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# Pollen-based evidence of extreme drought during the last Glacial (32.6—9.0 ka) in coastal southern California



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#### ABSTRACT

High resolution pollen analyses of sediment core LEDC10-1 from Lake Elsinore yield the first well-dated, terrestrial record of sub-centennial-scale ecologic change in coastal southern California between ~32 and 9 ka. In the Lake Elsinore watershed, the initial, mesic montane conifer forests dominated by *Pinus*, and Cupressaceae with trace amounts of Abies and Picea were replaced by a sequence of multiple, extended severe mega-droughts between ~27.5 and ~25.5 ka, in which halophytic and xerophytic herbs and shrubs occupied an ephemeral lake. This prolonged and extended dry interval, which corresponds with warm waters offshore, imply strengthening of the North Pacific High and persistent below-average winter precipitation. The subsequent, contrasting monotonic occurrence of montane conifers reflects little variation in cold, mesic climate until ~15 ka. Postglacial development of Quercus woodland and chaparral mark the return to more xeric, warmer conditions at this time. A brief reversal at ~13.1~~12.1 ka, as reflected by an expansion of *Pinus*, is correlative with the Younger Dryas and interrupts development of warm, postglacial climate. Subsequent gradual expansion of xeric vegetation post - Younger Dryas denotes the establishment of a winter hydroclimate regime in coastal southern California that is more similar to modern conditions. Pollen-based reconstructions of temperature and precipitation at Lake Elsinore are generally correlative with pollen-based paleoclimatic reconstructions and foraminiferabased sea surface temperatures from Santa Barbara Basin in marine core ODP 893. The conspicuous absence of the ~27.5—~25.5 ka glacial "mega-drought" in the Santa Barbara Basin pollen record highlights the sensitivity of Lake Elsinore to hydroclimate change, and thus, the importance of this new record that indicates that mega-drought can occur during the full glacial when climatic boundary conditions and forcings differed substantially from the present.

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#### 1. Introduction

Ecologically and economically damaging extreme weather events such as drought and winter storms characterize the Mediterranean climate of coastal southern California (CSC). The present "Great Drought" in California is extreme but not in terms of duration, especially for CSC where multi-decadal to centennial scale drought are inferred from the paleoclimatic record (Cook et al., 2004; Kirby et al., 2014). Predicted future changes in mean annual precipitation and temperature seasonality is likely to impact vegetation and associated ecosystems of the California Floristic Biodiversity Hotspot, wherein Lake Elsinore (LE) is

located (McDowell, 2008; Williams, 2012). Regional-scale shifts in vegetation are already occurring (Myers et al., 2000; Brooks et al., 2002). Future water deficits are projected to result in widespread changes in the distribution and composition of CSC ecosystems — the reduction and displacement of oak (*Quercus*) woodlands northwards and/or to higher elevations (Kueppers, 2005; McLaughlin and Zavaleta, 2012). Movement to higher elevations may mean southward to the coastal mountains (Loarie, 2008). The key to predicting the future response of CSC ecosystems to climate change is a paleoperspective — i.e., past reconstructions of vegetation and its response to climatic change. Unfortunately for CSC, how vegetation responded to past episodes of extended drought and/or wetness, especially during the last Glacial, is poorly known

Existing pollen-based reconstructions of glacial CSC climate vary in detail and temporal resolution. During the last interglacial (MIS

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5e), pollen deposited in Santa Barbara Basin (SBB) (ODP Hole 893A) from drought-adapted, Mediterranean type vegetation was comparable to, or even more expansive, than present (Heusser, 1995; Friddell, 2002). A short, mid-Wisconsinan pollen record in an organic deposit at Diamond Lake (~30 km east from Lake Elsinore) records expansion of more mesic montane ecosystems to lower elevations during near-peak glacial conditions (Anderson et al., 2002). Holocene pollen records from CSC are sparse and are generally low resolution—coarser than centennial scale (Cole and Liu, 1994; Heusser and Sirocko, 1997; Dingemans et al., 2014). An archival exception is a recent pollen reconstruction from SBB indicating a significant vegetative response to the drier-than-average Medieval Climate Anomaly (800—1300) and its transition into the early stages of the wetter-than-average Little Ice Age (~1300—1400) (Heusser et al., 2014).

Here, we present the first continuous, multi-decadal resolution pollen assemblage record from CSC (Lake Elsinore) spanning the late last glacial (32–9 ka). We compare this record to nearby Santa Barbara Basin sea surface temperatures (SST) and its pollen data to examine marine — terrestrial similarities and differences.

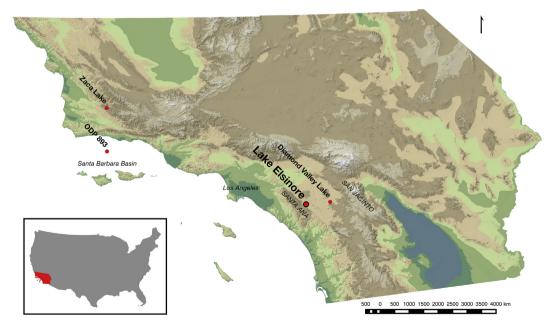
#### 2. Background

#### 2.1. Setting

Originally called *Lago Grande*, LE is the largest (~15 km²) natural lake in southern California (Fig. 1). Occupying a pull-apart basin ~380 masl in the Peninsular Range, the lake is a shallow (~3–13 m mean depth) but generally permanent lake, bordered by the Elsinore fault, one of the principal strands of the San Andreas fault system (Fletcher et al., 2006). The main water source for the lake is the small, ~1240 km², drainage basin of the San Jacinto River, supplemented by direct runoff from the Elsinore Mountains that rise abruptly ~610 m above the western edge of the lake (Mann, 1951; Lawson, 2007). Runoff, which is positively correlated with precipitation, is winter dominated and highly variable. During the last ~200 years, the lake has desiccated four times during extreme droughts and has briefly overflowed 20 times through a natural

outlet ~3 m above mean maximum depth (Lynch, 1931; Kirby et al., 2007).

The hydrology of LE reflects seasonal changes in annual precipitation/evaporation caused by broad changes in atmospheric circulation and oceanographic variability. The strength and position of the NE Pacific High pressure system (NEPH) redirects storm tracks to the north during the spring and summer and further south into California during the winter (Namias and Cavan, 1981: Cavan and Peterson, 1989; Seager et al., 2005). These large-scale atmospheric patterns, which control the average position of the polar front, affect the strength and character of the California Current System (CCS) and cause strong southward flow in summer and northward flow with cooler sea surface temperatures (SST) in winter (Hendy, 2002; Barron et al., 2003). A stronger polar jet produces increased storms in winter. During winter, as the eastern Pacific subtropical high weakens, polar storm systems shift southward and produce over 80% of the annual precipitation (Cayan, 1984). In summer, northerly winds around the northeast Pacific subtropical high block northern storm tracks, cool SSTs, and produce persistent coastal upwelling. The subtropical North American Monsoon (NAM) provides limited summer precipitation but negligible to the lake's annual hydrologic budget (Adams, 1997; Higgins et al., 1997). Tropical cyclones originating in the eastern Pacific Ocean contribute less than 20% of the total late-summer to early-fall precipitation and, like the monsoon, presently make no difference in the lake's annual hydrologic budget (Corbosiero, 2009). The semi-permanent high produces temperature inversions that trap air near the surface. Below the inversion laver. cool maritime air flows up the coastal slopes to ~400 m and condenses into fog and fog-drip that averages ~5.74 cm/month in May and June on the seaward side and ~2.41 cm/month on the leeward side (Vogl, 1973). Inter-annual winter precipitation variability is modulated by ocean-atmosphere conditions in the tropical and extra-tropical Pacific such as the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Castello, 2004; Kirby et al., 2010, 2014). During El Niño years, drainage basins in the southwestern United States are more likely to experience higher stream flow and sediment flux than during La Niña years (Inman,



**Fig. 1.** Map of Southern California showing location of Lake Elsinore and ODP Site 893, Core LEDC10-01 (33°40 N; 117°21′W, 376 masl); ODP Hole 893A (34°17.25′N, 120°02.19′W, 576.5 mbsf), Zaca Lake, and the San Jacinto and Santa Ana Mountains. Inset shows location of study area in relation to the U.S.

1999).

High pressure over the North Pacific in summer and intensification of the Aleutian low in winter are reflected in seasonal contrasts of warm dry summer and cold wet winters that are moderated by coastal waters. Modern marine and terrestrial temperature gradients along the California coast are remarkably similar. Average annual SSTs have a north to south gradient, ranging from 12 °C to 16 °C, and average annual temperatures directly onshore are closely comparable, ranging from 11 °C at 42°N to 17 °C at 32°N (Lyle et al., 2010). Mean July coastal temperatures reflect local sea surface temperatures (Minnich, 2007). Average annual coastal precipitation also has a very strong north-south gradient, ranging from ~1700 mm to <260 mm.

Strong orographic temperature and precipitation gradients characterize the LE region. Topographic relief of this area is between 380 m at LE and up to 3302 m in the San Jacinto Mountains (Mann, 1951). In the Santa Ana Mountains, temperature depression averages ~2.1 °C for each 305 m increase of elevation (Vogl, 1973). Average annual temperatures decrease from ~17  $^{\circ}C$  at LE (~380 masl) to ~8 °C on montane peaks. Average annual precipitation increases from ~300 mm at LE to 680 mm on Santiago Peak (1734 masl), where winter precipitation occasionally occurs as snow (Vogl, 1973). Above ~1000 m in the San Jacinto Mountains, the prevailing westerlies carry marine air which also moderates summer temperatures and produces fog and fog-drip many nights of the year (Vogl and Schorr, 1972). Mountains act as "sky islands", providing cooler temperatures for isolated ecosystems, and as "water towers" in storing and providing water to downstream ecosystems (Anderson and Goulden, 2011).

#### 2.2. Modern vegetation

Elevational gradients in precipitation are reflected in step-like changes in the natural vegetation groups, as vegetation cover in this semi-arid climate is closely related to mean annual evaporative fraction (Anderson and Goulden, 2011). Vegetation around LE and on the low-elevation (~400 m) flat/gentle hilly topography includes a mosaic of alluvial scrub, mixed chaparral (Ceanothus, Adenostoma, Q. dumosa, Q. wislizenii) and scrub oak woodland (Q. agrifolia, Poaceae), and California sage scrub (Artemisia californica, Salvia, Eriogonum), generally require ~300 mm of annual precipitation. Above ~1300–1500 m, scrub-shrub merges with oak (*Q. chrysolepis*, Q. kelloggii) and mixed evergreen oak-pine woodlands (Q. agrifolia, O. kelloggii, Pinus coulteri) which require ~625-650 mm precipitation and mean annual temperature of  $12^{\circ}$  – ~15 °C. Montane coniferous forest (P. coulteri, P. jeffreyi, P. ponderosa, Calocedrus dedcurren, Cupressus forbesii, Pseudotsuga macrocarpa, and Abies concolor) occurs above ~1850 m. Trans-montane slopes support open Piñon and juniper woodlands (P. coulteri -Juniperus californica), a disjunct, westernmost extension of Great Basin and Colorado vegetation (Vasek and Thorne, 1977).

Plant communities that may occur at various elevations include riparian *Populus/Platanus* woodland and montane *Q. agrifolia/Alnus* forest, fresh-water marshes (*Carex, Cyperus, Rorippa, Typha, Potamogeton*), ephemeral vernal pools, alkaline flats, alluvial fans, playas, and fine alluvial soils, (*Atriplex*, and other salt-tolerant plants of which the *Amaranthaceae* are the most numerous) (Vasek, 1966; Barbour and Major, 1977; Vasek and Thorne, 1977; Davis, 1999; Anderson and Koehler, 2003; Barbour, 2005; Clarke et al., 2007). The upslope vegetation zonation and climate gradients are captured by modern pollen assemblages from surficial samples taken in the cismontane region of southern California. In pollen assemblages from the San Jacinto Mountains, herbs dominate the lowland (<775 m), chaparral (Rosaceae with *Quercus* spp), occurs up to 1545 m interspersed with oak-conifer woodlands. The

higher elevation chaparral-conifer ecotone (*Q. kelloggii* and *P. coulteri*) is succeeded upslope by lower montane mixed conifer forests that include *Quercus*, *Pinus*, and Cupressaceae (Vasek and Thorne, 1977). *P. contorta* is prominent in pollen assemblages from the upper montane forest (Anderson and Koehler, 2003). Surface pollen assemblages from the Peninsular and Transverse Ranges of southern California show a similar altitudinal differentiation (Wahl, 2003a,b). Foothill and lower montane assemblages are dominated by *Quercus*. *Pinus* and Cupressaceae (*Juniperus*, *Calocedrus*) increase as elevation increases. *Pinus*, along with small amounts of *Abies*, occurs in the montane zone.

Our use of modern pollen/vegetation relationships in the San Jacinto drainage basin and the cismontane region as analogues for vegetation/climatic reconstructions from pollen deposited in LE is also based on observations that fluvial transport of pollen is the primary source of pollen deposited in lakes, and that pollen in rivers reflects the various ecosystems of the drainage basins (Bonny, 1978; Brown, 2007; Zhu et al., 2003). Reconnaissance studies of pollen in sediment samples from the San Jacinto River between 610 m-1630 m, and from the surface (~400 m) of LE (Byrne et al., 2004) show the altitudinal zonation of montane conifers and lowland shrubs and herbs. Large lakes receive a large absolute input of pollen from regional sources via fluvial input (Matthias and Giesecke, 2014). Lesser amounts of pollen deposited in LE may be derived from emergent and submergent littoral vegetation. Some local aeolian pollen transport is likely however long-distance transport in a montane environment is more equivocal (Solomon et al., 1982; McLennan, 1984; Jackson, 1999).

Our objective is to use high-resolution (decadal scale sampling) pollen analysis from a sediment core taken in Lake Elsinore to reconstruct past vegetation between ~32 and ~9 ka. Our goal is to develop a paleo-perspective of coupled ecologic — hydrologic dynamics that captures the range of variability from the last Glacial through the early Holocene for a better understanding of portending climate change and its potential ecologic consequences.

#### 3. Methods

#### 3.1. Core location and acquisition

Core LEDC10-1 (33°40 N; 117°21'W, 376 masl) was extracted from ~ 9 m to ~30 m below the sediment/water interface. Each drive of the hollow stemmed, lined auger coring system was 0.61 m. Recovery was ~90%. Initial data spanning 9–19 ka are described in Kirby et al. (2013).

#### 3.2. Pollen methods

Sediment samples (~5 cc) from core LEDC10-1, which were taken at ~10 cm intervals between 10.37 m and 30.05 m, were processed using standard procedures (Heusser and Stock, 1984). Known quantities of *Lycopodium* spores were added to each sample in order to calculate pollen concentration and pollen flux. Pollen recovery varied; however, in ≥270 samples, 300 pollen grains (upland, wetland, and aquatic) and spores were identified under a light microscope at 400×. Picea, which is absent from the region today, was included in the pollen sum. Reworked pollen (identified on the basis of pollen morphology) was rare. Pollen identifications were based on reference collections of modern pollen and published references. Identification varied taxonomically - from generic to familial levels – due to factors limiting identification of pollen of plant taxa, such as for the Cupressaceae. Inaperturate pollen grains that may have been produced by C. decurrens, Juniperus (J. californica, or Juniperus osteosperma), and/or Cupressus are here referred to as Cupressaceae (Munz, 1974). We note that

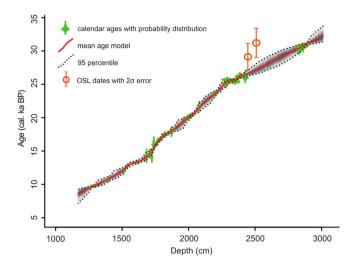
Pinaceae, which were all identified as diploxylon type, may represent several species that range from chaparral and foothill woodland (*P. attenuata*, *P. coulteri*) to montane forest (*P. ponderosa*). In our summary pollen diagram, *Abies/Picea* and Rosaceae/Rhamnaceae (*Adenostoma*, *Cercocarpus*, *Ceanothus*) are plotted together. *Artemisia* (sage) was separated from other Asteraceae. Obligate wetland taxa (*Typha*, *Potamogeton*, *Sparganium*, *Myriophyllum*, and *Isoetes*) are included in the pollen and spore sum. Pollen and spores were encountered less frequently, which are not shown in the summary pollen diagram, are included in calculating the pollen sum and relative abundance of taxa shown in the summary pollen diagram. Plant nomenclature follows (Munz, 1974). (Pollen data will be available from NAPD). Pollen flux (grains/cm²/yr) quantifies the rate of pollen deposition in LE over the time of record.

#### 3.3. Age model

Age control is based on 24 AMS radiocarbon dates from charcoal, wood, and/or seeds (Table 1). An age model was developed using the Bacon 2.2 age-depth modeling program (Fig. 2). Infrared Stimulated Luminescence (IRSL) signals from single grains of K-feldspar from two sandy units were used to assess a section of the core were datable organic material was poorly preserved. This independent analysis supports our age model.

#### 3.4. Statistical analyses

Principal components (PC) analysis and cluster analysis are used to reduce the dimensionality of the pollen percent data and to identify the underlying relevant structure. The R Project statistical computing environment was used for all statistical analyses. PC



**Fig. 2.** Age model for LEDC10-1 produced by BACON 2.2 program, using age data shown in Table 1.

analysis of pollen percent data was performed by singular value decomposition using the function prcomp(). We also performed an unconstrained cluster analysis by Ward's method on a matrix of Euclidean distance.

Cluster analysis separated the pollen samples into three distinct groups, assigned arbitrary numbers 1 through 3. The three groups determined by cluster analysis are also apparent in PC space (Figs. 3 and 5). The biplot shows the samples plotted by the PC axis 1 and 2 scores (Fig. 3). The colors and shapes of the points on this plot correspond with the group assignments from the cluster analysis.

**Table 1** Chronology for LEDC10-1.

LEDC10-1 depth range (cm)	Average depth (cm)	Material	ID	δ <sup>13</sup> C(‰) <sup>a</sup>	14C Age (BP) used in BACON (v2.2)	±	Calibration results <sup>b</sup>		Used in
							2-Sigma range	Age (cy BP)	age model
1274-1275	1274.5	Gastropods	*N93630	-25	8655	35	9541-9684	9613	
1274-1275	1274.5	Gastropods	*N93631	-25	8710	35	9548-9780	9664	9640
1396-1398	1397.0	Bulk	*94679	-25	10,155 (9450 Res. Corrected#)	46	11,685-12,030	11,858	10940*
1508-1510	1509.0	Bulk	*94680	-22.9	10,950 (10,240 Res. Corrected#)	46	12,648-12,964	12,806	11890*
1540-1542	1541.0	Bulk	*94681	-25	11,650 (10,940 Res. Corrected#)	46	13,334-13,691	13,513	12600*
1618-1620	1619.0	Bulk	*94682	-24.6	12,200 (11,490 Res. Corrected#)	46	13,887-14,202	14,045	13130*
1683-1685	1684.0	Mixed Discrete	*N95444	-25	12,140	280	13,437-15,067	14,252	14250
1710-1711	1710.5	Mixed Discrete	*N95445	-25	12,460	120	14,091-15,090	14,591	14590
1723-1725	1724.0	Mixed Discrete	^134836	-25	12,190	290	13,470-15,155	14,313	14310
		(0.035 mgC)							
1738-1739	1738.5	Mixed Discrete	*N95446	-25	13,420	230	15,390-16,932	16,161	16160
1747-1748	1747.5	Charcoal	*N94003	-25	13,260	35	15,578-16,699	16,139	16140
1778-1779	1778.5	Wood	*N94004	-25	13,775	35	16,734-17,049	16,892	16890
1823-1824	1823.5	Charcoal	*N94005	-25	14,360	30	17,154-17,790	17,472	17470
1823-1824	1823.5	Charcoal	*N94243	-25	14,310	30	17,082-17,706	17,394	17390
1870-1872	1871.0	Charcoal; Charred Grass	^134837	-25	14,740	200	17,460-18,424	17,942	17940
		(0.073 mgC)							
1997-1999	1998.0	Seeds	*N94006	-25	16,580	40	19,461-19,936	19,699	19700
2019-2020	2019.5	Seeds	*N94007	-25	16,880	40	19,832-20,321	20,077	20080
2081-2082	2081.5	Wood	*N94008	-25	17,980	180	20,911-22,128	21,520	21520
2198-2199	2198.5	Seeds	*N94010	-25	19,630	40	23,134-23,779	23,457	23460
2280-2282	2281.0	Small Twig	^134839	-23.4	20,870	90	24,881-25,516	25,199	25200
2292-2293	2292.5	Charcoal	^134840	-24.1	21,370	90	25,510-25,899	25,700	25700
2344-2345	2344.5	Charcoal	*N94245	-25	21,025	40	24,940-25,556	25,248	
2344-2345	2344.5	Charcoal	*N94011	-25	21,120	70	24,834-25,494	25,164	25210
2384-2386	2385.0	Charcoal	^118908	-25	22,010	80	26,078-26,843	26,460	26460
2425-2427	2426.0	Small Charcoal (0.16 mgC)	^134841	-23.9	21,760	210	25,650-26,481	26,061	26060
2830-2832	2831.0	Charcoal	^118909	-25	25,940	110	30,419-31,016	30,720	30720
2860-2861	2860.5	Wood	*150331	-25	26,550	90	30,970-31,262	31,116	
2860-2861	2860.5	Wood	*150337	-25	26,270	80	30,758-31,179	30,969	31040

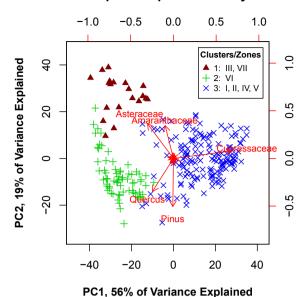
<sup>\*</sup> Identification number from measurements at Lawrence Livermore National Laboratory (LLNL).

<sup>^</sup> Identification number from measurements at University of California Irvine (UCI).

<sup>&</sup>lt;sup>a</sup> Bulk samples used to calculate reservoir effect <sup>14</sup>C age difference.

<sup>&</sup>lt;sup>b</sup> Bulk <sup>14</sup>C ages corrected for reservoir effect.

### **Principal Components Analysis**



**Fig. 3.** Principal Components (PC) Analysis of pollen data from Core LEDC10-01. Cluster 1 (red triangle), which includes Asteraceae, Amaranthaceae and *Pinus*, dominates pollen III and VIII. Cluster 2 (green +), composed of *Quercus*, dominates pollen zone VI. Cluster 3 (blue  $\times$ ), composed of Cupressaceae, dominates pollen zones 1,II, IV, and V. PC1, and PC 2 explain 56% and 19% of the variance respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Group 3, identified with blue X, is comprised of samples dominated by Cupressaceae pollen. This group is separated from the other two by PC axis 1 scores, as PC1 is most closely related to the percent Cupressaceae pollen. The other two groups are comprised of samples dominated by Asteraceae and Amaranthaceae pollen (group 3, red triangles) or *Quercus* and *Pinus* pollen (group 2, green +) and are separated by their PC2 axis scores. The groupings identified by cluster analysis and Principal Components Analysis support the Pollen Zones assigned by visual inspection of the pollen percent data (Fig. 5).

#### 4. Pollen results

The relative abundance of the diagnostic taxa LEDC10-1 core are summarized in Fig. 4. The most striking aspect of the pollen record is the contrast between the high-frequency variations in herbaceous vegetation that bracket the prolonged, monotonic dominance of *Juniper* and *Pinus*.

A brief peak in *Pinus* (28%) immediately followed by Cupressaceae peak (32%) initiates the base of the core (Fig. 4). *Pinus* values drop rapidly and remain low, in contrast to Cupressaceae, which averages 50% and reaches an acme (70%) at the end of the zone, as does Typha (~40%). Low values of Abies and Picea are sporadically present. Poaceae and Cyperaceae gradually increase, whereas Amaranthaceae, Asteraceae gradually increase and peak in the middle of PZ I. The peaks in Typha, Asteraceae and Amaranthaceae are brief ( $\leq$ 300 yr). *Eriogonum* remains consistently low ( $\leq$ 5%).

Cupressaceae ranges between 20 and 40%. Pinus ramps down to

≤10% as Amaranthaceae increase. Although minimal, *Abies* and *Picea* are best represented in this zone. *Asteraceae* values peak (~20%) in the middle of the zone. *Artemisia* and Poaceae remain as in PZI, while Cyperaceae declines and then recovers. Excluding *Typha*, wetland and aquatic taxa (*Potamogeton, Myriophyllum, Sagittaria, Rorippa, Azolla, Isoetes*) are only sporadically present.

Cupressaceae decreases from ~40% at the base of the zone to ~5%. (*Pinus* drops to <5%). The modest increase in *Quercus* (~8%) in this zone is not exceeded until PZ VI. Two Amaranthaceae peaks (~50% at ~25.3 and 41% at 23.5 ka) bracket an interval that encloses Asteraceae maxima (53% at 26.6 ka and ~45% at 25.6 ka). Except for one spike at ~26.6 ka, Cyperaceae pollen forms <~15% of the pollen sum, as does Poaceae, which begins to increase at the end of PZ 3. The abrupt increase in *Pinus* at the base of this zone initiates a series of periodic fluctuations that offset lower amplitude oscillations the gradually increasing, high abundance of *Cupressus* (mean = 43%). *Pinus* oscillates down to <5% between ~26.5 ka and 25.3 ka.

The abrupt increase in *Pinus* to 54% at the base of this zone initiates downward-ramping oscillations to ~20% that are mirrored in the low amplitude oscillations in the rise of Cupressaceae from ~10% to ~59%. A brief rise in Poaceae is followed by an extended increase in Cyperaceae, reach their highest values in the core. *Alnus* peaks briefly in this zone. A marked increased in *Typha* (~25%) briefly punctuates the Cyperaceae rise. Amaranthaceae and Asteraceae are minimal ( $\leq$ 5%). *Azolla, Rorippa, Sagittaria, Potamogeton* are present sporadically. *Isoetes* (~5%) occurs at the base of the zone and *Myriophyllum* increases to 15% at 23.4 ka and to 10% at 22.8 ka.

The predominance of Cupressaceae ( $\sum$  50%) is punctuated by periodic oscillations in *Pinus* ( $\sum$  25%). *Quercus* increases slightly in the middle of the zone. Abundance of herbaceous and shrub taxa, which remain comparable to the low levels of the preceding zone, show muted oscillations. Wetland taxa (1%) are rarely present.

The rise of *Quercus* to ~39%, the rapid decline of Cupressaceae to minimal values ( $\leq$ 1%), and a sustained increase in Rosaceae/Rhamnaceae (>15%) distinguish this zone from the rest of the core. Escalating from <5% at the beginning of this zone to ~39% at ~13.2 ka, *Quercus* gradually ramps back to 15% at 10.8 ka. Asteraceae, Poaceae, Cyperaceae (comparable to values in PZ III) show a substantial increase. *Typha* and *Alnus* are continuously present in low amounts throughout the zone. *Pinus*, on the other hand, continues to oscillate at values maintained through most of the record, with the exception of PZ III and the latter part of PZ I.

The dominance of Asteraceae, the resurgence of Amaranthaceae and Poaceae characterize this zone. Asteraceae varies from ~30% to ~50% between ~10.77 and ~8.89 ka. The relative abundance of Amaranthaceae escalates to 30% at the top of the core; the relative abundance of *Quercus* falls to background levels of <5%.

Principal components analysis distills the essence of pollen and spore data from core LEDC10-1 by reducing its dimensionality (Fig. 5). The importance of Cupressaceae in PZ I, II, IV and V is

## **Lake Elsinore**

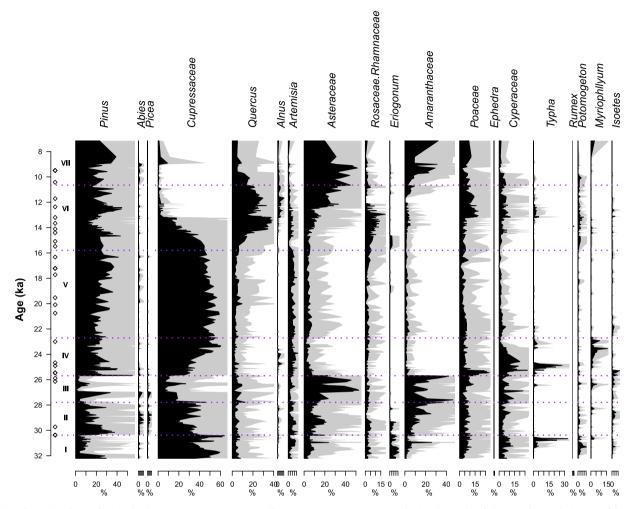


Fig. 4. The relative abundance of selected pollen taxa in Core LEDC10-01. Pollen zones (I—VII) were constructed using the results of cluster and PC analysis. Ages of dates used to construct the Age Model (Fig. 2, Table 1) are shown the right of the Age scale.

confirmed by high flux of Cupressaceae pollen in these zones. In PZ III, and PZ VII, positive PC axis 2 scores highlight the prominence of Asteraceae and Amaranthaceae. The inverse relationship between PC axis 2 scores and pollen flux, emphasize the role of halophytes and xerophytes in PZ II, III, VI, and VIII. High values of *Quercus* flux confirm the prominence of *Quercus* (high negative scores of PC2) at the beginning of the deglacial (~14,400). The rapid decrease in *Quercus* flux is matched by decreasing negative values of PC 2. The striking minima of Asteraceae and Amaranthaceae flux (PZ III and VII) contrasts with the prominence of these herbaceous taxa (high positive loadings) in PC2.

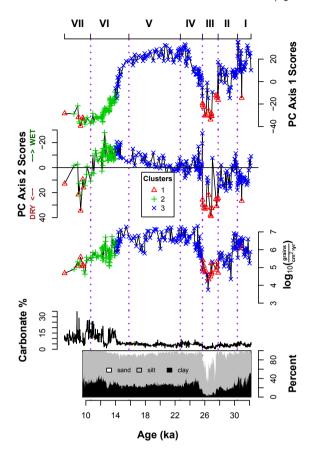
#### 5. Discussion

#### 5.1. Vegetation change between 32.6 and 9.0 ka

PZ I (32.6-30.5 ka)

Cupressaceae with lesser amounts of *Pinus*, dominated the LE drainage from ~32.6—30.5 ka (Fig. 4). Montane woodland and forests may well have extended close to the shores of the lake. The assemblage suggests cool, wet conditions. It is interesting to note that *Picea*, which is no longer present in the region, occurs

in trace amounts. Outliers of Picea sitchensis now occur on the California coast ~300 km to the north where average annual temperatures and precipitation are ~3° lower and ~800 mm higher than Lake Elsinore. Components of chaparral/foothill woodland (Rosacea/Rhamnaceae and Ouercus) were also present. A subsequent, rapid decrease in *Pinus* suggests increasing summer drought, as Pinus is less drought-tolerant than Cupressaceae (Linton et al., 1998; Willson, 2008). This is supported by a gradual coarsening of the clayey silts. Seasonal drought is also inferred from the expansion of low scrub (Asteraceae) and of halophytes (Amaranthaceae), plants that colonize ephemeral, desert-like sites that become dry in summer (Branson et al., 1967; Davis, 1999; Clarke et al., 2007). The expansion of emergent and submergent shoreline vegetation (Cyperaceae, Poaceae, Potamogeton) also suggests overall regression of the lake in this zone. Abrupt drops in lake levels are implied by rapid increases in herbaceous vegetation (tules/cattail marshes: Asteraceae, Amaranthaceae, and Typha) closer to the lake depocenter  $\sim$ 31 -  $\sim$ 30 ka. Pollen flux (grains/cm<sup>2</sup>/yr) in the clayey silts is high (Fig. 5). This is likely a function of sedimentation (hydrodynamically, pollen grains are approximately the same size as silt and clay), and of enhanced preservation in organic-rich silts and clays (Sangster and Dale, 1961; Tschudy, 1969).



**Fig. 5.** Principal Components 1 and 2, pollen flux (log (grains/cm²2/yr), and sediment composition of Core LEDC10-01 plotted to age are shown with pollen zonation (I–VII). PC axis 1 is dominated by variability in Cupressaceae pollen. In PC axis 2, positive values indicate Asteraceae and Amaranthaceae dominance, while negative values indicate Quercus and Pinus pollen dominance (Colors and symbols of the clusters and pollen flux derive from Fig. 3). The relative amount of sand, silt, and clay, and % carbonate are shown at the bottom of the figure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

#### PZ II (30.5-27.7 ka)

A step-like decrease in Cupressaceae abundance and an abrupt decrease in total flux to minimal values occurred between ~30.5—27.7 ka (Figs. 4 and 5). The decrease in Cupressaceae, the substantial increases in *Pinus*, and the presence of montane taxa (*Picea* and *Abies*) are interpreted as evidence of low annual temperatures, Fluctuations in Cupressaceae and *Pinus* may reflect variations in precipitation in the Lake Elsinore watershed. Increased summer drought is suggested by the increasing prominence of Amaranthaceae and Asteraceae (common components of seasonally-dry, ephemeral sites and scrub) (Koehler et al., 2005).

#### PZ III (27.7–25.2 ka)

In this Zone, repeated high-frequency oscillations in the relative abundance and total flux of halophytic and xerophyte littoral vegetation (Cluster 1, Amaranthaceae and Asteraceae) imply lengthy intervals in which the lake regressed and the shoreline prograded basinward, allowing salt- and drought-tolerant vegetation to expand periodically around and onto the former lake bed during persistent, extreme winter (and summer) droughts (Davis, 1999) (Figs. 4 and 5). Minimal relative abundance of montane conifers (Cupressaceae and Pinus) also suggests intervals of decreased effective moisture in the San Jacinto River watershed. The

substantial increase in xerophytic and halophytic vegetation is consistent with growth a sandy substrate (Fig. 5). Minimal total pollen flux (<81,00 grains/cm²/yr) is consistent with oxidation and degradation of pollen deposited on a coarse, sandy substrate (Solomon et al., 1982; Fall, 1987; Campbell, 1999; Davis, 1999). The relative abundance of sand, which reached values as high as 80%, was likely formed by a prograding littoral zone as lake level regressed.

It is possible that lake level regression and sand deposition is also related to tectonic activity on the Elsinore and nearby San Jacinto fault zones. One main shock has occurred along the Elsinore fault and five main shocks occurred along the San Jacinto fault zone during historic time. Over the past 40 ka, the mean horizontal slip on the Elsinore fault rate is ~1.6 mm/yr. Faulting is unlikely to account for more than 1–2 m of fault-generated lake base level change; whereas, hydrologically-forced lake base level change of up to 13 m has been noted in the historical record (Vaughan, 1999). Moreover, the minimal relative abundance of montane conifers (Cupressaceae and *Pinus*) correlative to the sandy unit cannot be explained reasonably by local tectonic activity.

Based on limited vertical displacement along the Elsinore fault and the altered montane contribution correlative to the sandy unit, we favor the climatic interpretation that PZ III represents a protracted interval of below average winter precipitation and annual drought.

PZ IV (25.3-22.5 ka)

Between 25.3 and 22.5 ka, Cupressaceae were the major component of the montane coniferous woodland that surrounded LE. The abundance and high flux rate of Cupressaceae- and Pinusdominated pollen deposited in Lake Elsinore indicates the expansion of montane forests close to the lake, which would imply treeline lowering >1000 m and estimated temperature depression on the order of ~11 °C (Anderson and Koehler, 2003). The minimal amount of *Quercus* and Rosaceae/Rhamnaceae, may have been derived from a limited area of oak scrub/chaparral that bordered the shore. Relative absence of Asteraceae, Amaranthaceae, and submergent vegetation implies lake levels were higher than in PZ III. Initially, wetland composed of Typha and Cyperaceae grew near the core site. As the lake level transgressed, marshland decreased and shallow-water aquatics (Myriophyllum) developed. The pulsating increase in Cupressaceae (PC 1) and correlative decrease in Pinus may reflect increased precipitation and/or decreased evapotranspiration due to lower summer and winter temperatures. The abrupt change in relative abundance and flux of pollen from drought-adapted vegetation to emergent and submergent aquatic vegetation corresponds temporally with the correlative change in the depositional environment – an abrupt shift from an organic-poor sandy silt/silty sand (shallow water) to an organic-rich, poorly to well-laminated clayey silt (deeper water) (Fig. 5).

PZ V (22.5-14.4 ka)

Cupressaceae-dominated montane woodlands and forest apparently covered much of the San Jacinto River catchment and the shores of LE between ~22.5 and ~14.4 ka. Subtle reduction in the prominence of Cupressaceae and increase in the relative proportion of *Pinus* continued through the last glacial maximum; however, the relative abundance and flux of Cupressaceae was always greater than that of *Pinus*. Although Cupressaceae-type pollen has been considered as over-represented in relation to *Pinus* (Hidalgo et al., 1999), in modern pollen assemblages from the cis-montane

region of southern California, the relative proportions of *Pinus* and Cupressaceae are considered to be valid representatives of their presence in the landscape (Wahl, 2003b). In this zone, we interpret the overall decrease in the relative abundance of Cupressaceae and increase in Pinus, which is less tolerant of summer drought, as evidence of increasing effective soil moisture due to decreasing summer drought and/or increasing effective precipitation (Wells, 1979: Linton et al., 1998: Mueller, 2005: Minnich, 2007: Willson, 2008). At no time during this 8.1 ka interval does the vegetation indicate significant drought. High lake levels during the LGM are inferred from the very low amount of littoral-zone pollen and the high rate of conifer pollen deposited in LE. The absence of littoral zone vegetation may reflect increased precipitation/runoff, which caused high lake levels to rise above the natural outlet, flooding and destroying littoral vegetation. We posit that the high flux of pollen deposited annually in this zone likely reflect increased precipitation and runoff in the LE watershed that also resulted in rapid transport and deposition of pollen and other silt and clay size particles in LE (Fig. 5).

#### PZ VI (14.4-10.8 ka)

The deglacial (~14.4-10.8 ka) is distinguished by the prominence of Quercus abundance and flux (Fig. 5), the sudden demise of Cupressaceae, and the increased presence of chaparral taxa (Rosaceae/Rhamnaceae). The relative abundance of oak woodland and chaparral deposited in LE approaches recent values (Byrne et al., 2004). In sharp contrast to the preceding relatively lowamplitude variation in basically two pollen types (Cupressaceae and Pinus), the dynamic deglacial pollen record consists of largeamplitude Quercus and Pinus-dominated oscillations, accompanied by a diversity of arboreal and nonarboreal pollen types. The initial rise of Quercus (~14.5–13.1 ka) corresponds with the Bølling-Allerød warming, and the subsequent Pinus peak corresponds with Younger Dryas cooling (~13.1—~12.1 ka) (Kirby et al., 2013). The, stepwise decline in the montane conifer Cupressaceae and the increase in *Quercus* woodland implies overall higher summer temperatures. The abrupt decrease in Cupressaceae and Pinus flux at the beginning of this zone may reflect a substantial decrease in precipitation in the LE watershed. The overall reduction in pollen flux undoubtedly reflects oxidation of pollen in the overall shallower lake and its now well-mixed, more oxic profundal zone (Sangster and Dale, 1961; Bryant et al., 1994; Kirby, 2005; Kirby et al., 2013) (Fig. 5).

Episodic variations in herbaceous (Asteraceae, Rosacea/Rhamnaceae), emergent (Cyperaceae, Poaceae, *Typha*), and aquatic (*Potamogeton*) vegetation imply shorelines close to the depocenter — a shallowing lake reflecting higher summer temperatures and/or decreased precipitation/runoff (Bryant et al., 1994; Davis, 1999; MacDonald et al., 2008; Kirby, 2005, 2013). The relatively high carbonate content of the sediment, which is regarded as a proxy for warmer epilimnion summer temperature and decreased water depth, supports this interpretation (Kirby et al., 2013).

#### PZ VII (10.8-9.0 ka)

We interpret the abundance of pollen from halophytic vegetation (Amaranthaceae) and semi-arid scrub (Asteraceae) as evidence of increased summer drought between ~10.8 and ~9.0 ka. The very low total flux rate may reflect significantly reduced precipitation and runoff (Fig. 5). This early Holocene herbaceous pollen assemblage resembles pollen assemblages deposited between 27.5 and 25.3 ka , a lengthy interval that we termed a glacial megadrought.

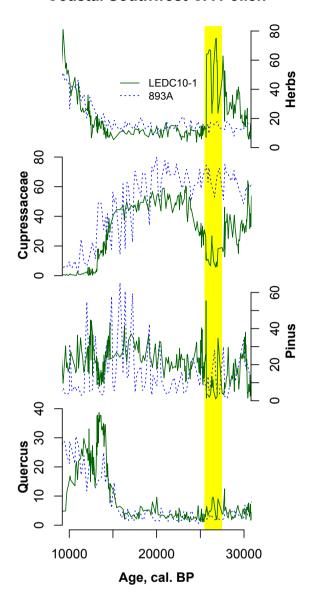
5.2. Coastal southern California: Lake Elsinore and Santa Barbara Basin pollen records

To develop a regional overview of vegetation change in CSC between ~32 ka and ~9 ka, we compare the pollen record from Lake Elsinore (this paper) with the pollen record from marine core ODP893A in SBB (Heusser, 1995). At present, there are no other continuous, high resolution records (~88 years between samples in Lake Elsinore and ~218 years between samples in ODP893A) of terrestrial ecosystems in coastal southwest North America. Although both localities (LE and SBB) are surrounded by summer dry/winter wet Mediterranean plant communities that range from montane forests to lowland chaparral, there are significant differences between the source of the pollen and the depositional sites. Pollen assemblages deposited in LE, a pull apart basin, integrate pollen from vegetation of the San Jacinto drainage (~1240 km<sup>2</sup>), including the broad (40 km), rolling hills of the San Jacinto Valley, as well as local runoff from the Elsinore Mountains. Pollen assemblages deposited in SBB, a deep, anoxic basin, integrate the composition and seasonal pollen production of vegetation in the large watershed of the Santa Clara River (4100 km<sup>2</sup>) that drains the nearby Transverse Mountains and a narrow coastal plain (Heusser et al., 2014). Although average annual temperatures in LE and Santa Barbara (SB) are similar, LE lies ~ 40 km inland on the leeward side of the Elsinore Mountains where average summer temperatures are ~ 8 °C higher than on the coast at SB. Average annual precipitation in LE (~304 mm) is approximately half of precipitation in Santa Barbara (Vogl and Schorr, 1972).

The similarity of the basic structure of the relative abundance of oak (Quercus) in both sites is striking (Fig. 6). Quercus values initially oscillate between 5 and 10% and subsequently level at minimal values between 25 and 15 ka. Rapid deglacial fluctuations during the deglacial may be correlative; however, the abrupt rise at ~13.5 to Holocene Quercus values in SBB apparently occurs ~1000 years after LE. This difference may reflect the usual age-model caveats (e.g. differences between oxygen isotope- and radiocarbon — based age-models) The postglacial decrease in Cupressaceae, the dominant taxon of both full-glacial records, also reflects an apparent 1000-year offset. A major difference between the early Cupressaceae records is the step-like decrease of Cupressaceae in LE. Relative abundance plunged from ~60% at the beginning of the record to ~10% at ~26 ka, and subsequently rose to maximum glacial values (~60%) at 23.2 ka. In SBB, however Cupressaceae varied within fullglacial values from the beginning of the record. In the early glacial record from LE (~32-~25 ka), repeated, high-frequency variation in the relative abundance of herbs (Artemisia, Amaranthaceae, and Asteraceae) differ markedly from the SBB low-frequency mode of herbal abundance that continued until ~13.5 ka. We suggest that the extended oscillations of pollen from halophytic and xerophytic vegetation reflect dynamic changes in the source and depositional environment -a seasonally-dry lake surrounded by semi-desert, rolling hills. The comparative absence of similar halophytic and xerophytic vegetation in the SBB record suggests that on the coast, increased effective moisture may have been buffered by persistent onshore fog.

Although the mean relative abundance of *Pinus* pollen deposited in LE and SBB is surprisingly similar (*Pinus* pollen can be overrepresented in marine sediments [Heusser and Balsam, 1977]), the basic trends in *Pinus* pollen abundance differ. In SBB, the relative amount of *Pinus* decreases overall from ~32 ka until the LGM, whereas in LE, *Pinus* abruptly decreases at 32 ka, 30 ka, and 25 ka, and then gradually increases until ~15 ka. In the LE *Pinus* record, the lengthy decrease from 14.8 ka to 12 ka contrasts with a correlative increase in *Pinus* at ODP893A. This may reflect the differential input of *Quercus* at the two sites.

# **Coastal Southwest CA Pollen**



**Fig. 6.** Comparison of coastal southern California vegetation from four diagnostic pollen groups deposited in Lake Elsinore and in Santa Barbara Basin between 9 ka and ~33 ka. For east of comparison, the very high frequency fluctuations in *Pinus* are smoothed with a 3-point moving average. Amaranthaceae, Asteraceae are grouped together as Herbs.

Pollen data from LE and SBB provide a continuous, regional pattern of CSC vegetation and climate change from 32 ka to ~10 ka that is supported by other CSC paleoenvironmental reconstructions. Full glacial, cool, wet conditions have been inferred from the presence of montane vegetation at low elevations in Los Angeles and evidence of glaciation in the San Bernardino Mountains (Anderson et al., 2002; Owen et al., 2003; Coltrain et al., 2004; Ward et al., 2005). In nearby Diamond Valley, montane *Juniperus* expanded to lower elevations at ~41 ka (Anderson et al., 2002) and in southeastern California, Cupressaceae and *Pinus* dominated full-glacial sediment (Davis, 1999; Atwater, 1986). Analysis of Baldwin Lake sediments deposited between ~27 and ~20 ka are interpreted as evidence of lake regression and formation of a playa lake (Blazevic et al., 2009). At Zaca Lake, ~50 km northeast of SBB, fluvial tufa deposits suggest increased precipitation, approximately at 11,

17, and 19 ka (Ibarra et al., 2014). Floral and lithologic evidence of glacial/postglacial evolution of cold, wet to warm, dry climates has been documented on the Channel Islands and at LE (Anderson et al., 2008, 2010; Kennett, 2008; Kirby et al., 2013). On the north coast of California and Oregon, cool wet glacial climates supported montane coniferous forests that were replaced by lowland *Sequoia sempervirens* (coastal redwood) and *P. sitchensis* rainforests after ~15 ka (Pisias et al., 2001). In drier regions inland, *Quercus* woodland expanded ~15 ka, as in LE.

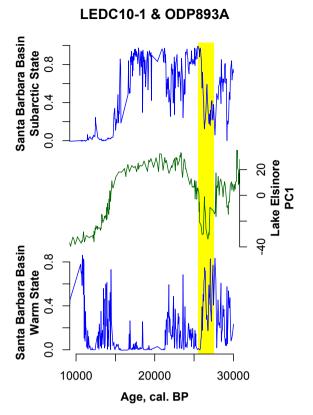
# 5.3. Paleoclimate change in coastal southern California and offshore waters of the North Pacific

The interaction between atmospheric circulation (the Aleutian Low and North Pacific High) and northeast Pacific sea surface temperature produce climate variations that drive large-scale variations in the composition and distribution of terrestrial ecosystems in CSC (Namias and Cayan, 1981; Trenberth and Hurrell, 1994; Harrison, 2003; Diffenbaugh and Ashfaq, 2007). Strong correlations between marine and continental records from coastal northern California and Oregon have shown that the response time of the two regions to changes in millennial scale climate forcing is similar, and that oceanographic conditions on these time scales have a direct impact on coastal climates (Pisias et al., 2001).

In Fig. 7, we compare the faunal response of the southern California margin with floral response onshore to climate variability between ~9 ka and ~32 ka. We use two planktonic foraminiferal assemblages in SBB that are associated with cool waters (Factor 1, sinistral *N. pachyderma* dominated), and with warm, stratified water (Factor 3, *G. bulloides, N. incompta* dominated). *N. pachyderma* is presently found in 6°–8 °C subpolar waters; *N. incompta* is presently found in SB waters that range from 14°–17.5 °C (Hendy, 2010).

We use floral assemblage PC1 from LE as a proxy for variations in effective moisture, which is a function of temperature and evaporation. When effective moisture is high, there is little moisture stress on plants and precipitation and runoff are high. The converse is true when effective moisture (EM) is low. Positive values of floral assemblage PC1 indicate the abundance of upper, montane, Cupressaceae (juniper)-dominated woodlands, in which annual precipitation is ~1000 mm (Fig. 3). Negative values indicate abundant Amaranthaceae-Asteraceae, halophytic and xerophytic vegetation of ephemeral playa lakes and vernal pools in which annual precipitation is ~500 mm (Thompson et al., 1998; Wahl, 2003a,b). Temperature depression averages ~2.1 °C for each 300-m increase of elevation in the San Jacinto Mountains (Vogl and Schorr, 1972).

Between 32 and 27.7 ka, effective moisture decreases in a steplike pattern. A major drop in EM (29.5-28.9 ka) occurs immediately after a sharp decrease in the subarctic state of SBB waters. The triple sequence of effective moisture minima at 27.5 ka. 26.6 ka. and 25.5 ka, each lasting ~500 years, represent drought-like conditions that persist for over ~2000 years. A similar duration (500 yr) of drought is inferred from late Holocene sediments from Zaca Lake, located 50 km north from SBB (Kirby et al., 2014). This drought similarity indicates that our proposed glacial megadroughts are not without more recent analogs; moreover, it suggests that megadroughts are a feature during both glacial and-interglacial conditions (Kirby et al., 2014). In SBB, during this terrestrial drought interval, a triple sequence of low values of the subarctic faunal factor generally correspond with low effective moisture onshore and with high values of the warm faunal factor. The gradual rise and sustained, monotonic high levels of effective moisture that continued until ~16.5 ka correspond with high values of the subarctic waters but they do not mirror the rapid and abrupt shifts in the subarctic and warm states of SBB. In like manner, the gradual,



**Fig. 7.** South coastal California marine and terrestrial paleoclimate reconstructions from 10 ka to 33 ka. Positive scores of LE PC 1 indicate greater effective moisture. Positive loadings of SBB PC 3 indicate greater presence of warm, stratified waters. Positive loadings of SBBPC1 indicate the presence of sub-arctic waters in SBB (Hendy, 2010).

postglacial decrease in effective moisture corresponds with a series of steplike changes in SBB. We interpret the peak in effective moisture at ~12.5 ka, which corresponds with a comparable increase in the subarctic state and decrease in the warm state of surface waters in SBB, as clear evidence of the Younger Dryas climatic event.

The general correspondence between offshore (SBB) temperature and onshore (LE) effective moisture suggests a direct buffering of continental temperatures by the thermal inertia of coastal waters as well as a linked response to large-scale atmospheric reorganization over the north Pacific and coastal southwest United States (Herbert et al., 2001; Barron et al., 2003; Lyle et al., 2010, 2012; Pisias et al., 2001).

#### 6. Conclusions

Pollen analysis of core LEDC10-1 from Lake Elsinore, California provides the first continuous, decadal-scale record of the response of CSC ecosystems to climate change from ~32 to ~9 ka mesic montane vegetation that initially dominated the site was replaced by high-frequency shifts to arid, herbaceous (Amaranthaceae, Asteraceae, Artemisia) vegetation that lasted from ~27.5 to ~25.5 ka — an unprecedented glacial megadrought. Minimal pollen flux at the same time reflects frequent, abrupt changes in the depositional environment likely associated with the rapid migration of the littoral zone; this also suggests persistent and sustained drought. Subsequent monotonic development of montane conifer forests (Cupressaceae with lesser amounts of *Pinus*), indicative of lower temperatures and increased precipitation, continued unabated

until ~16 ka. Rapid fluctuations in *Quercus* and other semi-arid lowland vegetation characterize the late Glacial to Holocene transition. The late-glacial resurgence of drought-adapted vegetation and low values of pollen flux resemble conditions not unlike those of the Glacial megadroughts in Lake Elsinore between ~27.5 and ~25.5 ka, and of Holocene multi-century droughts In SBB and at Zaca Lake during the Medieval Climate Anomaly (Heusser et al., 2014; Kirby et al., 2014).

Comparisons between marine surface water conditions (planktonic fauna) and terrestrial conditions (pollen-based proxy of effective moisture) show broad scale similarities. Correspondence between major climatic events, such as the Younger Dryas and Interstadials 2–5, suggest that nearby marine conditions may modulate the terrestrial response to climatic forcing.

The similarity of the broad patterns of terrestrial vegetation change that are reconstructed from Lake Elsinore and from Santa Barbara Basin (ODP Site 893) provide a regional synthesis of CSC vegetation change between ~32 and ~9 ka. However, there are significant differences. The extreme Glacial megadroughts that lasted from ~27.5 to ~25.5 ka inland at Lake Elsinore are not recorded by the pollen data from the Santa Barbara coast. The Lake Elsinore record apparently captures the response of semi-arid ecosystems to local edaphic and climatic change. The conspicuous absence of the ~27.5—~25.5 ka glacial "mega-drought" in the Santa Barbara Basin pollen record highlights the sensitivity of Lake Elsinore to hydroclimatic change, and thus, the importance of this new record. These results indicate that megadrought can occur even during the full glacial climatic boundary conditions and forcings.

Multi-century megadroughts in CS occur in both Glacial and Interglacial conditions. The duration of these arid intervals exceed anything observed in the recent or tree-ring records for CSC (Cook et al., 2004). As climate continues to change, might these megadroughts represent possible analogs for the future hydroclimatic state in CSC?

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