Reports

Uranium-Series Dating of Sediments from Searles Lake: Differences Between Continental and Marine Climate Records

Abstract. *One of the major unresolved questions in Pleistocene paleoclimatology has been whether continental climatic transitions are consistent with the glacial* $\delta^{18}O$ *marine record. Searles Lake in California, now a dry salt pan, is underlain by sediment layers deposited in a succession of lakes whose levels and salinities have fluctuated in response to changes in climate over the last* 3×10^6 *years. Uranium-series dates on the salt beds range from* 35×10^3 *to* 231×10^3 *years. This range of dates allows identification of lake-sediment horizons that are time correlatives of the boundaries of marine isotope stages from the recent 3/4 boundary back to the 8/9 boundary. The 5/6 boundary coincided with a deepening of the lake, but the analogous 1/2 boundary coincided with desiccation. The 3/4, 4/5, 6/7, 7/8, and 8/9 boundaries correspond in age to horizons that record little or no change in sedimentation or climate. These hydrologic results demonstrate that the continental paleoclimate record at this mid-latitude site does not mimic the marine record.*

High-latitude climatic change is well established from the marine oxygen-isotope record. An important remaining question is whether precipitation, temperature, and other climatic changes that affected mid-latitude continental landscapes were comparable in nature and similar in timing (*1*). Searles dry Lake in southeastern California (Fig. 1) is one site appropriate for testing the hydrologic component of that question. We report here the results of uranium-series dating of salt beds that identify the lacustrine horizons that are time correlatives of marine isotope stage boundaries 3/4 to 8/9.

Sediments beneath the surface of Searles Lake (Fig. 2), described elsewhere (*2, 3*), include a 700-m-thick sequence of clay, marl, and salt layers deposited during the last 3×10^6 years from a succession of lakes that fluctuated in size and salinity in response to climate change (*4*). Stratigraphic units in that record represent periods characterized by a particular climate, and boundaries between them represent times of change (*3*). During the wettest periods, when water stood at a level 200 m above the present dry surface, Searles Lake was the fourth in a chain of as many as six lakes that extended from Mono Lake east of the Sierra Nevada to Death Valley (Fig. 1). Most of the water supply came from the east side of the Sierra Nevada, which drained into the Owens River. During drier periods, flow in the Owens River was reduced, connections between the basins were interrupted, and dissolved salts that had accumulated in the terminal lakes were deposited.

The sediments down to 40 m have been dated by ^{14}C, with a maximum age of about 46×10^3 years (*2*). Paleomagnetic stratigraphy provides additional age control back to 3150×10^3 years (*5*). However, a 145-m gap exists between the deepest ^{14}C-age control and the first magnetic datum at 185 m, the 730×10^3 year Brunhes-Matuyama reversal. A ^{36}Cl date of 800×10^3 years on salts at 190 m is in agreement with the paleomagnetic stratigraphy (*6*). Until now, the ages of horizons between 40 and 185 m could be estimated only by extrapolation of sedimentation rates (*3*).

Peng *et al.* (*7*) determined uranium-series dates for a suite of samples from the upper and lower salts (Fig. 2) and found excellent agreement between their ^{230}Th ages and published ^{14}C ages. This finding opened the way for dating sediments from the upper part of the undated gap. This part of the section contains sediments equivalent in age to two important isotope stage boundaries, the 5/6 boundary (127×10^3 years) (*8*), which marks the end of the previous glaciation and beginning of the Sangamon interglaciation, and the 4/5 boundary (73×10^3 years), which marks the end of that interglaciation and the beginning of the Wisconsin glaciation.

We determined uranium-series isotopes on 24 pure salt samples collected from core LDW-6, located in the north-central part of Searles Lake (*2*). Samples were taken from about 36 to 153 m. Samples (10 g) were crushed, heated for 12 hours at 600°C, and then dissolved in aqua regia. Isotopes of uranium and thorium were isolated by ion-exchange chromatography and solvent extraction and analyzed by alpha spectroscopy according to the methods of Ku (*9*). We found that 16 of these samples had a sufficient uranium content and internally consistent isotope relations to permit

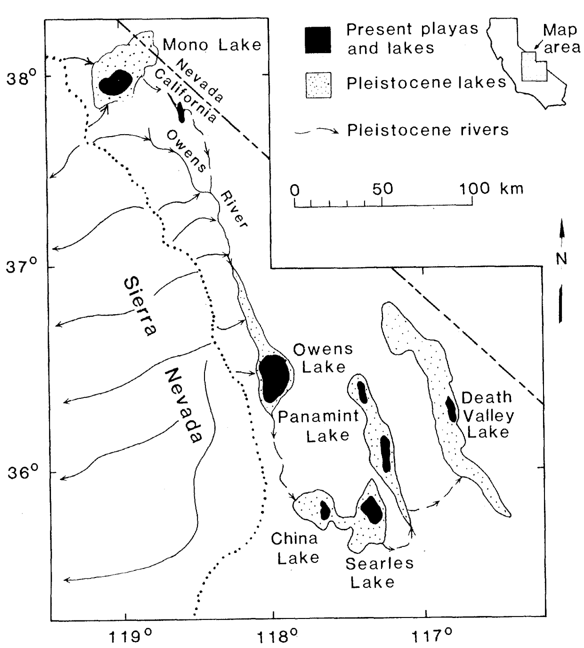

Fig. 1. Location of Searles Lake and other lakes that were connected with it in Pleistocene time [from Smith (*2*)].

calculation of absolute ^{230}Th dates (Table 1). None, however, had sufficient activity to permit utilization of the ^{231}Pa/^{235}U decay scheme. Of the 16 samples, ten yielded finite ages with an orderly increase in age with stratigraphic depth (Fig. 2). The remaining six, all from below 100 m, indicated isotopic equilibrium between ^{230}Th and ^{238}U and ages exceeding 330 × 10^3 years.

These new dates generally confirm the previously estimated ages of these climatically controlled lithologic boundaries, which present paleoclimatic dilemmas when compared with the ages of marine isotope stage boundaries (*4*). Three isotope stage boundaries (1/2, 2/3, and 5/6) closely correspond in age to

Table 1. Uranium-series analyses of salt beds from Searles Lake, California (drill core LDW-6). The abbreviations are explained in the caption of Fig. 2.

Sample	Depth (m)	Unit	Mineralogy	U (ppm)	^{234}U/^{238}U	^{230}Th/^{232}Th	^{230}Th/^{234}U	Age (10^3 years)
1	35.82	LS	Trona	0.22	1.25 ± 0.06	100	0.28 ± 0.02	$35.3^{+2.7}_{-2.4}$*
2	38.71	BM	Gaylussite	3.24	1.25 ± 0.02	11.5	0.42 ± 0.01	$58.4^{+1.5}_{-1.1}$
3	40.0	BM	Gaylussite	3.84	1.24 ± 0.03	10.9	0.46 ± 0.02	$65.5^{+3.3}_{-3.0}$
4	41.46	BM	Gaylussite	5.38	1.23 ± 0.01	8.5	0.48 ± 0.01	$69.8^{+1.8}_{-1.4}$
5	47.87	BM	Gaylussite	3.71	1.12 ± 0.06	11.3	0.57 ± 0.04	$89.3^{+9.3}_{-8.2}$
6	57.83	BM	Dolomite	25.7	1.14 ± 0.01	16.3	0.69 ± 0.01	$122.3^{+3.6}_{-3.0}$
7a†	67.46	ML (A + B)	Trona	2.70	1.11 ± 0.03	32.8	0.72 ± 0.02	$132.4^{+8.2}_{-7.0}$
7b†	67.46	ML (A + B)	Trona	3.69	1.13 ± 0.01	26.7	0.73 ± 0.02	$136.4^{+6.1}_{-5.1}$
8a†	68.11	ML (A + B)	Trona	0.51	1.16 ± 0.05	8.7	0.80 ± 0.03	$157.8^{+12.8}_{-10.8}$
8b†	68.11	ML (A + B)	Trona	1.69	1.14 ± 0.02	34.9	0.80 ± 0.02	$163.2^{+11.8}_{-9.9}$
9	79.57	ML (A + B)	Trona	3.47	1.16 ± 0.01	31.6	0.86 ± 0.02	$192.5^{+9.2}_{-7.5}$
11a†	83.48	ML (A + B)	Trona	0.19	1.28 ± 0.07	14.2	0.93 ± 0.05	$228.3^{+39.4}_{-28.6}$
11b†	83.48	ML (A + B)	Trona	0.18	1.19 ± 0.04	17.6	0.92 ± 0.03	$231.5^{+28.5}_{-21.6}$
13	99.16	ML (A + B)	Trona	0.67	1.13 ± 0.03	28.5	1.02 ± 0.03	∞ (>330)
14	110.49	ML (A + B)	Trona	0.37	1.09 ± 0.05	13.5	1.02 ± 0.04	∞ (>330)
15	113.1	ML (C)	Halite	1.20	1.06 ± 0.03	21.7	0.99 ± 0.03	∞ (>330)
18	126.52	ML (C)	Halite	2.65	1.05 ± 0.02	125.7	1.03 ± 0.03	∞ (>330)
21	142.37	ML (C)	Halite	1.18	1.02 ± 0.03	100	0.98 ± 0.03	∞ (>330)
24	153.0	ML (C)	Halite	0.21	1.03 ± 0.08	100	1.01 ± 0.07	∞ (>330)

*Based on counting error, 1 σ. †Duplicate splits from the same sample.

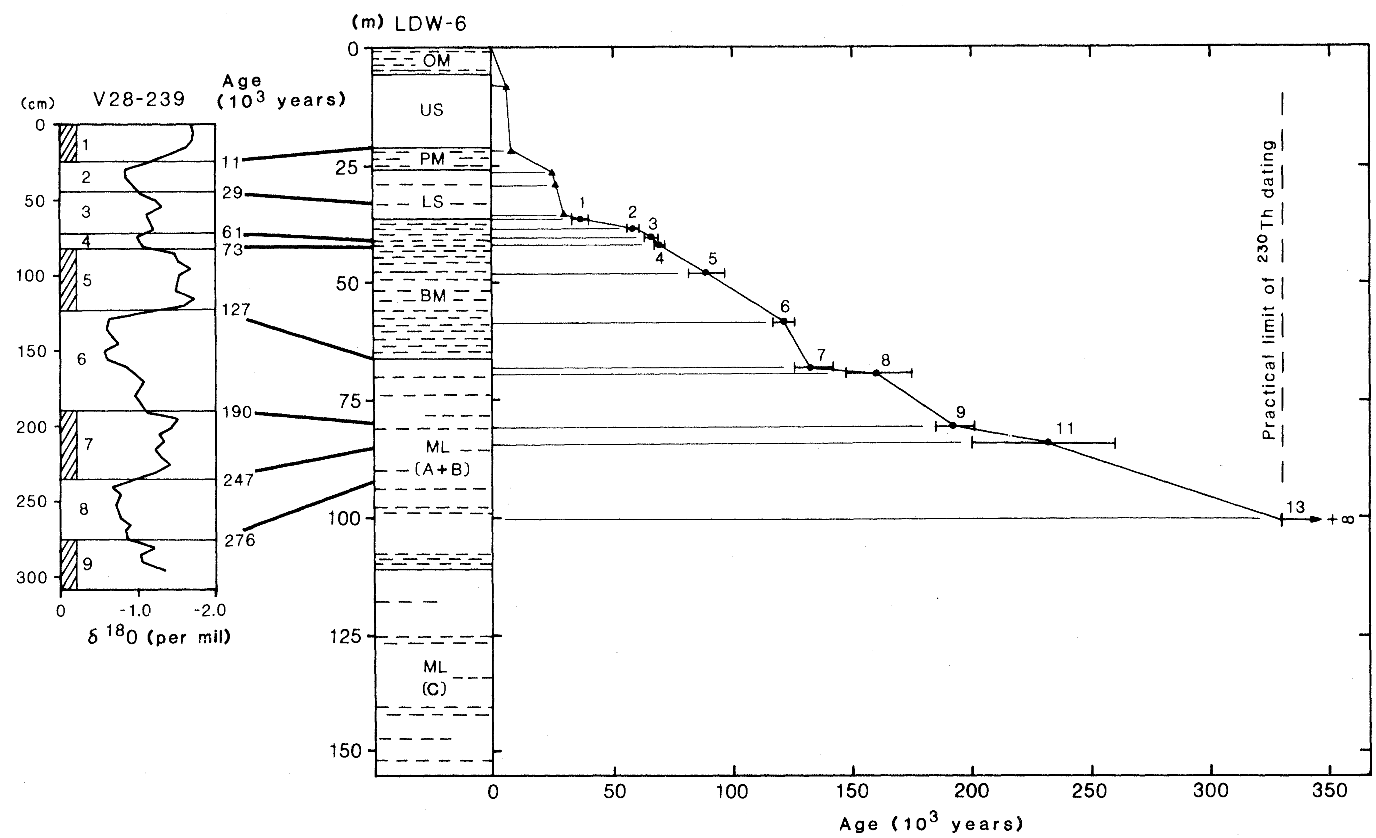

Fig. 2. Composite diagram showing the stratigraphy of Searles Lake core LDW-6, ^{230}Th ages from that core, and isotope variations and stage-boundary ages in Vema core 28-239, the standard section for marine isotope stages. Abbreviations: OM, overburden mud; US, upper salt; PM, parting mud; LS, lower salt; BM, bottom mud; ML, mixed layer with unit A + B and unit C of that sequence differentiated (*3*). Stratigraphic units are from Smith (*2*). The ^{230}Th ages from US and LS (triangles) are from Peng *et al.* (*7*); numbered ^{230}Th ages are from the present study (Table 1) with error bars representing counting uncertainties (1 σ). Isotope data for core V28-239 are from Shackleton and Opdyke (*11*); ages of boundaries are from Pisias and Moore (*8*).

lithologic boundaries in the Searles Lake sequence, and five stage boundaries (3/4, 4/5, 6/7, 7/8, and 8/9) do not (Fig. 2).

The similarity between the ages of both the 1/2 and 2/3 boundaries and the two ^{14}C-dated episodes of desiccation in Searles Lake has been noted (*4*). That study also noted the apparent correlation of the 5/6 isotope stage boundary at 127×10^3 years (*8*) and the estimated age of the contact between the mixed layer and the bottom mud (Fig. 2), but the age of that horizon was then too speculative to allow significant conclusions. The 5/6 stage boundary reflects a rapid change from glaciation to the beginning of the Sangamon interglaciation. At Searles Lake, the stratigraphic boundary represents a shift from an estimated 180×10^3 year period when lakes had intermediate depths and moderate salinities to a 100×10^3 year period when most lakes had great depths and low salinities (*2*). The new dates, therefore, confirm that the climatic changes seen in the marine and lacustrine records occurred very close to the same time. However, the nature of the indicated climate change was opposite to that occurring at the analogous 1/2 stage boundary when Searles Lake rapidly changed from a deep lake to a salt flat (*2, 4*).

The 3/4 and 4/5 isotope stage boundaries are equivalent in age to two horizons within the bottom mud. The lithology of the bottom mud, a dark green to black marl, indicates deposition in a series of mostly deep perennial lakes (*2*). Searles Lake sediments correlative with the 3/4 boundary (61×10^3 years) are bracketed by two dates within the bottom mud (samples 2 and 3). The 4/5 boundary at 73×10^3 years is equivalent in age to a horizon about 6 m below the top of the bottom mud, just below sample 4 (Fig. 2). No change in lake depth or sedimentation is evident during the time either horizon of the unit was deposited. Thus the lower 80 percent of the bottom mud is correlative with a time indicated by marine data as an interglacial period (Sangamon), and the upper 20 percent is correlative with the first half of the last glacial period (Wisconsin).

In core LDW-8, unit A + B of the underlying mixed layer is a sequence of about 30 monomineralic saline layers (mean thickness, 0.5 m) separated by brown- to olive-colored marl beds (mean, 0.7 m). The salines are predominantly trona or nahcolite which formed in a moderately saline lake that cooled seasonally. Marls indicate lake expansion, but the thinness of both the marl and the salt beds shows that the lake neither expanded nor precipitated salts for long periods (*3*). Horizons equivalent in age to the 6/7, 7/8, and 8/9 isotope stage boundaries, approximately 190×10^3, 247×10^3, and 276×10^3 years, lie within unit A + B of the mixed layer but do not correspond with any lithologic subdivisions (*3*). The youngest of these horizons is very close to sample 9. The two older horizons lie between samples 11 and 13, which precludes correlation of either stage boundary with the underlying contact between unit A + B and unit C of the mixed layer.

The new dates presented here confirm an earlier proposal (*4*) that there is an inconsistent relation between the marine isotope record of high-latitude glaciation and this record of mid-latitude hydrologic regimes. Is this hydrologic record a function solely of climate? Abrupt changes in water depths in Searles Lake could have been produced by nonclimatic processes such as faulting, stream piracy, or volcanism, and gradual change might have resulted from the topographic evolution of one or more basins and uplift of the Sierra Nevada. None of these processes, however, appears capable of causing repeated changes in the lake's inflow volumes that reached both low and high extremes several times. Furthermore, several direct lines of evidence indicate that the tributary region of Searles Lake over the past 300×10^3 years remained constant into the late Pleistocene (*3*). Except for the volcanic event that appears to have been responsible for the first lake in Searles Valley 3200×10^3 years ago (*3*), no eruptions appear to have had more than a temporary effect on the throughgoing drainage (*10*), and several lines of evidence suggest that the late Quaternary succession of basins resembled the middle Pliocene succession when the first lake formed.

We therefore interpret the lithologic changes observed in the cores and outcrops from Searles Valley as climatic in origin. Furthermore, there is circumstantial evidence from that record that glacial cycles did affect mid-latitude climates. The new dates, however, confirm the fact that those cycles had less impact on the intensity of local hydrologic regimes than other phenomena, and the suggestion (*4*) that the dominant factor was the 413,000-year orbital eccentricity cycle remains viable.

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Gas Exchange–Wind Speed Relation Measured with Sulfur Hexafluoride on a Lake

Abstract. *Gas-exchange processes control the uptake and release of various gases in natural systems such as oceans, rivers, and lakes. Not much is known about the effect of wind speed on gas exchange in such systems. In the experiment described here, sulfur hexafluoride was dissolved in lake water, and the rate of escape of the gas with wind speed (at wind speeds up to 6 meters per second) was determined over a 1-month period. A sharp change in the wind speed dependence of the gas-exchange coefficient was found at wind speeds of about 2.4 meters per second, in agreement with the results of wind-tunnel studies. However, the gas-exchange coefficients at wind speeds above 3 meters per second were smaller than those observed in wind tunnels and are in agreement with earlier lake and ocean results.*

Gas exchange across the air-water interface has received much attention (*1*) because it determines the degree of reaeration and the uptake and release of volatile pollutants in aquatic systems and because the oceans are a major sink for anthropogenic CO_2 (*2*). Gas-exchange processes have been studied in wind tunnels and in laboratory setups (*3*), and average oceanic gas-exchange coeffi-