# POLLEN ANALYSIS OF DEATH VALLEY SEDIMENTS DEPOSITED BETWEEN 166 AND 114 KA

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## Abstract

Salt Core DV93-1, from Badwater Basin in California's Death Valley, is a nearly complete sedimentary record of mud and evaporite deposits spanning the past 192 ka. Fossil palynomorph assemblages from core depths of 151.8 m (ca. 166 ka) to 103.5 m (ca. 114 ka) have been analyzed as part of a larger study which will eventually include all of core DV93-1. The palynological analysis discussed here reveals four pollen zones between 151.8 m and 103.5 m. Zone 1, the "Cheno–Am" zone (151.8 m to 143.5 m depth, 166–154 ka), has high percentages of Chenopodiaceae/*Amaranthus* (Cheno–Am) pollen, and is correlative with the end of marine Oxygen Isotope Stage (OIS) 7. Zone 2, the juniper zone (143.5 m to 117.3 m, 154–124 ka), correlates with OIS 6, as evidenced by high percentages of juniper (Cupressaceae) pollen and low percentages of *Ambrosia* pollen. Equivalent pollen assemblages are found at higher elevations in Death Valley today, where temperatures are 11° C cooler and rainfall is eight times greater. At the top of Zone 2 (124 ka), a simultaneous drop in juniper and increase in oak *(Quercus)* pollen occurs, followed by a replacement of *Artemisia* with *Ambrosia* in Zone 3, the oak zone. This event corresponds to warming associated with Termination II. The estimated age of this warming event is in agreement with the Termination II event visible in the pollen record from nearby Owens Lake (Litwin et al., 1997). Zone 4, the Asteraceae zone (108.8 m to 103.5 m, 119–115 ka), contains higher percentages of Asteraceae and Cheno–Am pollen, indicating further warming during this time.

## INTRODUCTION

The marine oxygen isotope record (Imbrie et al., 1982) has greatly influenced Quaternary climate studies. However, the correlation of the marine record with terrestrial paleoclimate records has been a matter of some debate (Winograd et al., 1992, 1997; Imbrie et al., 1982, 1992; Crowley and Kim, 1994; Johnson and Wright, 1989; Schaffer et al., 1996; etc.). Additional long terrestrial records of Quaternary climate change are therefore of great scientific value in resolving this debate. One such record is presently being assembled for the southwestern United States using core DV93-1, a 186-meter section of mud and evaporite deposits from Badwater Basin in California's Death Valley (Text-Figure 1). Lithologic indicators from core DV93-1 show that the closed Death Valley Basin has experienced repeated wet–dry periods over the past 200 ka (Li et al., 1996; Lowenstein et al., 1999). The mudflat environment, exemplified by the Amargosa River delta south of Badwater (Text-Figure 1), is indicated in the core by clay and silt with associated mudcracks and disrupted sand layers. The saltpan environment, which exists today in the Badwater Basin, is indicated by halite with dissolution pipes and vugs. During wet phases, paleo-lake "Manly" occupied the basin. The lithologic indicators of a lake are saltpan facies during the early lake stage, banded thenardite and mud, and a cap of massive primary halite from the latest lake stage (Li et al., 1996). This paper presents the results of a palynological analysis of a portion of core DV93-1, spanning 103.5 to 151.8 m depth, and ages from 114 to 166 ka. Pollen from the upper section of the core is presently being analyzed at the University of Arizona.

The palynological analyses will be added to a substantial body of existing work on DV93-1. The core was collected by T.K. Lowenstein and a Denver USGS drilling crew in 1993, from Death Valley northwest of Badwater, N 36° 13' 46.4", W 116° 46' 4.4" (Lowenstein, 1993). Twelve U-series dates from evaporites in the core provide chronological control for the past 200 ka. Li et al. (1996) compiled a chronology of changes in lake levels using core sediments. In addition, Li et al. (1997) used the mineralogy of the sediments to identify the sources of water flow into the Badwater Basin. Roberts et al. (1997) and Lowenstein et al. (1999) have analyzed fluid inclusions in halite within the core to estimate paleotemperatures.

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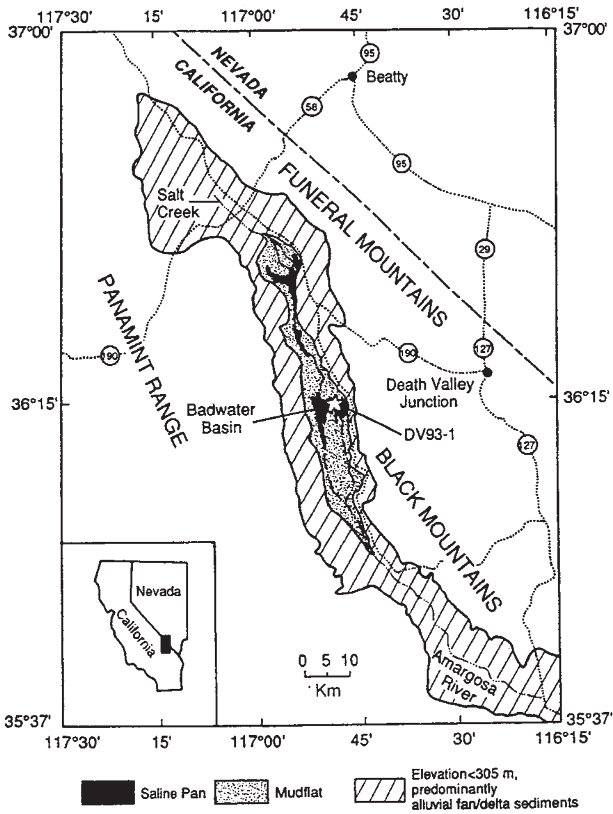


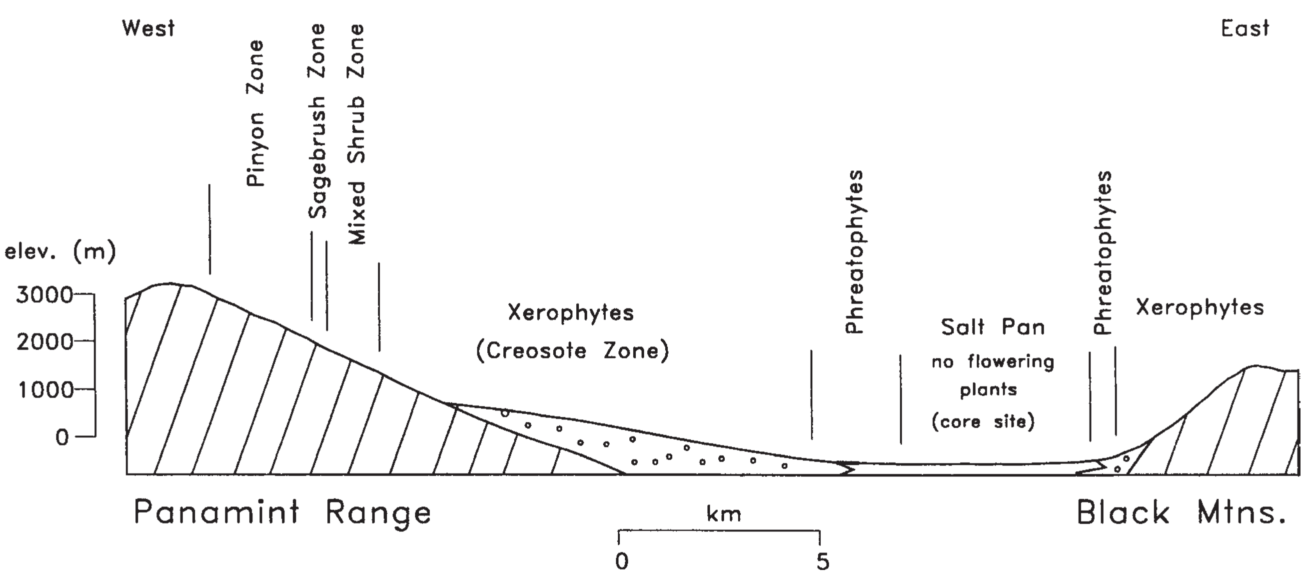

Text-Figure 1. Area map showing location of core DV93-1 (from Lowenstein, 1999). Circled numbers are highways.

The results of this study offer a valuable opportunity to compare paleoclimate indicators from Death Valley with paleoclimate indicators from other long terrestrial records. Due to its low elevation and extreme temperature fluctuations, Death Valley could be considered the most "continental" climate in the Western Hemisphere. Two nearby long records are core DH-11 from Devils Hole (Winograd et al., 1992), a record of stable isotopes from vein calcite 50 km east of Death Valley, and the Owens Lake pollen record (Litwin et al., 1997), from a playa 90 km west of Death Valley.

## MODERN VEGETATION DISTRIBUTION

Death Valley is located in a transitional zone between the low-elevation Mojave desert to the south and the higher-elevation Great Basin desert to the north. The floor of Death Valley's Badwater Basin reaches 86 m below sea level, and Telescope Peak in the adjacent Panamint Range rises to 3368 m elevation (Text-Figure 2). As the elevation increases, the climate changes from a high-temperature, low-rainfall regime typical of the Mojave desert to a cooler, wetter Great Basin climate (Beatley 1975). Vegetation zones can be defined at different elevations in the mountains according to the presence of key taxa (Table 1). Mojave desert-type taxa such as *Larrea tridentata* and *Ambrosia dumosa* characterize low elevations. At high elevations, Great Basin types such as *Artemisia tridentata* are dominant.

Peterson (1986) defined 4 zones in the Cottonwood Mountains in the northern Panamint Range adjacent to




Text-Figure 2. A generalized cross section of Badwater Basin, Death Valley, with modern vegetation zones. (Adapted from Hunt, 1966)

TABLE 1. The dominant species of modern Death Valley vegetation zones, and their associated pollen types from Text-Figure 4. Zone elevations are approximate. Pollen types in parentheses were absent or rare in the fossil spectra.

| | Dominant species | Common name | Pollen type |
|---|---|---|---|
| Pinyon zone: 2000m-3000m | *Pinus monophylla* | pinyon pine | *Pinus* |
| | *Juniperus osteosperma* | Utah juniper | Cupressaceae |
| | *Artemisia tridentata* | big sagebrush | *Artemisia* |
| | *Artemisia nova* | black sagebrush | *Artemisia* |
| Sagebrush zone: 1900m-2000m | *Artemisia tridentata* | big sagebrush | *Artemisia* |
| | *Artemisia nova* | black sagebrush | *Artemisia* |
| Mixed shrub zone: 1500m-1900m | *Ericameria cooperi* | Cooper golden bush | other Asteraceae |
| | *Atriplex confertifolia* | shadscale | Cheno-Am |
| | *Atriplex canescens* | four-wing saltbush | Cheno-Am |
| | *Grayia spinosa* | hopsage | Cheno-Am |
| | *Ephedra viridis* | green joint-fir | *Ephedra* |
| | *Ephedra nevadensis* | boundary joint-fir | *Ephedra* |
| | *Coleogyne ramosissima* | blackbrush | Cercocarpus |
| | *Purshia glandulosa* | sticky cinquefoil | Cercocarpus |
| | *Eriogonum fasciculatum* | wild buckwheat | *Eriogonum* |
| | *Lycium andersonii* | wolfberry | (Solanaceae) |
| Xerophyte zone: on gravel fans up to 1500m | *Atriplex hymenelytra* | desert holly | Cheno-Am |
| | *Atriplex polycarpa* | cattle spinach | Cheno-Am |
| | *Ambrosia dumosa* | white bursage | *Ambrosia* |
| | *Encelia farinosa* | brittlebush | other Asteraceae |
| | *Hymenoclea salsola* | cheesebush | *Ambrosia* |
| | *Larrea tridentata* | creeosote bush | (*Larrea*) |
| Phreatophyte zone: at margins of salt pan | *Atriplex canescens* | four-wing saltbush | Cheno-Am |
| | *Allenrolfia occidentalis* | pickleweed | Cheno-Am |
| | *Suaeda suffrutescens* | inkweed | Cheno-Am |
| | *Pluchea sericea* | arrowweed | other Asteraceae |
| | *Distichlis spicata* var. *stricta* | salt grass | Poaceae |
| | *Sporobolus airoides* | alkali sacaton grass | Poaceae |
| | *Prosopis juliflora* | honey mesquite | (*Prosopis*) |

Death Valley (Text-Figure 2); from low to high elevation, these are the creosote zone, mixed shrub zone, sagebrush zone, and pinyon zone. The creosote zone is characterized by *Larrea tridentata*, which grows below 1800 m elevation (this is the same as the xerophyte zone of Hunt, 1966, see below). In the upper part of this zone, *Larrea* is associated with *Ambrosia dumosa*, *Atriplex confertifolia*, and *Dalea emoryi*. This community is typical of the Mojave desert flora. Above the limit of *Larrea* is the mixed shrub zone, from between 1500 m and 1900 m, which contains flora that are transitional between the Mojave and the Great Basin types. The mixed shrub zone in the Cottonwood Mountains hosts *Ericameria cooperi*, *Atriplex confertifolia*, *A. canescens*, *Grayia spinosa*, *Ephedra viridis*, *E. nevadensis*, *Coleogyne ramosissima*, *Purshia glandulosa*, *Eriogonum fasciculatum*, and *Lycium andersonii* (Peterson, 1986). The upper limit of the mixed shrub zone is marked by the presence of sagebrush (*Artemisia tridentata* and *A. nova*). *A. tridentata* and *Atriplex confertifolia* are characteristic plants of the Great Basin desert (Beatley, 1975). Sagebrush grows from about 1220 m to 3300 m (Thorne, 1982), but typically dominates from about 1900 m up to the lower limit of the pinyon zone. The pinyon zone characterizes elevations above about 1950 m, where precipitation exceeds 200 mm annually (Woodcock, 1986). The plant community of the pinyon zone is an open forest of *Pinus monophylla* and *Juniperus osteosperma* growing with *Artemisia*. The area near Telescope Peak in the Panamint Range (summit 3368 m) is high enough to support a limited forest of *Pinus jeffreyi* and *Pinus longaeva* (Parish, 1930).

In the valley floor, vegetation zones are not defined by elevation, but by their proximity to the water table (Hunt,

1966) (Text-Figure 2). Phreatophytic plants occupy the lowest elevations in the basin, since the salt pan itself is barren of plant life. Phreatophytes inhabit a zone about a mile wide surrounding the salt pan, in which the soil is sandy and the water table is close to the surface. The common phreatophytes are *Atriplex canescens*, *Allenrolfia occidentalis*, *Suaeda suffrutescens*, *Pluchea sericea*, *Distichlis spicata* var. *stricta*, *Sporobolus airoides*, and *Prosopis juliflora*. Surrounding the zone of phreatophytic plants are broad, coalescing alluvial fans. The gravels composing the fans are well drained and the water table is far below the surface. Only xerophytic plants grow in this zone. These include *Atriplex hymenelytra*, *Atriplex polycarpa*, *Encelia farinosa*, *Ambrosia dumosa*, *Hymenoclea salsola*, and *Larrea tridentata* (Hunt, 1966).

## MODERN POLLEN

Pollen was extracted from a salt sample taken from the surface in Badwater Basin, near the location of core DV93-1 (Table 2). A high percentage of *Ambrosia* pollen and low percentages of *Artemisia* and Cupressaceae pollen in the surface sample are reflections of Mojave desert vegetation, and the hot climate in Death Valley today. It is noteworthy that the core was taken from the salt pan, which supports no plant life. Therefore, any pollen which settled in the core location must either have been blown in or washed in from some distance away. This causes the signal from wind-pollinated taxa, such as *Pinus* and *Quercus*, to be amplified in the pollen record compared to insect-pollinated taxa such as *Larrea*, which have short pollen transport distances.

Martin (1964) collected modern surface pollen along a transect in the Panamint Range between 910 m and 2430 m elevation (Text-Figure 3). Although a surface pollen record is not directly comparable to a pollen record from a playa lake (Fall, 1992), some useful generalizations can be made concerning the modern pollen rain. Below 1800 m elevation, Cheno–Ams and Asteraceae (including *Ambrosia*) dominate the pollen samples. At samples above 1800 m, *Artemisia* and Cupressaceae dominate. The samples from core DV93-1 should presumably exhibit a higher percentage of *Artemisia* and Cupressaceae pollen during cold periods when conditions in the basin were similar to those at higher elevations today.

## METHODS

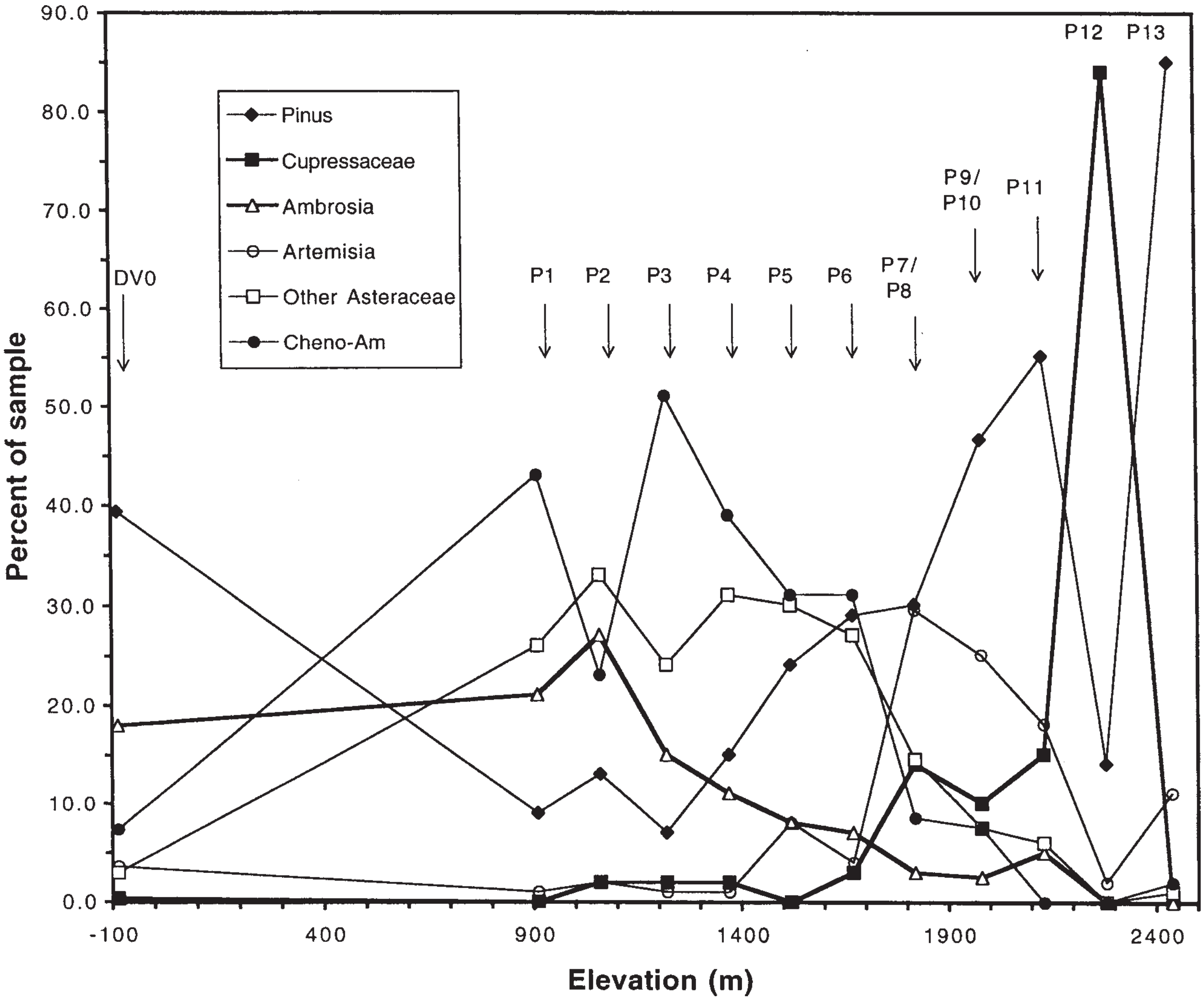
The ages of the samples were estimated using U-series dates of 12 core horizons provided by Ku et al. (1998). These authors targeted the tops and bottoms of salt-rich layers in DV93-1, and extracted primary halite crystals enclosing clays and organic material suitable for U-series dating. Details of the $^{230}Th/^{234}U$ technique are fully discussed by Bischoff and Fitzpatrick (1991) and Luo and Ku (1991). The five dates which are applicable to this study are listed in Table 3. Errors for the dates were calculated using the method of Luo and Ku (1991), which takes into account the radiochemical errors of $^{230}Th/^{234}U$ and $^{232}Th/^{234}U$ and the scatter errors of detrital $^{230}Th/^{232}Th$ ratios. Estimated sample ages were obtained by assuming a constant rate of deposition throughout each interval between pairs of U-series ages, then interpolating to find ages for specific depths.

Pollen was extracted from the sediment samples by routine acid digestion (Table 4). Palynomorphs were tabulated for each sample until an upland pollen sum of 300 grains was attained, if possible. Each pollen type was then converted to a percentage of the total (upland pollen including deteriorated) sum (Text-Figure 4). Low pollen sums reduce the reliability of percentage data in some samples (Text-Figure 5).

The number and placement of the pollen zones was determined informally by defining boundaries based on changes in the proportion of types which are believed to be climatically significant. In addition, an analysis of squared-chord distance ($d_{ij}$) was employed as a measure of dissimilarity between each fossil sample and each of the modern pollen samples, defined as:

TABLE 2. Palynomorph types from the Badwater surface sample, -86 m elevation. Individual types which are below 2% of the total are not listed.

| Type | Percent |
|---|---|
| *Pinus* | 39.4 |
| *Quercus* | 3.4 |
| *Ephedra* | 2.5 |
| *Ambrosia* | 18.0 |
| *Artemisia* | 3.6 |
| Other Asteraceae | 2.9 |
| Cheno-Ams | 7.4 |
| Algal Spores | 3.8 |
| Fungal Spores | 6.5 |
| Charcoal | 6.2 |
| Total trees | 44.3 |
| Total shrubs | 2.8 |
| Comps+Chenos+Grass | 32.7 |
| Total herbs | 2.1 |
| Total wetland woody types | 1.0 |
| Total wetland herbs | 1.1 |
| Deteriorated | 18.1 |




Text-Figure 3. Modern pollen percentages. At left ("DV0"), Badwater surface sample. Other elevations represent surface samples in the Panamint Mountains (P1, P2, etc.) (Martin, 1964). The mean of samples 7 and 8 and samples 9 and 10 are displayed here, as 7 and 8 were both collected at 1880 m elevation, while 9 and 10 were both collected at 1920 m elevation.

$$d_{ij} = \sum_k \left( \sqrt{p_{ik}} - \sqrt{p_{jk}} \right)^2$$

where $i$ represents a fossil sample, $j$ represents a modern sample, and $P_{ik}$ represents the proportion of pollen type $k$ in sample $i$.

In this manner, each fossil sample could be assigned a paleo-elevation, that is, the elevation at which the closest analogue to the fossil pollen assemblage is found today (Text-Figure 6). The boundaries resulting from this analysis were then compared to the boundaries assigned to pollen zones based on the pollen diagram. Results from this method should be interpreted with care, as fossil samples from a playa lake are not directly comparable to surface samples (Fall, 1992).

Paleoclimate interpretations can be based on a number of variables from a pollen analysis. Litwin et al. (1997) use the relative frequency of Cupressaceae pollen as a percentage of the total upland sum minus *Pinus*. In Death Valley, *Juniperus osteosperma* is the principal source of Cupressaceae-type pollen. *J. osteosperma* is a useful indicator taxon because it is sensitive to changes in climate, particularly moisture (Miller and Wigand, 1994). High percentages of Cupressaceae pollen generally correspond to colder intervals in the southern Great Basin and Mojave Desert region. Another way to model climate change in Death Valley is to compare Mojave (hot,

TABLE 3. Applicable U-series ages from core DV93-1 (from Ku et al., 1998).

| Sample no. | Depth in core (m) | $^{234}U/^{238}U_{auth}$ | $^{230}Th/^{234}U_{auth}$ | Age ($10^3$ yrs) |
|---|---|---|---|---|
| S3-B | 86.7 | 1.556 ± 0.028 | 0.618 ± 0.027 | 97.1 ± 6.8 |
| S4-T | 109.3 | 1.424 ± 0.015 | 0.698 ± 0.007 | 120 ± 3 |
| S4-B | 126.8 | 1.453 ± 0.023 | 0.727 ± 0.017 | 128 ± 6 |
| S5 | 138.2 | 1.480 ± 0.028 | 0.783 ± 0.014 | 146 ± 6 |
| sub-S5 | 152 | 1.498 ± 0.019 | 0.826 ± 0.036 | 166 ± 15 |

low elevation) pollen, represented by *Ambrosia*, with the cold, high-elevation Great Basin Desert indicators *Artemisia* and Cupressaceae. This can be accomplished by using the ratio *Ambrosia*/ (*Ambrosia* + *Artemisia* + Cupressaceae) (Text-Figure 7), which should yield values near 1 during warm periods, and lower values during cold periods. *Pinus* pollen, which is abundant in all four zones, indicates the importance of long-distance pollen transport.

TABLE 4. Pollen extraction by acid digestion.

A. Add 1 $cm^3$ sample to ca. 50 ml water with detergent, agitate 10 min.
B. Swirl solution and screen (180 (m mesh, stainless steel) into second beaker.
C. Transfer to 50 ml test tubes, rinse, add 10 ml 10% HCl.
D. Add 1 *Lycopodium* tablet (average 13,911 spores).
E. Transfer screened solution to 50 ml Nalgene test tubes repeat "D", centrifuging, until complete.
F. Add 10 ml conc. HCl, mix, add 30 ml $H_2O$, mix centrifuge, decant, water rinse.
G. Add 40 ml HF, let stand overnight centrifuge, decant, water rinse, transfer to 15 ml glass tubes.
H. Acetolysis:
1. Add 5 ml glacial acetic acid centrifuge and decant.
2. Stir sample, add 5 ml acetic anhydride (volumetric dispenser).
3. Add 0.55 ml $H_2SO_4$ to acetic anhydride solution (volumetric pipet), mix, centrifuge, decant into glacial acetic acid.
4. Add 5 ml glacial acetic acid centrifuge and decant.
5. Centrifuge, decant, water rinse.
I. Add 10 ml hot 10% KOH 2 min. from boiling water bath centrifuge, decant, rinse with hot water until clear.
J. Stain with safranin "O".
K. Transfer to labeled 1 dram shell vials.
L. Add a few drops of glycerine.
M. Desiccate.

## RESULTS: DV93-1 POLLEN ZONES

### Zone 1: Cheno–Am zone, 151.8–143.5 m, 166–154 ka

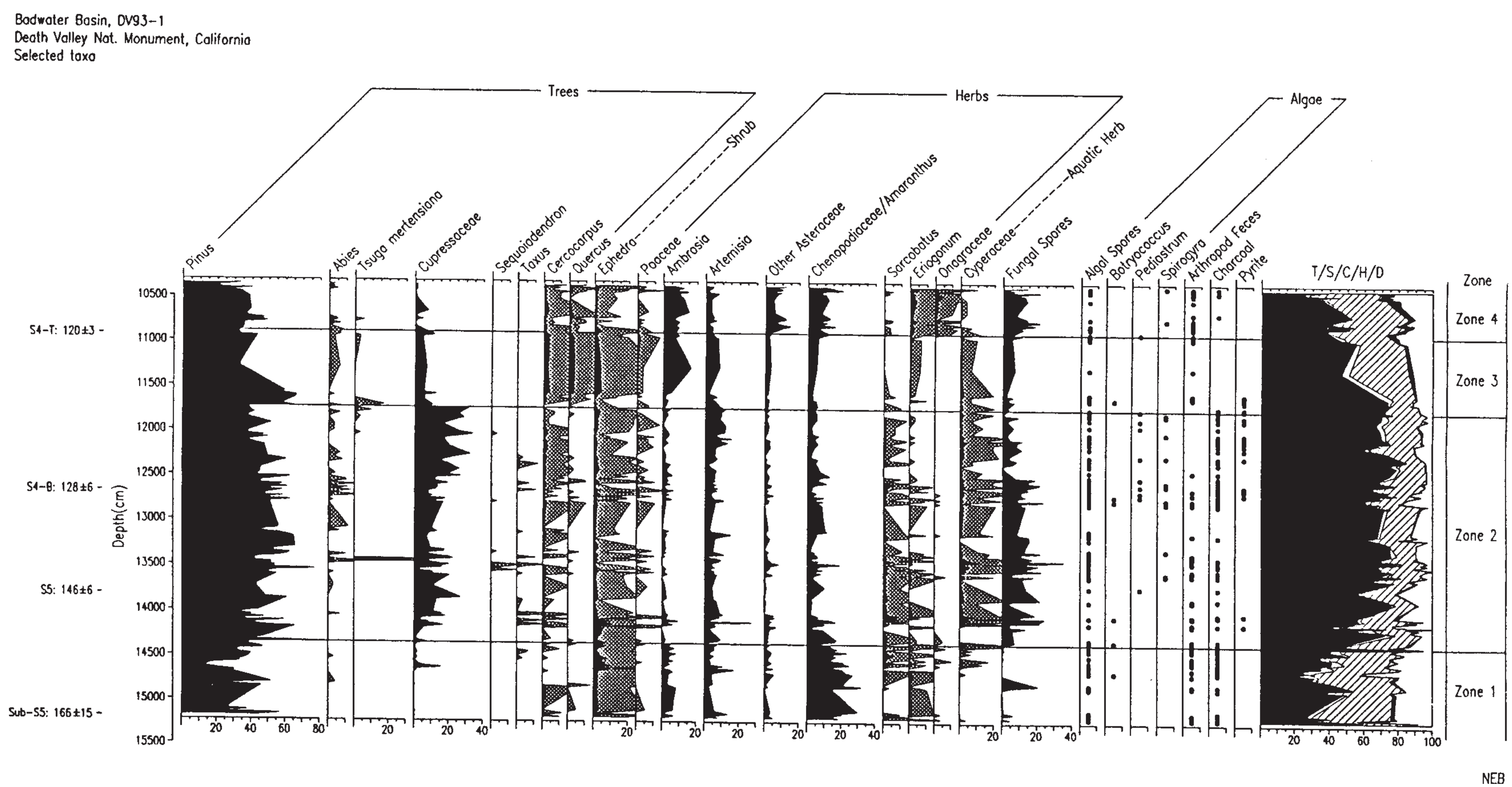
Zone 1 is characterized by low percentages (averaging 1.8%) of Cupressaceae pollen compared with Zone 2, and by high percentages (averaging 20%) of Cheno–Am pollen (Text-Figure 4). Modern Death Valley plants which produce Cheno–Am pollen include the basin-dwelling halophytes *Atriplex canescens*, *Allenrolfia occidentalis*, and *Suaeda suffrutescens* from the phreatophyte zone and *Atriplex hymenelytra* and *Atriplex polycarpa* from the xerophytic zone, as well as shadscale, *Atriplex confertifolia*, a Great Basin resident. *Ambrosia* percentages in Zone 1 are higher than in Zone 2. Algal spores were numerous in the lower part of Zone 1.

### Zone 2: Juniper zone, 143.5–117.3 m, 154–124 ka

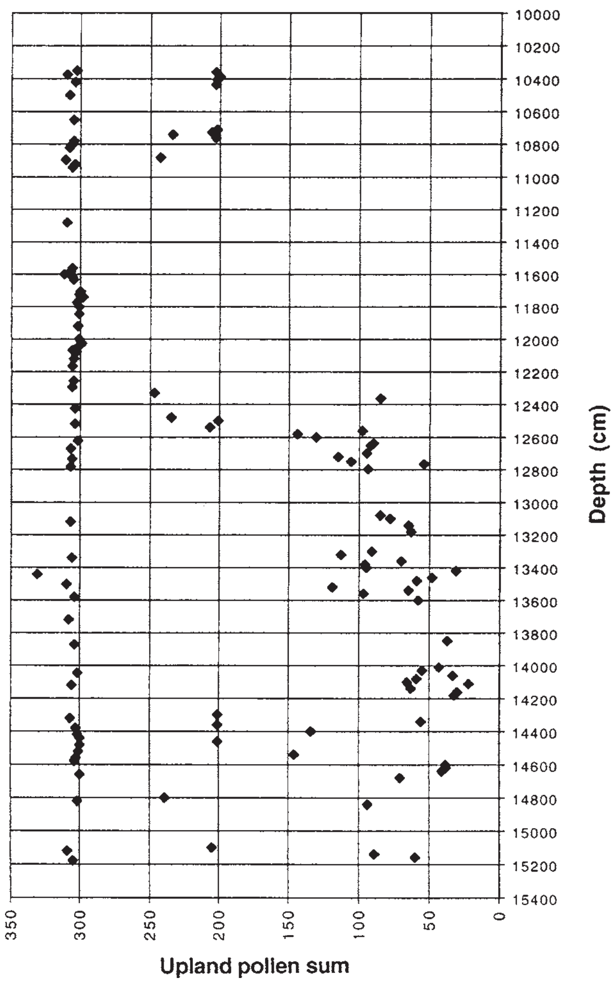
Zone 2 is defined by high percentages of Cupressaceae pollen. Pollen of this type in Death Valley is probably attributable to *Juniperus osteosperma*, which grows today principally between 1500 m and 2400 m elevation throughout southern California (Thorne, 1982). Cupressaceae averages 16% of the sum, but reaches about 30% in the upper part of Zone 2.

### Zone 3: Oak zone, 117.3–108.8 m, 124–119 ka

Zone 3 is defined by low percentages of Cupressaceae pollen, and by high percentages (1.6%) of *Quercus* (oak) pollen relative to the other zones. The lowermost boundary of this zone (124 ka) is notable for the abrupt decline of Cupressaceae pollen, which falls from 30% to about 8%. Simultaneously, *Quercus* appears, but in small amounts. *Quercus* pollen, like *Pinus* pollen, is over-represented in the pollen rain, and it is possible to find low percentages of *Quercus* pollen even if there are no oak trees in the area




Text-Figure 4. Diagram of selected fossil pollen percentages for core DV93-1. The composite diagram on the right represents total trees (dark), total shrubs (white), composites & Cheno-Ams & grass (pattern), herbs (dark), and deteriorated & unidentified (white).




Text-Figure 5. Upland pollen sums of the samples from DV93-1.

(Davis, 1984). Slightly above this transition, at ca 115.7 m and 123 ka, *Ambrosia* percentages rise and *Artemisia (A. tridentata* and *A. nova)* percentages fall. Today, *Ambrosia* pollen in Death Valley is produced mainly by white bursage *(Ambrosia dumosa)*.

Zone 4: Asteraceae zone, 108.8–103.5 m, 119–115 ka

Zone 4 is defined by relatively high percentages of Asteraceae pollen, and by the increase of Cheno–Am pollen and the further decline of *Artemisia*. *Ambrosia* percentages remain consistently high from Zone 3. Common producers of Asteraceae-type pollen in Death Valley include the low-elevation species *Pluchea sericea*, *Encelia farinosa*, and *Ericameria cooperi* from the mixed shrub zone.

## INTERPRETATION AND DISCUSSION

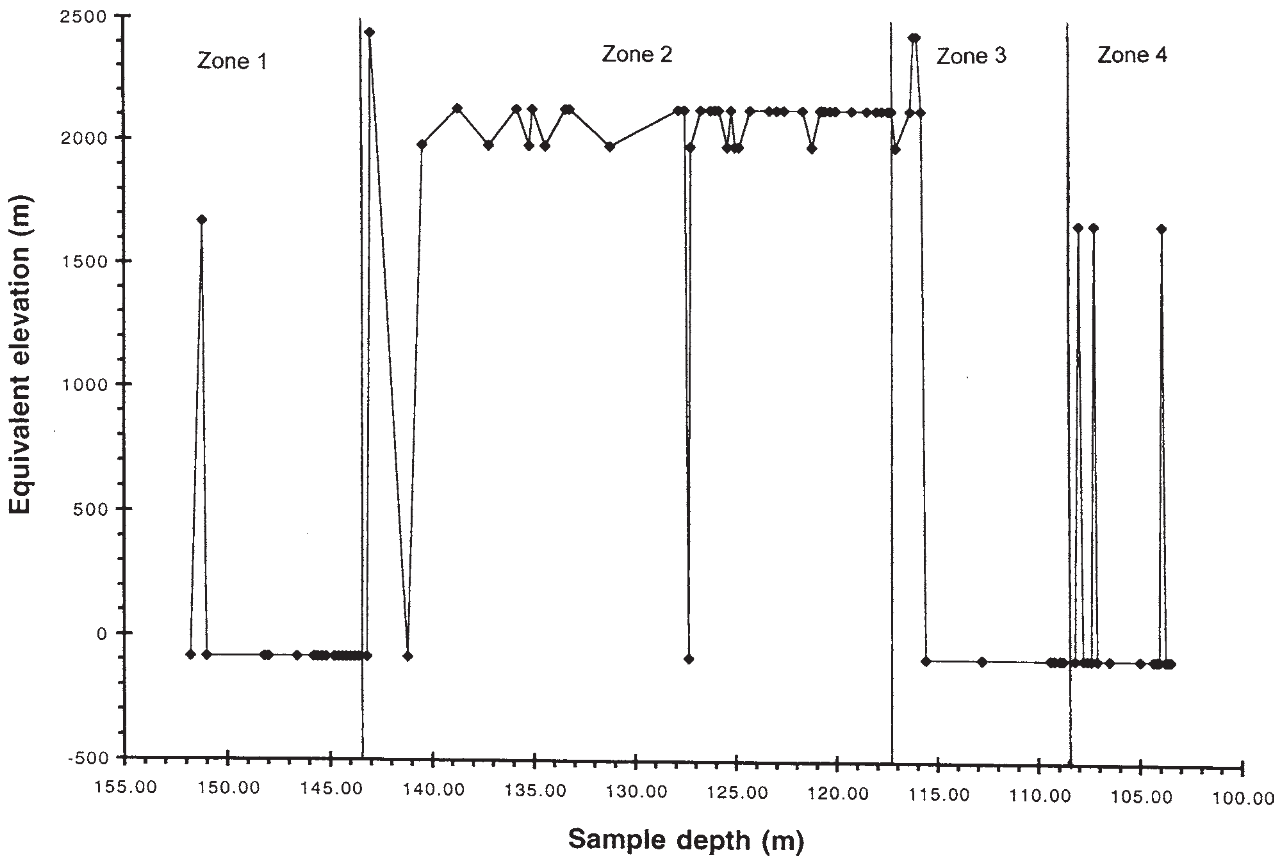
Zone 1: Cheno–Am zone, 151.8–143.5 m, 166–154 ka

The interpretation of Zone 1 climate is difficult. The analysis of squared-chord distance suggests a warm interval throughout Zone 1 (Text-Figure 6). Fossil pollen assemblages from 151.8–143.5 m most closely match the modern sample from Badwater Basin. This interpretation is in conflict with other lines of evidence (e.g., Lowenstein et al., 1999; Ku et al., 1998) which indicate that a deep lake, and therefore a cool climate, existed in Death Valley at this time.

The presence of abundant Cheno–Am pollen could indicate low lake levels, which allow phreatophytes such as *Atriplex canescens* to colonize the margins of the basin floor. However, the modern Cheno–Am pollen is only around 8% of the total in the basin sample adjacent to the phreatophyte zone. Martin (1964) found that Cheno–Am-type pollen was greater than 20% in Panamint surface samples between elevations of 910 m and 1670 m, reaching a maximum of 51% at 1220 m. This suggests that the Cheno–Am signal in Death Valley could also indicate the presence of higher-elevation taxa such as *Atriplex confertifolia*.

Lithologic indicators from this section of the core suggest that this interval was significantly wetter than today. The core sediments are dense, greenish–gray muds, indicating the presence of a perennial lake in Death Valley (Lowenstein 1993). The pulse of algal spores in the pollen samples between 151.8 m and 148.4 m also supports the presence of standing water. However, mudcracks at 145.5 m and again at 143.5 m in the core indicate that the lake dried at 156 and 154 ka.

Additional evidence for a lake during the beginning of the Zone 1 interval is provided by U-series dates from lacustrine tufas (Ku et al., 1998). Prominent horizontal terraces of tufa and carbonate-cemented gravel representing a shoreline of one of Lake Manly's high stands occur at 90 m, 175 m above the salt pan. Ku et al. determined that carbonate from the tufas was unrecrystallized and contained low levels of detrital $^{230}$Th ($^{230}$Th/$^{232}$Th >15), and therefore should yield reliable U-series dates. The dates suggest that one of the shorelines at 90 m was deposited from ca.185 to 160 ka. This shoreline is 335 m above the sediments of equivalent age in DV93-1. Hence, Lake Manly was possibly as much as 335 m deep between 185 to 160 ka, if basin subsidence is ignored, or about 175 m deep if sedimentation kept pace with basin subsidence (Ku et al., 1998). Ku et al.'s dates are in agreement with previous dates from Hooke and Lively (1979), whose 18 U/Th dates indicate the deposition of the tufas at 90 m from 200–120 ka.




Text-Figure 6. Analysis of squared-chord distance. X-axis is the depth in the core of each pollen sample from core DV93-1. Y-axis is the elevation of the surface pollen sample that it most closely resembles.

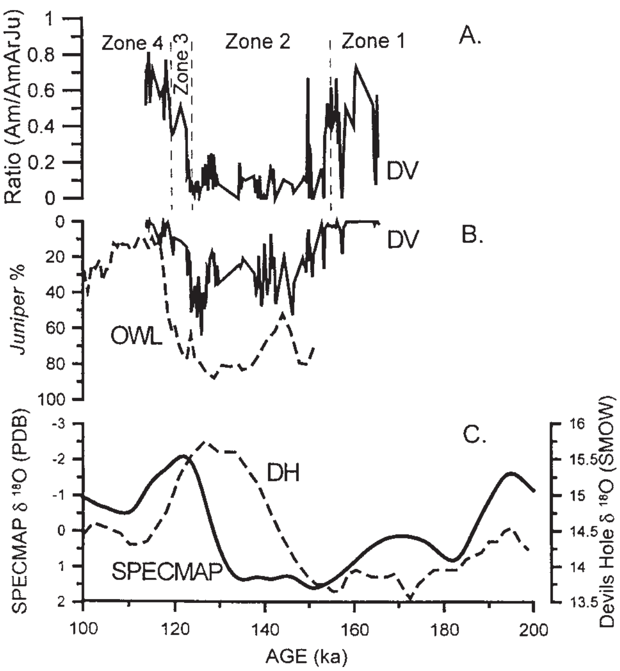
A warm period corresponding to Zone 1 (from 151.8–143.5 m, 166–154 ka) is not apparent in the SPECMAP and DH-11 records (Text-Figure 7). However, due to the large uncertainty on the sub-S5 U-series date (Table 3) (Ku et al., 1998), the interpolated age of the Zone 1-Zone 2 boundary (143.5 m, 154 ka) has an associated uncertainty of about ± 9.5 ka. It is therefore possible that Zone 1 does correspond to the OIS 7 of the SPECMAP curve, since the probable age of the Zone 1-Zone 2 boundary in DV93-1 is any age between 163 and 144 ka. The equivalent boundary in the Owens Lake record is at about ~155 ka according to *Pinus* percentages, although Cupressaceae percentages drop much earlier, at ~170 ka (Litwin et al., 1997).

Zone 2: Juniper zone, 143.5–117.3 m, 154–124 ka

In Zone 2, the high percentages (~16%) of Cupressaceae pollen indicate a cold period. Modern Cupressaceae pollen in the Panamint Range exceeds 10% of the total only at elevations between 1820 m and 2280 m (Martin, 1964), but exceeds 70% at 2280 m, within the juniper woodland. This suggests that during the time in which Zone 2 pollen was deposited, the juniper woodland was growing just a few hundred meters above the surface of Lake Manly. The pollen preservation is good throughout Zone 2, suggesting rapid burial of pollen and sediment underwater.

The analysis of squared-chord distance indicates that fossil assemblages from Zone 2 most closely match modern surface samples taken from between 1980 m and 2130 m elevation in the Panamint Range (Text-Figures 3, 6). The mean annual temperature at this elevation today is between 13 and 14° C, and the mean annual rainfall is ca. 40 cm (Davis, 1995). In the basin the mean annual temperature is ca. 24–25° C, and rainfall averages less than 5 cm/year (U.S. Weather Bureau, 1964). This implies that the area of pollen deposition may have been 11° C cooler and received roughly eight times the rainfall as today.

Lithologic features associated with Zone 2 suggest that a perennial lake with fluctuating volume existed at this time (Lowenstein, 1993). The sediments can be divided into 4 stratigraphic sections. The lowest section (143–140 m)




Text-Figure 7. A comparison of some long climate records. (A) shows the ratio *Ambrosia* divided by (*Ambrosia*+*Artemisia*+Cupressaceae) (see text). (B) shows Cupressaceae percentages from Death Valley (DV) and Owens Lake (OWL). Y-axis values are reversed to show similarity to the isotopic curves. (C) shows the SPECMAP curve (solid line) plotted with the Devils Hole (DH) curve.

consists of dense black muds associated with a perennial lake environment. From 140–137.5 m are muds interbedded with primary halite layers, indicating an increase in lake salinity. However, salinity probably remained < 3000 ppm, as evidenced by the presence of the salinity-sensitive ostracod *Candona caudata* in this section (Lowenstein et al., 1999). Above this, from 137.5–127 m, dense black mud indicates a perennial lake environment. The upper section, from 127–117.3 m, contains primary halite which marks the return to a perennial saline lake; however, *C. caudata* is present from 126–125 m (Lowenstein et al., 1999), providing a salinity maximum for that interval.

Ku et al. (1998) identified tufas from two shorelines, one at 72 m and the other at 57 m elevation, whose U/Th ages match this section of the core. The four dates, two from each shoreline, range from ca. 150 to 130 ka. This suggests that maximum lake levels at 130 ka (Zone 2) were as much as 30 m lower than at 160 ka (Zone 1).

Pollen from the upper boundary of Zone 2, at 117.3 m, makes a sharp transition from cold Great Basin vegetation to hot Mojave desert scrub. The (ca. 4.4 ka uncertainty for this depth estimated from U-series samples S4-T and S4-B (Table 3) indicates that this event occurred between 128 and 119 ka. The timing and rapidity of the transition suggests that the boundary between pollen zones 2 and 3 correlates with Termination II, the OIS 6/5e transition. Interestingly, the Devils Hole chronology, which is only 50 km away from Death Valley, does not agree with this age for Termination II. The Devils Hole chronology shows the Termination II event occurring at (ca. 140 ka, compared to the estimate of 124 ka from Death Valley's pollen record and of 125 ka from the Owens Lake pollen record. Since DH-11 is extremely well-dated (Ludwig et al., 1992), it is likely that the discrepancy is partly due to the fact that these two types of records are products of different environmental indicators.

Zone 3: Oak zone, 117.3–108.8 m, 124–119 ka

*Ambrosia* pollen in Zone 3 is probably attributable to *A. dumosa* (white bursage), a Mojave desert indicator. The replacement of juniper, a high-altitude taxon, and *Artemisia*, a cold Great Basin desert taxon with *A. dumosa*, a Mojave desert species, indicates a warmer climate during Zone 3 pollen deposition.

The zone boundaries found using squared-chord distances are very similar to the boundaries of the diagrammed zones (Text-Figures 4, 6). The squared-chord analysis indicates that Zone 3 fossil assemblages >123 ka (115.7 m in core) are most similar to surface samples of ~2100 m elevation in the Panamint Range, and thereafter (<123 ka) are most similar to the Badwater Basin surface sample. The boundary between these zones based on the squared-chord method is therefore somewhat higher in the core than the boundary between Zone 2 and Zone 3. This is probably due to the fact that the Zone 2/3 boundary is defined solely by the decline of Cupressaceae pollen, whereas the boundary indicated by the squared-chord distance analysis was affected by changes in *Ambrosia* and *Artemisia* pollen as well. However, the difference in interpolated age between the two boundaries is <1000 years.

The core throughout Zone 3 is composed of thin mud layers interbedded with primary halite (Lowenstein, 1993), indicating a continuation of the perennial saline lake phase. From 113–116 m, however, the presence of *C. caudata* indicates that salinity was <3000 ppm (Lowenstein et al., 1999). Several pollen samples from immediately above the Zone 2/3 transition contained large numbers of pyrite crystals, visible at 45x magnification. The reasons for this pyrite pulse are uncertain. Salt Creek and the Amargosa river, Death Valley's main tributary waters, contain high concentrations of dissolved sulfate (Li et al., 1997), so the availability of sulfate probably does not limit pyrite formation. Iron is delivered to the system as detritus (Berner, 1970, 1984), so it seems unlikely that changes in sediment delivery would be enough to account for a large pulse of pyrite. Perhaps the samples containing pyrite were produced during an episode during which lake-bottom conditions became anoxic enough to permit sulfur-reducing bacteria to thrive, thereby making incoming detrital iron minerals available for the formation of iron sulfide. A sudden shift to an anoxic environment could be caused either by stratification of the water or by the addition of large amounts of organic matter to the lake, such as would be expected from a sudden water level rise inundating the vegetation on the banks. It is peculiar, therefore, to see a pyrite increase when maximum lake levels are apparently dropping. Perhaps the rapid climate shifts associated with Termination I (e.g., the Younger Dryas) also characterized Termination II, leading to brief flooding during the earliest part of Zone 3.

### Zone 4: Asteraceae zone, 108.8–103.5 m, 119–115 ka

The pollen types common in Zone 4 indicate further warming. High percentages of Asteraceae and Cheno–Am pollen indicate the dominance of plants which today are found at low elevations. Martin (1964) recorded the highest percentages of *Ambrosia* and other Asteraceae pollen and high Cheno–Am pollen in the lowest elevation surface samples from the Panamint Range. The further retreat of the cold Great Basin scrub is indicated by declining *Artemisia* percentages and the continued dominance of hot Mojave-type communities (represented by *Ambrosia*).

Squared-chord analysis reveals that the pollen assemblages in this section of the core are most similar to the Badwater Basin surface sample, suggesting that the climate during the deposition of Zone 4 was similar to the hot climate of today.

Throughout Zone 4, the core is composed of muds and halite layers thought to have been deposited in a mudflat environment (Lowenstein, 1993). The transition from a perennial saline lake to a mudflat agrees with the hypothesis of warming.

## CONCLUSIONS

From ca. 166 to 154 ka, Lake Manly was deep, as the 90 m elevation shorelines indicate (Ku et al., 1998). Pollen from *Ambrosia*, a characteristic hot desert type, remained below 10% of the total. These data suggest that the climate in Death Valley was warmer than full-glacial conditions, but cooler and wetter than Death Valley is today. This type of climate appears to match that at the end of OIS 7, during which the global ice volume was increasing (Imbrie et al., 1992) (Text-Figure 7). Pollen from Zone 2 (163–144 ka) first reflects full glacial (OIS 6) conditions. The climate had cooled enough that montane Great Basin vegetation like sagebrush and juniper grew at elevations not far above the lake, although junipers must not have been as near the basin as in the higher-elevation Owens Lake, where Cupressaceae pollen was greater than 60% during the glacial (Litwin et al., 1997). Interestingly, during the time in which the pollen record indicates a full-glacial period, the lake level may have dropped by as much as 30 m (Ku et al., 1998), and the lithologic indicators show that the lake volume fluctuated throughout this interval (Lowenstein, 1993).

The cold period lasted until ca. 124 ka (Text-Figures 4, 7), when a rapid warming event, corresponding to Termination II, is evident in the pollen spectra. Juniper sharply declined and cold Great Basin taxa (e.g., *Artemisia*) were displaced by Mojave Desert vegetation such as *Ambrosia*. The same abrupt transition is visible at this time in the Owens Lake pollen diagram. Following the transition to Zone 3, which corresponds to the beginning of OIS 5e, evaporation began to exceed precipitation, and layers of primary halite were deposited in the basin as lake levels declined. By 119 ka, the beginning of Zone 4, Lake Manly had evaporated and a mudflat took its place. *Ambrosia*, the Mojave Desert-type indicator, was dominant, as were members of the Asteraceae and Chenopodiaceae. The climate was similar to that of Death Valley today. Zones 3 and 4 are not differentiated in the Owens lake analysis (P5). This is hardly surprising, as both Zone 3 and Zone 4 are warm periods, and the differences between the two zones are not as dramatic as are the other boundaries.

The ratio of *Ambrosia*/(*Ambrosia* + *Artemisia* + Cupressaceae) yields an index used here to contrast the Mojave Desert and Great Basin Desert environments in Death Valley. Using this ratio, the Zone 1 peak is much larger than the equivalent peak for OIS 7 in the SPECMAP curve (Text-Figure 7). Otherwise, the ratio matches the SPECMAP curve quite well. The DH-11 core from Devils Hole (Winograd et al., 1992) matches the DV93-1 pollen analysis in form but not in timing, as the two curves are offset by nearly 20,000 years; the Devils Hole chronology places Termination II at ca. 140 ka., but the pollen from DV93-1 shows the equivalent transition at ca. 124 ka and the pollen from Owens Lake shows the transition at ca. 125 ka.

Since long climate records for North America are relatively few, it is particularly fortunate that there are now three independent long climate records, all from adjacent basins in the southern Great Basin region, to compare with one another and with the marine record. These nearby systems at different elevations reacted similarly but asynchronously to what presumably are similar environmental stimuli. When completed, the palynological analysis of the top section of the core will further illuminate the relationships between these long climate records.

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