of early Holocene aridity (10,000–4500 ^{14}C yr B.P.) is documented by Anderson and Smith (1994) for high-elevation lakes and meadows of the Sierra Nevada.

Early-Holocene aridity resulted in the desiccation of Walker

and Owens lakes. The sediments of Walker Lake (Fig. 1) provide a detailed record of climatic change from 30,000 to 15,000 ^{14}C yr B.P., but the lake, which is now 35-m-deep, dried from ca. 15,000–4650 ^{14}C yr B.P. After the lake's refilling, an interval of low lake level 2500–2100 ^{14}C yr B.P. is recorded by the pollen and seeds of halophytic *Ruppia* and radiocarbon-dated tufa deposits. However, the climatic interpretation of the lake-level record is complicated by diversions of the Walker River into and out of the lake basin (Bradbury *et al.,* 1989).

Pollen analysis of Owens Lake core OL-92 likewise is truncated by early Holocene lake desiccation (Woolfenden, 1996; Litwin *et al.,* 1997). The late-glacial pollen spectrum is dominated by *Juniperus* (20–60%), and the early Holocene spectrum by increasing *Ambrosia, Artemisia,* and Chenopodiaceae-*Amaranthus.* Packrat midden analysis provides a similar vegetation chronology. Middens from the Alabama Hills (Koehler and Anderson, 1995), just north of Owens Lake (Fig. 1), record the demise of juniper woodland (*Juniperus utahensis*) and the establishment of Holocene taxa such as wolfberry (*Lycium andersoni*) 11,000–8000 ^{14}C yr B.P.

Pollen frequencies in the middens are similar to those of Owens and Black lakes, with juniper pollen dominating during the full- and late-glacial time, and the Holocene assemblage dominated by Chenopodiaceae-*Amaranthus, Ambrosia, Artemisia,* and other Compositae.

METHODS

The sediment core was taken in 280-cm water depth on the western margin of Mono Lake (Fig. 1) on August 31 and September 1, 1986, when the water surface elevation was 1945 m, 3 m above the historic minimum. The coring locality was selected on the delta of Post Office Creek to ensure rapid sedimentation and to provide terrestrial plant macrofossils for radiocarbon dating.

Volcanic ashes were analyzed by Andrei Sarna-Wojcicki and Jill Onken, and radiocarbon samples were sent to Beta Analytic and the University of Arizona NSF accelerator facility. Because the carbon cycle of Mono Lake is not in equilibrium with the atmosphere, bulk sediment, which contains the remains of aquatic organisms, cannot be used for radiocarbon dating. Sufficient wood was present at 60–70 cm for dating by standard methods, but accelerator-dating samples were hand-picked terrestrial macrofossils.

Routine pollen extraction, including the addition of tracers, acid digestion, and acetolysis, produced abundant, well-preserved pollen (Davis and Kailey, 1990). The identification of *Sequoiadendron* pollen is based on the presence of a papilla. Although this morphological character also appears on *Sequoia* and *Taxodium* pollen, the presence of these taxa in the Sierra Nevada during the late Pleistocene is not plausible. Cupressaceae pollen probably is mostly *Juniperus* pollen, but *Calocedrus* pollen might also be present.

Dates used for the lake core are interpolated ^{14}C dates, based on the radiocarbon analyses presented in Table 1.

RESULTS AND INTERPRETATIONS

The 752-cm core consists of finely laminated gyttja (lake mud), sands, and volcanic ashes (Table 1, Fig. 2). The entire core was black and emitted a strong odor of hydrogen sulfide when first taken. The core slowly oxidized to dark yellowish brown (10YR 3/4). Distinct laminations from 230 to 594 cm (Table 1) are currently under study. The sediment stratigraphy of the core is similar to that of cores taken by Stine (1990) and Newton (1994), except that it is longer and more complete. Newton (1994, Fig. 11) presents an illustration for the core that does not match the description in Table 1. In particular, I see no evidence that the thinolite crystals at 611–666 cm are redeposited. I see no erosional surface at the base of the thinolite unit, and the basal layer of sand (748–752 cm) is thin, is not cross-bedded, and is not a volcanic ash.

Six radiocarbon dates and six volcanic ashes provide chronologic control for the core (Table 1, Fig. 2). Three radiocarbon dates are not used in calculating sedimentation rates in the core. The wood sample at 60–70 cm contains only 0.4 g C, and its date of 1950 ^{14}C yr B.P. (Table 1) is older than the underlying tephra and radiocarbon dates. The date of 4605 ^{14}C yr B.P. is rejected in favor of the date on pollen (AA 6873, Table 1; Long *et al.,* 1992). The date of 12,260 ^{14}C yr B.P. at 365–375 cm is clearly wrong and illustrates the potential hazard of dating small plant remains or charcoal from lake sediment.

Eight volcanic ashes are present in the core (Table 1). Five of these are identified by Sarna-Wojcicki as Mono Craters ashes, which are differentiated based on stratigraphic considerations and hydration rind thickness (Onken, 1991). Two of the ashes are from Mount Mazama (6700 and 6990 ^{14}C yr B.P., Table 1). Mono Lake is the southernmost reported occurrence of these ashes. The ash at 200 cm (ca. 3730 ^{14}C yr B.P., Table 1) was overlooked during preliminary description of the core, and it has not been studied. The ash at 445 cm is a Mono Craters ash that has not previously been reported or dated.

The resultant age model (Fig. 2) for the Mono Lake core shows only one apparent gap in sedimentation of greater than a few centuries duration, between 60 and 70 cm depth (560–1200 ^{14}C yr B.P.), bracketed by the North Panum and Mono Tephra 2 ashes (Table 1). In general sedimentation is slower (0.52 mm/yr) after 7000 ^{14}C yr B.P. than before (0.94 mm/yr, Fig. 2).

The various sand layers in the core (Table 1) may result from lowstands, flood deposits, avalanche debris, or un-recognized volcanic tephra. Sand layers at 1, 62–69, 160, 217–225, 594–507 cm (Table 1) probably represent lowstands. The surface sand layer is correlated with the historic lowstand when the lake surface was near the elevation of the sediment surface at the coring site. The sandy units, including the surface one, generally match hot–dry intervals discussed below. The ten sandy layers below 666 cm (9550 ^{14}C yr B.P.) may record lake drying, but they could result from floods or avalanche debris.

The dense layer of thinolite tufa from 661–666 cm indicates intensely cold water. Shearman *et al.* (1989) have analyzed the development of thinolite in Great Basin lakes. The thinolite crystals diagenetically replace ikaite, which forms ca. 0°C. For ikaite to form in the sediment, the entire water column must have been near freezing. The thinolite zone (611–666 cm (9000–9520 yr B.P.), Table 1) matches a cold period in the climate reconstruction (discussed below).

The pollen diagram (Fig. 3) is dominated by *Pinus* (up to 90%) and *Artemisia* (sagebrush, 10–20%). Arboreal types (Cupressaceae, *Tsuga mertensiana, Quercus,* and *Sequoiadendron* (giant sequoia)) are relatively abundant, and non-arboreal types are generally scarce. The pollen concentration is higher (average 60,600 grains/cm^3) before 700 ^{14}C yr B.P., and lower (average 24,500 grains/cm^3) from 7000–2000 ^{14}C yr B.P. The higher sedimentation rate during the earlier period (0.94 mm/yr, Fig. 2) yields a much higher pollen accumulation rate before 7000 ^{14}C yr B.P. (5700 grains/cm^2/yr vs. 1270 grains/

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TABLE 1

Mono Lake Core Sediment Stratigraphy, Radiocarbon Dates, and Volcanic Ashes

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Sediment depth (cm)	Sediment description	[14]C date depth (cm)	Lab number	[14]C age (^{14}C yr B.P.)	Volcanic ash depth (cm)	Volcanic ash identification	Reported ash age (^{14}C yr B.P.)
1–62	Gyttja, silty, laminated from 37–59 cm, sand 0–1 cm				65	North Panum[a]	560 ± 20
62–69	Sand, wood fragments (cf. *Populus*) common	60–70	Beta-21036	1950 ± 110[b]			
69–130	Gyttja, silty, laminated from 147–154 cm				72	Tephra 2[a]	1200 ± 40
130–230	Sand and silt, dense sand units at 160, 217–225 cm, volcanic ash at 135 and 200 cm, ostracods present below 200 cm	140–150 200–205 200–205	AA-2517 AA-6873 A-6267	2060 ± 75 3730 ± 60 4605 ± 60[b]	135 200	Tephra 3[a] Unidentified	1730 ± 30 (3730 ± 60)
230–594	Gyttja, finely laminated ca. 10 laminations per cm, volcanic ashes at 349, 363, 405, and 445 cm	365–375 450–460	AA-2518 AA-2519	12,260 ± 120[b] 7485 ± 120	349 363 405 445	Mazam[b] Tsoyowata[b] Mono Craters ? Crooked Mdw. A1[e]	6700 ± 100[c] 6990 ± 300[d] (7200) 7270 ± 80
594–597	Sand (ca. 8880 yr B.P.)						
597–611	Gyttja, very finely laminated ca. 13 laminations per cm	600–610	AA-2520	8990 ± 105			
611–666	Large thinolite tufa crystals, upright and penetrating sediment layers	655–660	AA-5802	9450 ± 95			
666–752	Gyttja, coarsely laminated ca. 2 laminations per cm, thin sand layers present at 684–686, 704–705, 707–708, 713–715, 717–718, 720–721, 723–725, 731–732, 741–742, and 748–752 cm	710–720	AA-4692	10,765 ± 105			

[a] Onken (1991).
[b] [14]C data not used in age model.
[c] Mehringer *et al.* (1977).
[d] Davis (1978).
[e] Identification by A. Sarna-Wojcicki.

cm^2/yr). Given the relatively minor changes in pollen percentages ca. 7000 ^{14}C yr B.P., it is unlikely that the different accumulation rates result from vegetation change. Rather, the changes in sedimentation and accumulation rates probably are due to changes in pollen transport to the lake, i.e., greater discharge of the streams flowing into the western margin of the lake (Fig. 1) prior to 7000 ^{14}C yr B.P. The increased pollen concentration after 2000 ^{14}C yr B.P. can be given a similar interpretation, high stream discharge carrying pollen and clastic sediment into the lake.

The major features of the pollen diagram (Fig. 3) include modest increases (5%) of Chenopodiaceae-*Amaranthus* and *Sarcobatus* pollen 9000–5000 ^{14}C yr B.P. and establishment of modern pollen frequencies after 2000 ^{14}C yr B.P. These features are consistent with other pollen diagrams of the area (Fig. 1; Black Lake (Batchelder, 1970); Alabama Hills (Kohler and Anderson, 1995)) that call for early-Holocene aridity. Likewise, the higher (>10%) Cupressaceae values prior to 11,000 ^{14}C yr B.P. and the increased *Artemisia* and Chenopodiaceae-*Amaranthus* after 2000 ^{14}C yr B.P. are consistent with these studies. However, the abundant (5–20%) *Sequoiadendron* pollen is a unique feature of this diagram (Fig. 3). The frequencies are <1% after 10,700 ^{14}C yr B.P., and the latest occurrence is

ca. 7800 ^{14}C yr B.P. In surface sample studies, Anderson (1990) found that *Sequoiadendron* pollen drops to background values (<5%) within 1 km of big tree (*Sequoiadendron*) groves. *Sequoiadendron* appears to have occurred east of the Sierra Crest, near Mono Lake, during the early Holocene, but without macrofossil confirmation, an alternative explanation of strong transport of pollen from the western Sierra Nevada cannot be eliminated.

Coenobia and zygospores of freshwater algae (*Botryococcus, Pediastrum,* and *Spirogyra*) are common below 620 cm (9250 ^{14}C yr B.P.). These microfossils indicate low salinity, but their presence in the thinolite unit (Table 1) suggests they occupied a freshwater epilimnion above saline hypolimnion, which implies a deep lake. Today a chemocline develops at 13 m depth in open water (Mason, 1967), but the surface water is usually hypersaline, so water depth 40 m above the thinolite unit (Table 1) is not unreasonable (i.e., lake surface ca. 1980 m; cf. 1980 m for 3800 ca. yr B.P. maximum (Stine, 1990) and 2134 m for pluvial maximum (Putnam, 1950)).

Low percentages of *Botryococcus, Pediastrum,* and *Spirogyra* from 670 to 720 cm (10,000–10,800 ^{14}C yr B.P.) are bracketed by peak values of these types and for charcoal (Fig. 3). Also, *Sequoiadendron* and Cupressaceae percentages fall
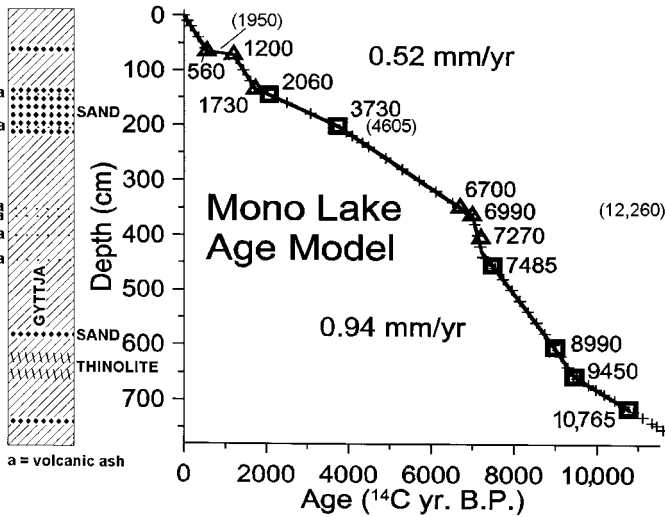
FIG. 2. Sedimentation age model for the Mono Lake core. Average sedimentation rates shown for after and before 7000 yr B.P. Small numbers are radiocarbon ages of sediment, dates (squares), or volcanic ashes (triangles); "+" symbols are positions of pollen samples. Numbers in parentheses are not used in age model. Sediment composition shown at left. Nine narrow (less than 2 cm) sand layers between 685 and 742 cm are not shown.

tions for the interval are similar to the rest of the early Holocene (Fig. 4).

Figure 4 illustrates the calculation of vegetation change and climate based on Mono Lake pollen stratigraphy. Vegetation change is computed as the squared chord distance between adjacent samples (Jacobson and Grimm, 1986). The calculations are based on 17 upland pollen types with peak abundances greater than 2%. These analyses show variability in the early and late Holocene, and peak values of change 11,000, 4000, 2400, and 1130 ^{14}C yr B.P. The 11,000 ^{14}C yr B.P. peak marks the decline of Cupressaceae and *Sequoiadendron* and the increase of *Pinus* pollen (Fig. 3). The 4000, 2400, and 1130 ^{14}C yr B.P. events coincide with sand layers in the core (Table 1) and likely reflect major upland vegetation change coinciding with Mono Lake lowstands. Similarly, the frequent peaks of vegetation change (Fig. 4) and the numerous sand layers (Table 1) may indicate near drying of the lake during the early Holocene. One of the coldest events in the record (9400–9200 ^{14}C yr B.P. (654–640 cm), Fig. 4) coincides with the thinolite unit in the core (Fig. 2), but no thinolite is present at 520 cm (8140 ^{14}C yr B.P.), an even colder event in Figure 4.

The climate reconstructions (Fig. 4) are based on comparison of each fossil sample with a database of 1400 contemporary surface samples (Davis, 1995). Annual precipitation and temperature are calculated as the average of the precipitation

during this "low algae" interval (Fig. 3). The dates match those of the Younger Dryas, so environmental change coincident with this event is recorded; however, the climate reconstruc-
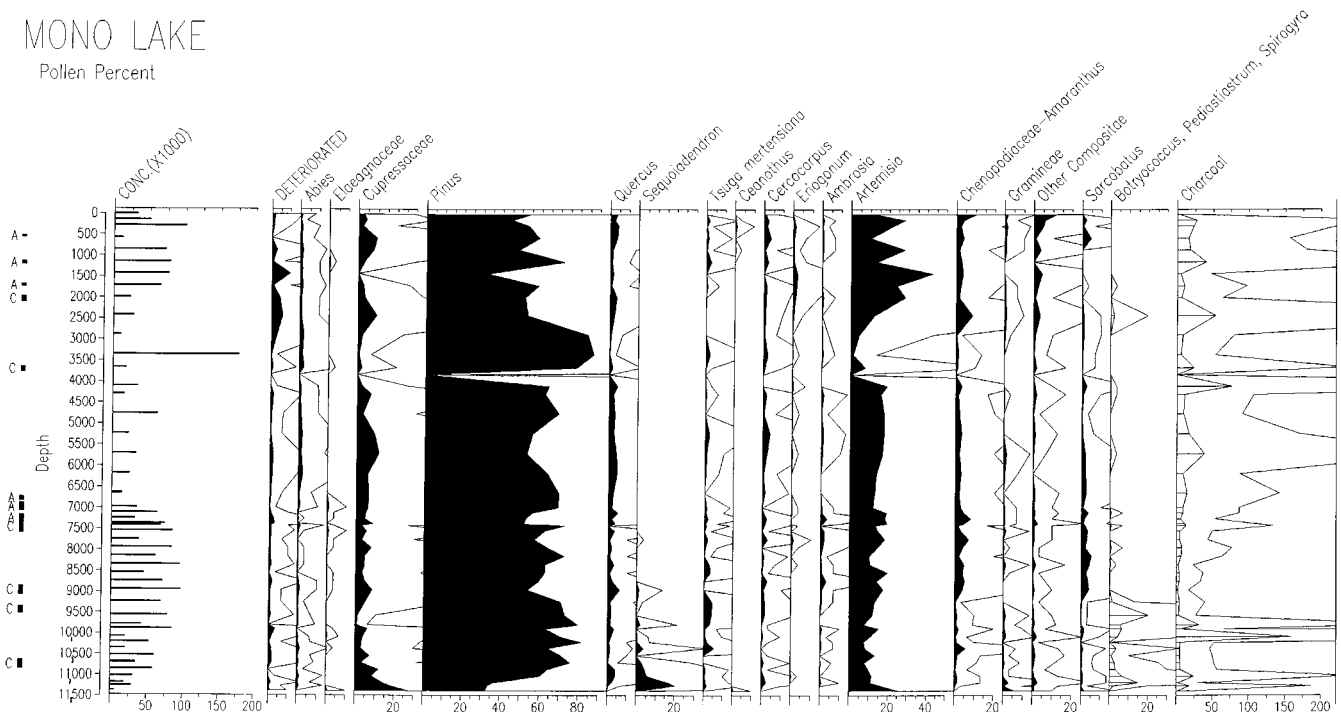

FIG. 3. Summary pollen diagram for the Mono Lake 1986 core. Positions of age controls are shown on left. "A" is volcanic ash. "C" is a radiocarbon date for the sediment. Lines to the right of filled curves are 10× exaggerations. Algae and charcoal (far right) are not included in the pollen sum, but their abundances are recorded as percentages of the pollen sum.
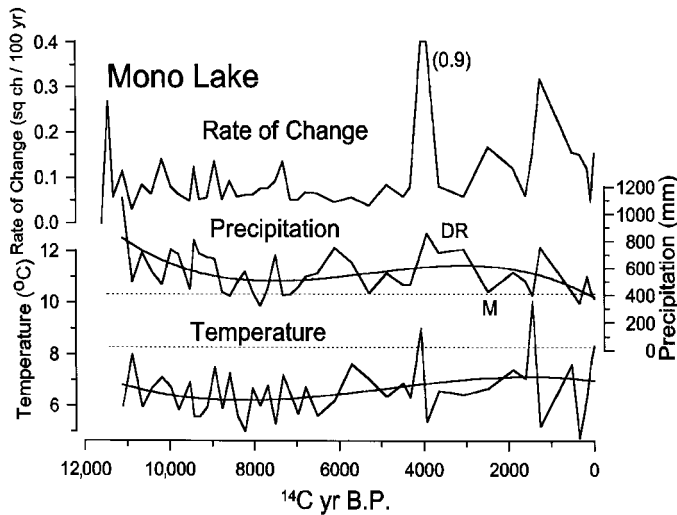
FIG. 4. Reconstruction of vegetation change and climate for the Mono Lake 1986 pollen core. Vegetation change calculations are squared chord distances between adjacent samples, corrected for sedimentation between dated horizons. Climate reconstructions are averages for best analogs (squared chord distances <0.14) in a 1400-sample database of modern samples. "DR" is Dechambeau Ranch highstand. M is Marina lowstand.

and temperature values of the modern analogs. Note that samples older than 11,000 ^{14}C yr B.P. (with high *Sequoiadendron* values) do not have analogs (Fig. 4), so no climate values are calculated. The temperature in modern giant sequoia groves (10–15°C; Harvey *et al.,* 1980) is higher than the early-Holocene values shown in Figure 4.

The climate reconstructions show considerable variability during the early and late Holocene, corresponding to frequent pulses of vegetation change (Fig. 4). Compared to the late glacial, the average climate (smooth curve in Fig. 4) is relatively dry and cool—ca. 100 mm less and 0.5°C below late glacial values. Note that the uppermost values (modern) are drier and hotter than nearly all of the preceding values (Fig. 4). This is consistent with LaMarche *et al.*'s (1984) anomalously large historic tree-ring widths for the White Mountains, but not with Graumlich's (1993) tree-ring reconstructions of climate for the western Sierra Nevada.

Sharp temperature peaks precede the 4000 and 1130 ^{14}C yr B.P. vegetation-change maxima (Fig. 4). The coincidence of these peaks with vegetation-change maxima and sand layers (Table 1) indicate that high temperatures led to lake lowstands and vegetation change. However, the lowstands apparently produced gaps in the sediment record so that detailed reconstruction of lake history is not possible. For example, the sand layer from 62–69 cm is bracketed by volcanic ashes dated 560 and 1200 ^{14}C yr B.P. (Table 1). The vegetation change calculated for this interval is the second greatest in the core, but Stine (1990) records two lake-level fluctuations during this time period, indicating a gap in the sedimentary record. Higher percentages of deteriorated pollen during the last 3000 ^{14}C yr

(Fig. 3) probably result from oxidation during lowstands and reworking during subsequent highstands.

CONCLUSIONS

Late-Glacial and Early Holocene: 11,600–7000 ^{14}C yr B.P.

Lake levels were high but fluctuating based on sedimentation rates, pollen concentration, moderate percentages of freshwater algae, and sand layers. Before 9000 ^{14}C yr B.P., the lake was deep (surface elevation ca. 1980 m (Stine, 1990)) and chemically stratified, based on the coincidence of thinolite tufa (saline hypolimnion) and freshwater algae (fresh epilimnion). The high sedimentation rates and high pollen concentration indicate that stream discharge from the adjacent Sierra Nevada range was sufficient to maintain relatively high lake levels. However, the 8800 ^{14}C yr B.P. (594–597 cm) sand layer (Table 1, Fig. 2) may record a drying event. If so, it was of much shorter duration than the desiccation of other lakes in the region (Bradbury *et al.,* 1989; Litwin *et al.,* 1997).

The transition from late-glacial to Holocene vegetation— marked by reduced Cupressaceae and *Sequoiadendron* percentages—took place 11,000 ^{14}C yr B.P., accompanied by high vegetation-change rates. The high (20%) *Sequoiadendron* values are a unique feature of the Mono Lake pollen study. Giant sequoia may have lived east of the Sierra crest. After 9000 ^{14}C yr B.P., precipitation was lower, but lower temperature and, therefore, lower evaporation kept lake levels relatively high. Low temperatures are suggested by the presence of thinolite tufa 9520–9000 ^{14}C yr B.P. and the low temperature recorded 9400–9200 ^{14}C yr B.P. (654–640 cm, Fig. 4), and low precipitation is suggested by the elevated values of Chenopodiaceae-*Amarantus* and *Sarcobatus* pollen, which indicate development of halophytic vegetation.

Middle Holocene: 7000–4000 ^{14}C yr B.P.

This period is characterized by lake levels more constant than during the preceding interval, based on preserved fine sedimentary structure and the absence of sand layers. The presence of ostracods (Table 1) implies water less saline than during the subsequent late-Holocene, so lake-levels were intermediate (1980–1950 m (Stine, 1990)). Charcoal percentages and reconstructed temperatures generally were raised during the period, suggesting climatic control of fire.

Late Holocene: 4000 ^{14}C yr B.P.–Present

The last 4000 ^{14}C yr are characterized by fluctuating lake levels. Three intervals of peak vegetation change coincide with lowstands ca. 4000, 2400, and 1100 ^{14}C yr B.P., when the lake surface was near or below the historic minimum of 1942 m. These events coincide with reconstructed low precipitation or high temperature (Fig. 4) and gaps in sedimentation (Table 1). Following the 4000 ^{14}C yr B.P. drought, *Pinus* percentages exceed 80%, the highest values in the core (Fig. 3), and

reconstructed precipitation reaches maximum values (Fig. 4). This interval is marked "DR" in Figure 4, indicating correlation with Stine's (1990) Dechambeau Ranch highstand. The subsequent low-precipitation interval 2400 is labeled "M," corresponding to Stine's (1990) Marina lowstand. Further correlations with Stine's detailed chronology of lake fluctuations are not possible, due to apparent gaps in the sedimentary record.

The percentages of low elevation shrubs (*Artemisia, Eriogonum,* other Compositae, and Chenopodiaceae-*Amaranthus*) are higher after 2000 ^{14}C yr B.P., as the modern vegetation of Mono Basin developed. High charcoal percentages indicate fires were common in the developing sagebrush steppe.

ACKNOWLEDGMENTS

REFERENCES

Anderson, R. S. (1990). Modern pollen rain within and adjacent to two giant sequoia (*Sequoiadendron giganteum*) groves, Yosemite and Sequoia national parks, California. *Canadian Journal of Forest Research* **20,** 1289–1305.

Anderson, R. S., and Smith, S. J. (1994). Paleoclimatic interpretations of meadow sediment and pollen stratigraphies from California. *Geology* **22,** 723–726.

Batchelder, G. L. (1970). "Postglacial Ecology at Black Lake, Mono County, California." Unpublished Ph.D. dissertation, Arizona State University, Tempe.

Bradbury, J. P., Forester, R. M., and Thompson, R. S. (1989). Late Quaternary paleolimnology of Walker Lake, Nevada. *Journal of Paleolimnology* **1,** 249–267.

Davis, J. O. (1978). "Quaternary Tephrochronology of the Lake Lahontan Area, Nevada and California." Nevada Archeological Survey Research Paper 7.

Davis, O. K. (1990). Preliminary report of the pollen analysis of Tulare Lake. *TULARG, Tulare Lake Archaeological Research Group* **3,** 2–5.

Davis, O. K. (1995). Climate and vegetation patterns in surface samples from arid Western U.S.A.: Application to Holocene climatic reconstructions. *Palynology* **19,** 95–117.

Davis, O. K., and Kailey, J. (1990). "Pollen Analysis of a Sediment Core from Mono Lake, Mono County, California." Report to Brian White and Susan Rowgahni, Los Angeles Department of Water and Power.

Harvey, T. H., Shellhammer, H. S., and Stecker, R. E. (1980). "Giant Sequoia Ecology, Fire and Reproduction." National Park Service Scientific Monograph Series No. 12.

Graumlich, L. J. (1993). A 1000-year record of temperature and precipitation in the Sierra Nevada. *Quaternary Research* **39,** 249–255.

Jacobson, G. L., and Grimm, E. C. (1986). A numerical analysis of Holocene forest and prairie vegetation in central Minnesota. *Ecology* **67,** 958–966.

Koehler, P. A., and Anderson, R. S. (1995). Thirty thousand years of vegetation changes in the Alabama Hills, Owens Valley, California. *Quaternary Research* **43,** 238–248.

Kruse, S. M. (1990). "Climatic Water Budgets, Effective Moisture, and Elevation in the Southern Sierra Nevada, California, 1951–80." Document submitted to Cooperative Park Resources, U.C. Davis.

Lajoie, K. (1968). "Quaternary Stratigraphy and Geologic History of Mono Basin." Ph.D. thesis, University of California, Berkeley.

LaMarche, V. C., Graybill, D. A., Fritts, H. C., and Rose, R. R. (1984). Increasing atmospheric carbon dioxide: Tree ring evidence for growth enhancement in natural vegetation. *Science* **255,** 1019–1021.

Litwin, R. J., Adam, D. P., Frederiksen, N. O., and Woolfenden, W. B. (1997). An 800,000-year pollen record from Owens Lake, California: Preliminary analyses. *In* "An 800,000-Year Paleoclimatic Record from Core OL-92, Owens Lake, Southeast California" (G. I. Smith and J. L. Bischoff, Eds.), pp. 143–160. Geological Society of America Special Paper 317.

Long, A., Davis, O. K., and De Lanois, J. (1992). Separation and ^{14}C dating of pure pollen from lake sediments: Nanofossil AMS dating. *Radiocarbon* **34,** 557–560.

Mason, D. (1967). "Limnology of Mono Lake, California." University of California Publications in Zoology 83.

Mehringer, P. J., Jr., Arno, S. F., and Petersen, K. L. (1977). Postglacial history of Lost Trail Pass Bog, Bitterroot Mountains, Montana. *Arctic and Alpine Research* **9,** 345–368.

Mono Basin Ecosystem Study Committee (1987). "The Mono Basin Ecosystem, Effects of Changing Lake Level." National Academy Press, Washington, DC.

Newton, M. S. (1994). Holocene fluctuations of Mono Lake, California: The sedimentary record. *SEPM Society for Sedimentary Geology Special Publication* **50,** 143–157.

Onken, J. (1991). "The Effect of Microenvironmental Temperature Variation on the Hydration of Late Holocene Mono Craters Volcanic Ashes from East-Central California." Unpublished M.S. thesis, University of Arizona.

Phillips, F. M., Zreda, M. G., Benson, L. V., Plummer, M. A., Elmore, D., and Sharma, P. (1996). Chronology for fluctuations in Late Pleistocene Sierra Nevada Glaciers and Lakes. *Science* **274,** 749–751.

Putnam, W. C. (1950). Moraine and shoreline relationships at Mono Lake, California. *Geological Society of America Bulletin* **61,** 115–122.

Russell, I. C. (1889). "Quaternary History of the Mono Valley, California," pp. 261–394. U.S. Geological Survey 8th Annual Report 1.

Scholl, D. W., Von Huene, R., St. Amand, P., and Ridlon, J. B. (1967). Age and origin of topography beneath Mono Lake, a remnant Pleistocene Lake, California. *Geological Society of America Bulletin* **78,** 583–600.

Shearman, D. J., McGugan, A., Stein, C., and Smith, A. J. (1989). Ikaite, $CaCO_3 \cdot 6H_2O$, precursor of the thinolites in the Quaternary tufas and tufa mounds of the Lahontan and Mono Lake Basins, western United States. *Geological Society of America Bulletin* **101,** 913–917.

Stine, S. (1990). Late Holocene fluctuations of Mono Lake, eastern California. *Paleogeography, Paleoclimatology, and Paleoecology* **78,** 333–381.

Vorster, P. (1985). "A Water Balance Forecast Model for Mono Lake, California." Earth Resources Monograph, USDA Forest Service Region 5, No. 10.

Woolfenden, W. S. (1996). "Late-Quaternary Vegetation History of the Southern Owens Valley Region, Inyo County, California." Unpublished Ph.D. dissertation, University of Arizona, 347 pp.