200 k.y. paleoclimate record from Death Valley salt core

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ABSTRACT

A 186-m-long core (DV93-1) from Death Valley, California, composed of interbedded salts and muds contains a 200 k.y. record of closed-basin environments and paleoclimates, interpreted on the basis of sedimentology, ostracodes, homogenization temperatures of fluid inclusions in halite, and correlation with shoreline tufa. The 200 k.y. paleoclimate record is dominated by two dry and/or warm and wet and cold cycles that occurred on a 100 k.y. time scale. These cycles begin with mud-flat deposits (192 ka to bottom of core, and 60 ka to 120 ka). Wetter and/or colder conditions produced greater effective moisture; saline pan and shallow saline lake evaporites overlie mud-flat sediments (186 ka to 192 ka and 35 ka to 60 ka). Eventually, enough water entered Death Valley to sustain perennial lakes that had fluctuating water levels and salinities (120 ka to 186 ka and 10 ka to 35 ka). When more arid conditions returned, mud-flat deposits accumulated on top of the perennial lake sediments, completing the cycle (120 ka and 10 ka). Of particular significance are the major lacustrine phases, 10 ka to 35 ka and 120 ka to 186 ka (oxygen isotope stages 2 and 5e–6), which represent markedly colder and wetter conditions than those of modern Death Valley. Of the two major lake periods, the penultimate glacial lakes were deeper and far longer lasting than those of the last glacial.

INTRODUCTION

Arid closed-basin lacustrine deposits contain noteworthy paleoclimate records because the types of evaporites and associated sediments accumulated are sensitive to climate-related factors such as inflow water volumes, temperatures, regional storm tracks and wind patterns, and evaporation rates. Here we summarize results from DV93-1, a 186-m-long core composed of interbedded salt and mud, drilled in Death Valley, California (Figs. 1 and 2). The cored sediments contain a 200 k.y. record of closed-basin environments and paleoclimates ranging from dry mudflats, similar to the modern floor of Death Valley, to temperate-climate, deep perennial lakes. The paleoclimate record is based on sedimentology, ostracode species, correlations with shoreline tufa, and homogenization temperatures of fluid inclusions in halite.

Earlier workers suggested that Death Valley (Lake Manly) was the last of a chain of five lakes in southeastern California (Owens Lake, China Lake, Searles Lake, Panamint Lake) that were sometimes connected by successive spillover during wet periods of the Pleistocene (Smith, 1979). Although the exact timing of spillover from Panamint Lake into Death Valley is still uncertain, comparison of paleoclimate histories from Death Valley with Owens Lake, the first lake in the chain, gives a regional picture of paleoclimate. The paleoclimate record from Death Valley is also compared to the well-known cave calcite $\delta^{18}O$ record from nearby Devils Hole, Nevada. Death Valley is currently fed by inflow from the Amargosa River, which drains areas to the east of Death Valley in southern Nevada, including the Devils Hole (Fig. 1).

CORE DV93-1

Evaporite minerals from 12 stratigraphic intervals were dated using the uranium-series isochron method (Luo and Ku, 1991) (Figs. 2 and 3E). Dates not directly obtained via the U-series isochron method were calculated by interpolation, assuming constant accumulation rates for stratigraphic intervals with similar sediment types and depositional environments. Sedimentation rates, averaged over the 186 m core, are 1 m/k.y. Salts, predominantly halite, were deposited rapidly, 1.7–3.8 m/k.y., whereas muds accumulated more slowly, at rates of 0.4 to 1.0 m/k.y.

Paleoenvironments

Paleoenvironments existing in Death Valley over the past 200 k.y. have been interpreted on the basis of comparison between sedimentary structures and petrographic textures in modern closed-basin sediments and those observed in core DV93-1 (Smoot and Lowenstein, 1991; Roberts et al., 1994; Li et al., 1996) (Figs. 2 and 3A). Death Valley has been a mud-flat and saline pan over the past 10 k.y. (0–7.7 m: disrupted muds overlain by a 0.25-m-thick surface halite crust). Climate was arid with the water table normally below the surface. A perennial saline lake existed in Death Valley for a 25 k.y. period, from 10 to 35 ka (7.7–18 m: mud with rare ostracodes interlayered with subaqueous halite cumulates, chevrons, pisoids, and upward-directed, bottom-grown crystals). Periods of mud deposition represent the deepest, least saline, lake phases, whereas salts accumulated in shallower saline lakes. Saline pan evaporites, present from 35 to 60 ka (18–60 m: halite with extensive dissolution pipes and cavity cements) indicate that Death Valley was commonly desiccated at that time (Lowenstein and Hardie, 1985), but received enough inflow water to supply the solutes required to accumulate salts rapidly, at rates of 1.7 m/k.y. Five thin halite intervals between 43 and 52 m (ca. 50 to 54 ka) contain textures indicating that during this time, shallow saline lakes existed in Death Valley. From 60 to 120 ka (60–109 m), subaerially exposed mud-flat envi-

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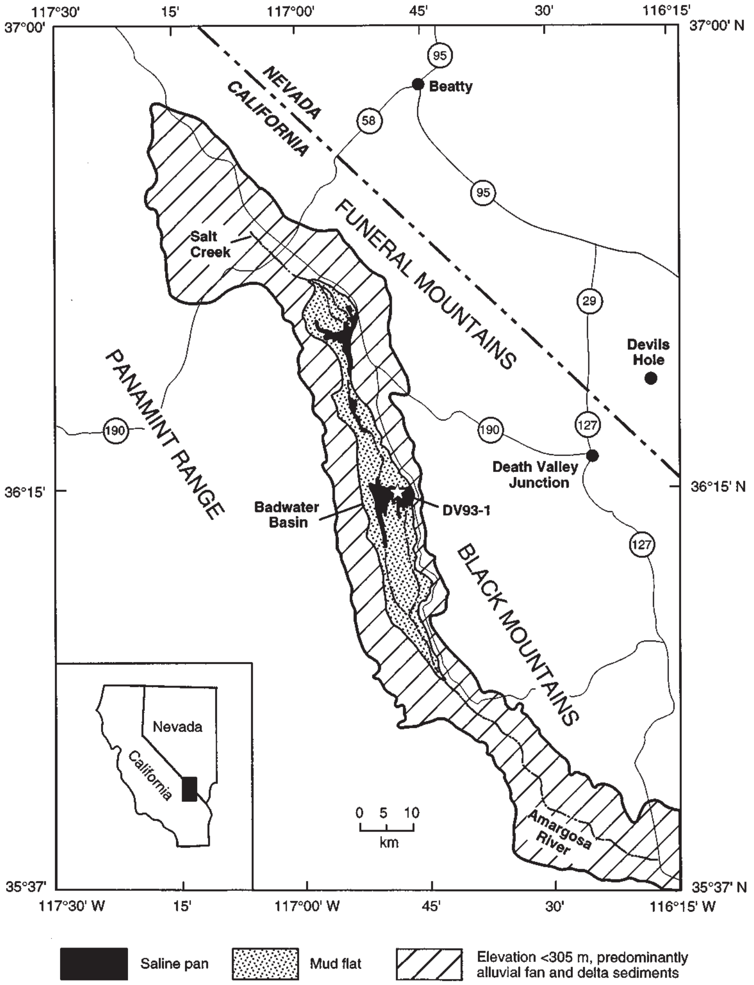

Figure 1. Map of Death Valley, California, and location of core DV93-1. Circled numbers are highways.

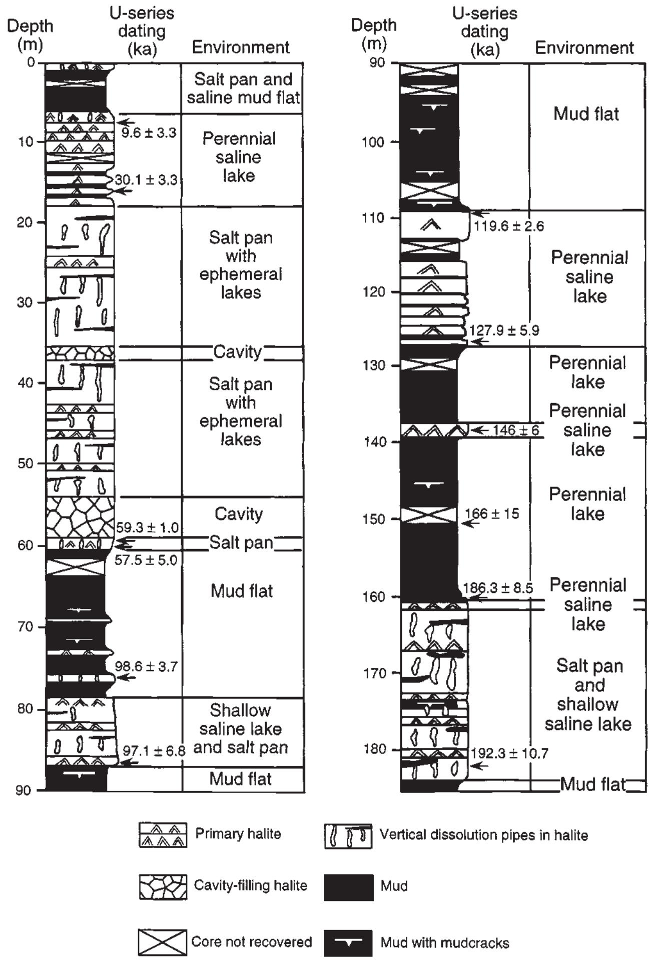

Figure 2. Stratigraphic column, core DV93-1, with U-series ages, sediment types, and paleoenvironments. Given age errors are one standard deviation derived from counting statistics and from fitting of isochrons.

ronments with subordinate saline pans dominated Death Valley, indicating basin aridity similar to modern conditions (silty muds with mudcracks, sand patch textures, and diagenetic saline minerals formed from ground-water brines)(Smoot and Lowenstein, 1991; Roberts et al., 1994). One halite interval, interpreted to have been deposited in shallow saline lake and saline pan settings, occurs from 74 to 87 m (ca. 98 ka).

Dark lacustrine muds (127–161 m) overlain by saline lake halites interlayered with muds (109–127 m) form a thick sequence of dominantly perennial lake sediments deposited over a period of 65 k.y., between 120 and 186 ka (Roberts et al., 1994). Halite layers at 152 m (166 ka) and 137.5 to 139.5 m (146 ka) indicate high salinities and probable shallower lake waters during deposition of these intervals. It is likely that lake levels and water salinities commonly fluctuated over the entire 65 k.y. lacustrine phase. The upper 18 m of the perennial lake succession consist of interlayered subaqueous halite and mud that record two major shallowing events between 120 and 128 ka, and final desiccation at 120 ka. The bottom 25 m of the core, 186 to 192 ka (161 to 186 m) is predominantly halite, formed in saline pan and shallow saline lake environments. The lowest meter of the core is composed of mudcracked silty mud, interpreted as a mud-flat deposit.

Ostracodes

Ostracodes from core DV93-1 (Fig. 3B) constrain the lower salinity limits of the two major perennial lakes in Death Valley during the last glacial period, 10–35 ka, and the penultimate glacial period, 120–186 ka (marine oxygen isotope stages 2, 5e–6). Perennial lake muds contain ostracode species *Limnocythere staplini*, *Limnocythere sappaensis*, *Limnocythere ceriotuberosa* and *Candona caudata*, which, although not abundant, indicate that the salinity of the Death Valley lakes in which the ostracodes lived was typically <10000 ppm, and at times, less than 3000 ppm for the salinity sensitive species *C. caudata* (Forester, 1987). Such less saline brackish lake phases are interpreted from *L. ceriotuberosa* and *C. caudata* occurrences at 10 m, 14 m, and 18 m (ca. 16 ka, 25 ka, and 34 ka) for the last glacial lake and 113–116 m, 125–126 m, 138–143 m, 157 m, and 162 m (ca. 121–123 ka, 127–129 ka, 146–154 ka, 179 ka, and 186 ka), for the penultimate glacial lake. Further details of the last glacial lake are missing because muds from depths of 9–14 m (ca. 12 to 25 ka) were partially lost during coring.

Shoreline Carbonate Tufas

Shoreline carbonate tufas provide information on the depths of Pleistocene lakes in Death Valley (Fig. 3C). Shoreline tufas, most prominent 90 m above sea level (175 m above the salt pan in Badwater basin), form horizontal terraces encrusting bedrock on the eastern side of Death Valley (Black Mountains between Badwater and Mormon Point) (Hooke, 1972). These tufas indicate former lake depths of up to 335 m, ignoring faulting, and adding 130 to 160 m of basinal sediments to reach equivalent age lacustrine sediments in core DV93-1. Tufas consist of porous, fine-grained carbonate as downward radiating “bushes” composed of micrite and concentrically banded “ball” structures composed of micrite and, less commonly, radial sparry calcite or radial fibrous calcite fans. Electron microprobe mapping of tufas revealed chemical zonation of Mg

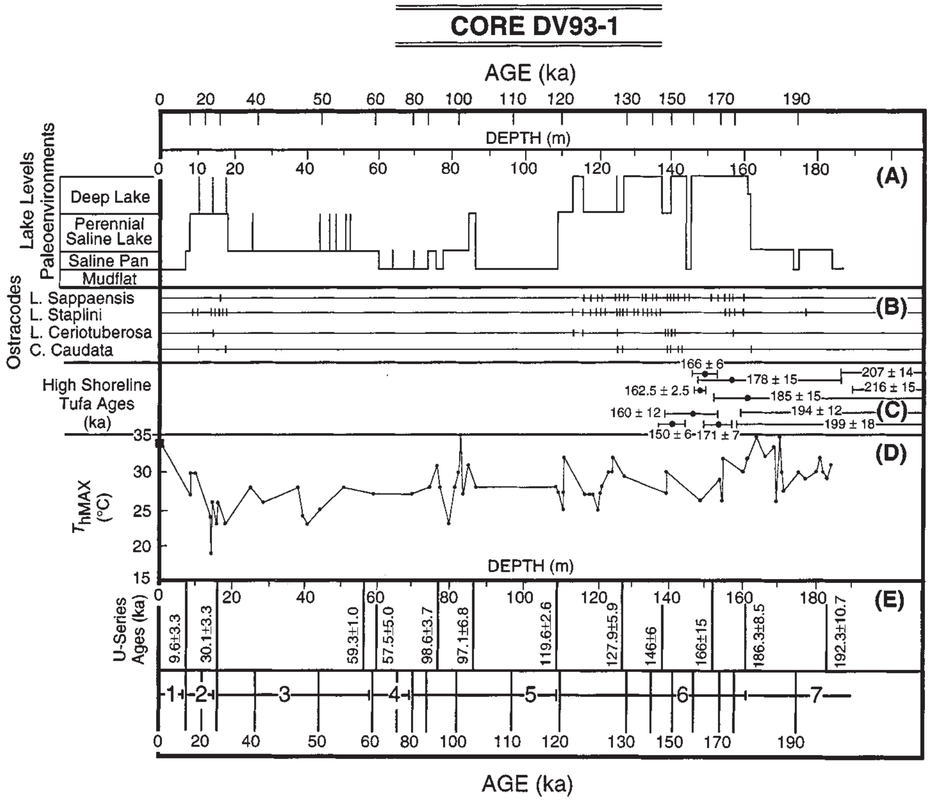

Figure 3. Paleoclimate record, Death Valley, over past 200 k.y. A: Lake levels and paleoenvironments, from driest to wettest: mud-flat, saline pan, perennial saline lake, and deep lake. B: Ostracodes. C: Uranium-series ages of high shoreline (about 90 m above sea level) carbonate tufas, Black Mountains, Death Valley. D: Maximum homogenization temperatures of fluid inclusions in halite (T_{hMAX}). E: Uranium-series ages, interpolated ages, and marine oxygen isotope stages.

and Sr coincident with textural and mineralogical (calcite and minor aragonite) boundaries. The above textural and geochemical features indicate that the tufas are not recrystallized nor have they undergone major cementation, both of which may complicate interpretation of age dates (Benson et al., 1990). Eleven tufas from the 90 m shoreline were dated by uranium-series methods (Luo and Ku, 1991). Of the 11 samples, 7 are 150–185 ka, which correlates with perennial lake sediments observed in core DV93-1 from 128 to 186 ka, and which therefore serves as an independent check confirming the reliability of the dating methods. In addition, a majority of tufas sampled from the same shoreline elevation by Hooke and Dorn (1992) had age dates between 120 and 200 ka. Four high shoreline tufas, from 73 to 90 m above sea level, dated between 194 and 216 ka, are older than any sediments from core DV93-1. These oldest tufas suggest the existence of yet a third perennial lake stage in Death Valley, ca. 200 ka, which is consistent with earlier age dating (Hooke and Dorn, 1992).

Fluid-Inclusion Paleotemperatures

The paleotemperature component of the Death Valley climate record is obtained from homogenization temperatures of fluid inclusions in subaqueously formed halites from core DV93-1, which record brine temperatures during salt crystallization (Goldstein and Reynolds, 1994; Roberts and Spencer, 1995; Lowenstein et al., 1998) (Fig. 3D). Shallow saline lake temperatures, in turn, correlate closely with air temperatures in modern settings (Roberts et al., 1997; Lowenstein et al., 1998). Crystals of halite with textures diagnostic of crystallization in a lacustrine environment and with initially one-phase liquid inclusions are chilled in a freezer at –5 °C to –20 °C in order to nucleate vapor bubbles without freezing the inclusions (Roberts and Spencer, 1995). These crystals, now with abundant two-phase liquid-vapor inclusions, are slowly heated to the temperature at which the vapor phase disappears and the fluid inclusions “homogenize” back to one liquid phase. The temperatures of homogenization record the original brine temperatures at which the crystal grew in the Death Valley saline lakes. Here we use maximum homogenization temperatures of fluid inclusions in halite, (T_{hMAX}), as a record of maximum brine temperature and maximum air temperature during halite crystallization, as was demonstrated for precipitation of halite from Death Valley in 1993 (Roberts and Spencer, 1995; Lowenstein et al., 1998). Halites in 66 stratigraphic intervals of DV93-1, from depths of 0 to 183.5 m (0–192 ka) have fluid inclusion homogenization temperatures commonly below the modern T_{hMAX} of 34 °C (maximum brine and air temperature during halite precipitation, late April and early May, 1993). Lacustrine halites deposited during the last glacial period, 10–35 ka, have low fluid-inclusion maximum homogenization temperatures (T_{hMAX} = 19 to 30 °C), which suggests brine temperatures ~4 ° to 15 °C below modern late April and May values. Ephemeral saline lake halites precipitated from 35 to 60 ka have T_{hMAX} between 23 and 28 °C, 6 to 11 °C below the modern T_{hMAX} values. A relatively low temperature interval, 10 °C below the modern, existed ca. 47 to 50 ka. Limited data from fluid inclusions in two halite intervals, ca. 80 and 92 ka, suggest generally cool conditions, 6 to 7 °C below modern late April–May temperatures. Relatively higher T_{hMAX} values, to 34 °C and 35 °C in halite dated as ca. 100 ka, and to 32 °C in halite dated as 120 ka, may record climate regimes more similar to the modern. However, these temperatures are still below modern mid-summer temperatures in Death Valley (average air temperatures in Death Valley are 39 °C in July and 37 °C in August; average maximum air temperatures are 46 °C in July and 45 °C in August).

Generally colder conditions are recorded in most fluid inclusions in halite for the 120–186 ka perennial lake sequence, where T_{hMAX} values range from 25 to 32 °C, but only 3 of 22 stratigraphic intervals have T_{hMAX} >30 °C. A combination of homogenization temperatures of fluid inclusions in halite and petrographic evidence of possible pseudomorphs of hydrohalite suggest that temperatures in the perennial lakes may have dropped below 0 °C at times and that temperatures over this period probably averaged 10 to 15 °C below the modern (Roberts et al., 1997). In the bottom 25 m of DV93-1 (164 to 184 m, 186 to 192 ka), homogenization temperatures are relatively high. Of 19 stratigraphic intervals analyzed, 14 have T_{hMAX} values greater than or equal to 30 °C, which is similar to those obtained from halite precipitated in Death Valley in late April and early May.

SUMMARY AND COMPARISONS WITH OTHER PALEOCLIMATE RECORDS

The 200 k.y. paleoclimate record of Death Valley is dominated by two dry and/or warm and wet/cold cycles that occurred on a 100 k.y. time scale (Fig. 3). These cycles begin with mud-flat deposits (192 ka to bottom of core, and 60 to 120 ka). Wetter conditions, colder climates, or both, produced greater effective moisture, evidenced by saline pan and ephemeral saline lake sediments that overlie the mud-flat sediments (186 to 192 ka and 35 to 60 ka). Eventually, enough water was supplied to sustain fluctuating perennial lakes (120 to 186 ka and 10 to 35 ka). When the perennial lake phases ended (120 ka and 10 ka) dry conditions led to the accumulation of mud-flat deposits, completing the cycle. Of particular importance are the major lacustrine phases at 10 to 35 ka and 120 to 186 ka (oxygen isotope stages 2, 5e/6), which represent markedly colder and wetter conditions than those in modern Death Valley. Of the two perennial lake periods, the penultimate period had deeper and far longer lasting lakes than the last glacial lake.

The Death Valley salt core closely matches the paleoclimate record in core OL-92 from nearby Owens Lake, California (Bischoff et al., 1997; Bradbury, 1997; Menking et al., 1997; Smith and Bischoff, 1997), which suggests that climate fluctuations in the region were roughly synchronous over the past 200 k.y. Although dating techniques for cores DV93-1 (uranium-series isochron) and OL-92 (radiocarbon, known age of Bishop ash bed, constant mass accumulation rates) differed, most major paleoenvironmental changes in both basins occurred at more or less the same time. High calcite content, abundant smectite, and saline diatoms were criteria used to establish that relatively dry, closed-lake conditions existed at Owens Lake between ca. 53 and 118 ka, which matches the long interval of dry climate in Death Valley between ca. 60 and 120 ka. Low calcite and freshwater diatoms were criteria used to interpret high spillover conditions in Owens Lake between 10 and 50 ka and from 120 to 155 ka or earlier (Bischoff et al., 1997; Bradbury, 1997; Menking et al., 1997), which overlap equivalent wet periods in Death Valley. Bischoff et al.(1997) identified five intervals of relatively high plagioclase feldspar content in core OL-92 (14 to 27 ka, 31 to 37 ka, 48 to 60 ka, 120 to 140 ka, and 146 to 155 ka) which were interpreted as contributions from glacial rock flour and hence, records of glacial advances. These periods overlap with times of glacial advance established from ^{36}Cl dates on Sierra Nevada glacial moraines (Phillips et al., 1990) and with low fluid inclusion T_{hMAX} values in core DV93-1 between ca. 25 and 34 ka, 47 to 50 ka, and 120 and 186 ka.

The major changes in paleoenvironments in Death Valley (mud-flat) and Owens Lake (closed-lake) at 120 ka merit further discussion because the timing is different from Termination II established from the marine record (128 ka) and from the Devils Hole (142 ka) (Winograd et al., 1997). In Death Valley, dominantly freshwater lake deposits (128 to 186 ka) are overlain by saline lake deposits (120 to 128 ka) and then mud-flat deposits at 120 ka. The shift toward more arid conditions in Death Valley began sometime before 128 ka, when lake waters underwent progressive evaporative concentration ultimately leading to halite precipitation at ~128 ka. The same appears to be true in Owens Lake, where δ^{18}O values from lake carbonates begin to increase after 145 ka, signaling progressively more closed lake conditions. Therefore, correlations between the Owens Lake and Death Valley climate records and the Devils Hole appear to be proxy dependent (Menking et al., 1997).

Comparison of Death Valley fluid inclusion paleotemperatures with the Devils Hole calcite δ^{18}O record shows agreement between ca. 60 and 100 ka and from ca. 150 to 186 ka, with low values of δ^{18}O and low T_{hMAX} (Winograd et al., 1997). However, in contrast to the high δ^{18}O values in Devils Hole calcites beginning ca. 145 ka and lasting until ca. 120 ka, the Death Valley fluid inclusion record, although limited during this wet period (120 to 128 ka, 146 ka), does not show major warming. Death Valley fluid inclusion T_{hMAX} values are highest at ca. 100 ka, also apparently at odds with the Devils Hole record where δ^{18}O falls to low values (Winograd et al., 1997). Additional dating studies of core DV93-1 and other climate records will be needed to further resolve the timing of regional climate changes in the southwestern United States during the end of the penultimate glaciation and the last interglacial period.

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