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The Rambla highstand shoreline and the Holocene lake-level history of Tulare Lake, California, USA

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Abstract

The stratigraphy associated with a highstand, wave-cut shoreline and with sites farther out into the lake plain constrain the Holocene lake-level history of Tulare Lake, California, USA as follows: Seven to eight major fluctuations in lake level occurred during the past 11,500 yr. Lake level was generally higher during the early Holocene (prior to ~6000 cal yr BP) peaking in two highstands (65–70 masl) at 9500–8000 cal yr BP and 6900–5800 cal yr BP. Thereafter, it fluctuated at lower amplitude until reaching a major highstand during the most recent millennium between ~750 and 150 cal yr BP. Two lake-level rises of lower amplitude were centered on 3300 and 1600 cal yr BP. At least three, probably brief, lowstands (<58 masl) occurred at: ~9700, 5500, and soon after 3000 cal yr BP. None of the trenches studied penetrated materials as old as the Clovis era, suggesting that the prolific, near surface Clovis shoreline sites found at the southern margin of Tulare Lake are absent at the western margin. An archeological midden of middle to late Holocene age was found near the top of the highstand shoreline feature. This site was probably occupied for much of the Holocene after 5000 cal yr BP, a time interval during which the lake would have been much lower in elevation than that of the site and several hundreds of meters distant from the site.

1. Introduction

Tulare Lake is located in the San Joaquin Valley of central California between the Coast Ranges and the Sierra Nevada (Fig. 1). Over the past few hundred millennia, the surface elevation of Tulare Lake fluctuated by several tens of meters in response to climate variations and to changes in the relative elevation of its spillover sill located near the north end of the lake where the Kings River presently enters the lake (Fig. 1) (Atwater et al., 1986). In this paper, we focus on the Holocene, a sufficiently short time interval for climate change, rather than geomorphic processes, to be the major influence on lake level. That is, during this time interval Tulare Lake behaves primarily as a closed-basin lake system that has not yet appreciably eroded into its spillover sill, a hydrologic barrier built by anomalously large alluvial fan activity during the most recent (MIS2) glacial maximum (Atwater et al., 1986).

The past 15,000–10,000 years is a particularly important time period in the Tulare Lake region. First, the level of this lake may have influenced the distribution of archeological sites. For example, high concentrations of Clovis-aged and younger artifacts are found in an areally restricted, elongate region that is parallel to the southern margin of the lake basin at an elevation of 56–58.5 masl (Riddell and Olsen, 1969; Wallace and Riddell, 1988; West et al., 1991; Fenenga, 1993) (Fig. 1). The location of the associated occupation sites was thus proposed to have been the result of a stable (and low) surface elevation of Tulare Lake for an extended period of time during the "Clovis Drought" of Haynes (1991) at 12,900 cal yr BP and later in the Holocene. Despite the plethora of artifacts, precise dating independent of the presumed ages of projectile point

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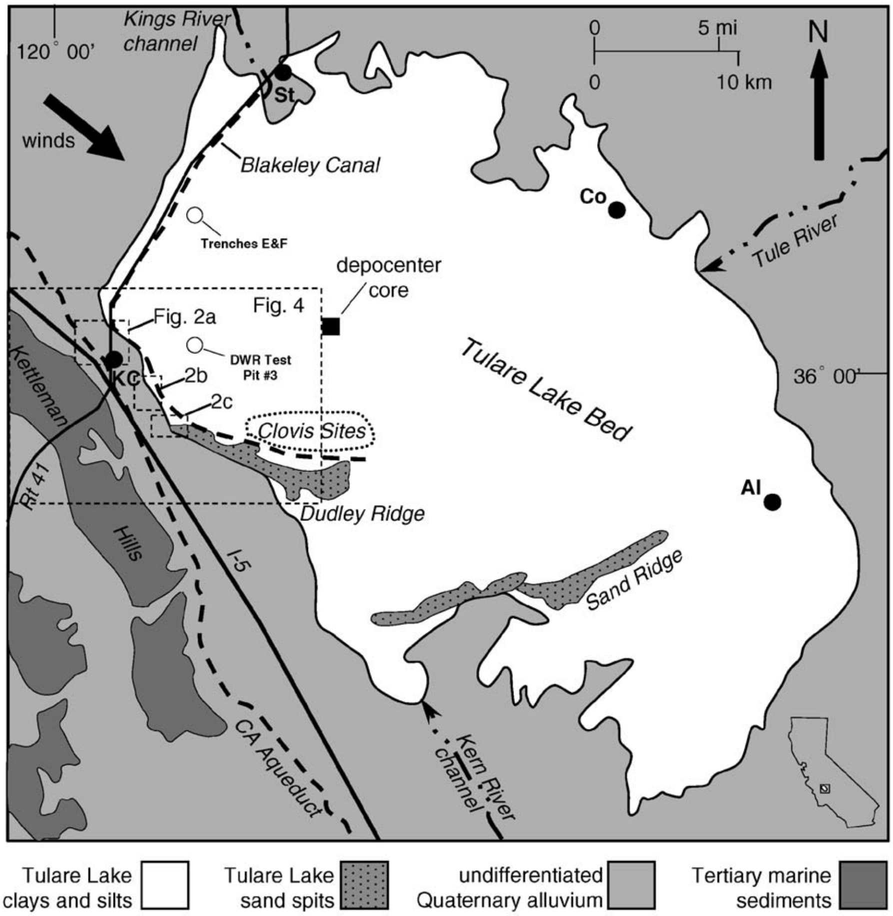


Fig. 1. Generalized geological and landmark map of study area (after Page, 1986). The location of the depocenter core studied by Davis (1999) is indicated by the solid square symbol. The locations of Lake Plain Trenches E and F and DWR Pit #3 are shown as open circles. Locations of communities are shown by the following abbreviations: Kettleman City (KC), Stratford (St), Corcoran (Co), Alpaugh (Al).

types has proven elusive, largely due to agricultural and other historical disturbances that have disrupted or destroyed most of the stratigraphic relationships at these sites. An improved lake-level history will serve as the basis for improved hypotheses regarding the distribution of paleoindian and Native American occupations in the region.

Second, the lake-level history of Tulare Lake is also a potentially important data source toward the understanding of paleoclimatic change in western North America following the most recent ice age. This is particularly true of the south-central California region west of the Sierra Nevada, an area in which few such lake records exist (Davis, 1999; Kirby et al., 2005 and references therein).

Davis (1999) provided an important record of late Quaternary climate for the Tulare Lake region based on the palynology of a depocenter core (Fig. 1). This study included conclusions regarding relative lake levels throughout the Holocene. Here we build on these results with improved constraints on absolute elevations and ages of past lake levels from two trench sites at higher elevations in the basin and mapping of related geomorphic features.

2. Background

2.1. Modern climate

The study area is hot and dry with low velocity winds (Preston, 1981). Mean temperatures in July range from highs of 37–38 °C (98–100°F) to lows of 18–20 °C (64–68°F). In January, they range from highs of 12–13 °C (54–56°F) to lows of 0–2 °C (32–36°F). Mean annual rainfall is in the range of 15–23 cm/yr (6–9 in/yr). Based on on-line climate summary data for the towns of Hanford, Corcoran, and Kettleman City from the Western Regional Climate Center at the Desert Research Institute, January, February, and March are the wettest months, and July and August are the driest. Winds blow predominantly (65% of the time) from the northwest and west-northwest (Fig. 1), with speeds usually between 5 and 25 kmph (3–15 mph). Due to the high temperatures and low precipitation values, evaporation rates of standing water (i.e., lake water) exceed precipitation rates by at least one m/yr (Atwater et al., 1986). Thus, it is clear that local precipitation contributes little to the waters of Tulare Lake at the present time and that most of the water in this basin is provided by streamflow.

2.2. Hydrology

Several major streams feed the Tulare Lake Basin. The largest of these originate in the Sierra Nevada. They are, from north to south, the Kings, Tule, and Kern Rivers (Fig. 1). The much smaller, currently ephemeral streams entering Tulare Lake from the Kettleman Hills do not greatly affect the hydrologic budget and, thus, the surface elevation of Tulare Lake (Atwater et al., 1986). However, they are significant to the geomorphic development of the local study area in that they have formed alluvial fans that protrude into the basin.

Although subsidence due to groundwater pumping has greatly affected the elevation of much of the San Joaquin Valley, the elevation of this study area has subsided less than 0.3 m (1.0 ft) due to groundwater withdrawal (Poland and Davis, 1956; Lofgren and Klausing, 1969; Poland et al., 1975; Galloway and Jones, 1999). Thus, subsidence should not significantly affect the conclusions of this study regarding paleolake levels.

Tulare Lake is currently dry due to stream diversions for agricultural purposes. The bottom of the lake basin sits at an elevation of ~55 masl. Prior to stream diversion, the level of the lake occasionally reached an elevation of 66 masl (216 fasl) during wet years in the nineteenth century (Atwater et al., 1986).

2.3. Geological setting

The San Joaquin Basin has been the site of deposition, predominantly in a marine setting, for more than 100 million years (e.g., Harden, 2003). For the past million or so years, deposition in the San Joaquin Basin has been mainly in a nonmarine setting. During this time, depositional environments have ranged from alluvial fan to lacustrine settings dependent on proximity to source streams around the margins of the basin (Lettis and Unruh, 1991). Lacustrine deposits, primarily found near the center of the basin, are predominantly fine-grained clays and silts but also include sand deposits associated with beaches, spits, and deltas.

The study area is in the vicinity of Kettleman City on the west side of the Tulare Lake Basin (Fig. 1). This area is comprised predominantly of fine-grained sediments deposited subaqueously. Toward the west, between the lake bed and the Kettleman Hills, the lacustrine deposits are overlain and/or intercalated with the deposits of small alluvial fans corresponding to ephemeral stream systems. Several kilometers to the southeast of Kettleman City, a ridge of sand protrudes east-southeast into the southernmost part of the Tulare Lake Basin. The sand deposits are currently being reworked by eolian processes to form dunes and, hence, have been mapped as dune sand (Page, 1986). However, the origin of the sand deposits is likely from a lacustrine environment, probably as a result of the interaction of wind-driven longshore currents in Tulare Lake and outflow from the mouth of the Kern River. These sediments and similar sediments found further to the southeast, are mapped here as sand spits (Fig. 1).

3. Methods

3.1. Mapping

The following mapping resources were used in this study: USGS 7.5 min topographic maps, digital elevation models (DEM), digital orthophotoquads, NAPP aerial photographs, and USDA Soil Survey Maps of Arroues and Andersen (1986). Shaded relief maps were constructed from the DEM data using ArcView™ and Natural Scene Designer™ software.

3.2. Trenching

Two series of trenches were excavated to provide detailed lake-level records in context with the geomorphic features identified in the mapping component of this study. Trenching was conducted with backhoes supplied both by the California Department of Water Resources (DWR) and by Tyack Construction, Inc., of Bakersfield, California. Elevations at trench sites or of shoreline features were either surveyed in from benchmarks or estimated from 7.5′ topographic maps.

Detailed lithologic descriptions were completed by the two primary authors for all of the stratigraphic units exposed in the trenches. The relative elevations of individual stratigraphic columns within each trench were tied to each other via level line. Samples of all stratigraphic units were taken routinely for radiocarbon dating, fossil and mineral identification, and the determination of total organic and inorganic carbon (TOC and TIC) content. Radiocarbon dates were run on shell, bone, charcoal and bulk sediment with high organic content (Table 1). TOC and TIC were determined by the loss-on-ignition method (e.g., Dean, 1974). In addition to the above analyzes, samples were collected and processed for pollen analysis, which yielded no pollen. Instead, lake-level indicators from these and other analyses were placed in context with the previously published pollen data of Davis (1999) from a nearby depocenter core, as well as our new analysis of raw pollen and algae data graciously provided by Dr. Davis from this same core (Fig. 1).

4. Mapping results

4.1. The Rambla highstand shoreline

A prominent wavecut shoreline feature was identified in all of the mapping resources and is evident in the field as a topographic bench (Figs. 2–5). The northern segment of the shoreline appears as relatively closely spaced, parallel

Table 1
Summary of radiocarbon ages

Site	Lab no.	Elevation (masl)	Material	^{14}C age	±	Cal age range BP
DWR test pit #3	Beta-170144	56.9	Organic sediment	2370	40	2682–2331
Lake plain trench E	Beta-170145	56.9	Organic sediment	2410	40	2699–2345
Lake plain trench B	Beta-170148	56.9	Organic sediment	2510	70	2745–2364
Lake plain trench E	Beta-170146	56.9	*Anodonta* sp. shell	2740	40	2925–2759
Lake plain trench D	Beta-170143	56.9	Organic sediment	3340	80	3824–3393
Rambla shoreline trench 2	Beta-170147	63.3	Fish bone	100	50	274- -4
Rambla shoreline trench 2	Beta-170150	63.3	*Anodonta* sp. shell	180	50	303- -3
Rambla shoreline trench 2	Beta-170149	62.0	Gastropod shell	820	40	892–673
Rambla shoreline trench 2	WW-5304	60.9	Organic sediment	5900	35	6795–6645
Rambla shoreline trench 2	Beta-170151	60.9	Organic sediment	6190	40	7241–6974
Rambla shoreline trench 2	WW-5305	60.7	Charcoal	7250	35	8166–7984
Rambla shoreline ditch	Beta-167851	69.8	*Anodonta* sp. shell	2880	40	3157–2879
Rambla shoreline ditch	Beta-167852	69.8	Bone	4360	70	5280–4817
Depocenter (Davis, 1999)	A-5412	53.9	Organic sediment	2030	80	2301–1818
Depocenter (Davis, 1999)	A-5413	52.5	Organic sediment	6770	110	7829–7438
Depocenter (Davis, 1999)	A-5414	51.3	Organic sediment	9100	160	10,675–9739
Depocenter (Davis, 1999)	A-5415	50.4	Organic sediment	9460	220	11,273–10,195
Depocenter (Davis, 1999)	A-5416	48.6	Organic sediment	10,110	350	12,788–10,763

All lake plain samples are from the organic-rich units correlated to Unit 4a from Trench D, which is at an elevation of 56.9 masl. "Beta" dates were processed and run at Beta Analytical, Inc.; "WW" samples were processed at the USGS radiocarbon laboratory of the USGS in Reston, VA, USA and run at the Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory, Livermore, CA, USA. Radiocarbon ages were converted to calibrated years BP using Calib 5.01 software (Stuiver et al., 2005) and the calibration dataset of Reimer et al. (2004). Calibrated ages are reported as 2 sigma ranges.

contour lines at elevations from 210 fasl (64 masl) to 230 fasl (70 masl) on the Kettleman City 7.5′ USGS topographic map in the western halves of Sections 7 and 18, T22S, R19E (Fig. 2a). The shoreline is also prominently displayed on the DEM of Fig. 4 and on aerial photographs due to its relatively bright signature (e.g., Fig. 5). The northern segment can be traced along a N20W bearing for ~2 km from the eastern end of Kettleman City and from this same point along a S60E bearing for a similar distance. The feature also recurs farther south with a S30E trend, appearing as a ~1.0-km-long segment in the southeast corner of Section 29 on the Los Viejos 7.5′ map (Fig. 2b). Finally, it appears as a 2.0-km-long segment, trending more easterly (S70E) in the southern halves of Sections 3 and 4 of T23S, R19E before it merges with the northern edge of Dudley Ridge (Fig. 2c). The southernmost segment is named "La Rambla" on the topographic map, presumably after its Spanish meaning of "sandy or dry gully." We hereafter refer to related geomorphological features as the "Rambla" slope or shoreline.

In the field, the Rambla shoreline exhibits a discernable slope that interrupts an otherwise flat-lying featureless landscape (Fig. 3a). The surface of the slope contains numerous fragments of gastropods and bivalves including *Anodonta* sp.

A topographic profile of the shoreline was generated across its northern segment using elevations surveyed with a level and stadia rod, supplemented by data on the margins picked from topographic maps (Fig. 3b). The base of the feature is at an elevation of 62.5 masl (205 fasl) and its top is just below 70 masl (230 fasl). This elevation range includes both the elevation of the modern spillover sill (66 masl/210 fasl) and the highest lake-level elevation observed during historical times (67 masl/220 fasl) (Atwater et al., 1986). This observation, in conjunction with the fact that the morphology of the profile is consistent with that of a feature cut by wave action into a uniform slope of unconsolidated sediments (Currey, 1994), indicates a wavecut terrace origin for the Rambla shoreline.

4.1.1. *Relationship of Rambla shoreline to Dudley Ridge*

Further support for the wavecut origin of the Rambla slope feature is its slightly higher elevation relative to Dudley Ridge (maximum elevation = 67 masl/219 fasl), a feature that we interpret as a sand spit formed in shallow water during Tulare Lake highstands. Dudley Ridge is a ridge of sand that projects southeastward from the Kettleman Hills outward into the Tulare Lake plain (Figs. 1 and 4). Our interpretation that Dudley Ridge originated as a sand spit is supported by the following observations: (a) its linear morphology, (b) its projection out into the lake basin downwind of and normal to the shoreline, and (c) its point of origin from an abruptly eastward jutting spur of the lake basin, a feature that would serve to deflect longshore transport of beach sands basinward.

4.1.2. *Relationship of Rambla shoreline to alluvial fans*

Fig. 4 is a shaded relief map generated in Natural Scene Designer^{TM} from USGS DEM files corresponding to the Kettleman Hills (NW), Los Viejos (SW), and Dudley Ridge (SE) 7.5′ quadrangles. This map clearly depicts the three main segments of the Rambla shoreline, as well as Dudley

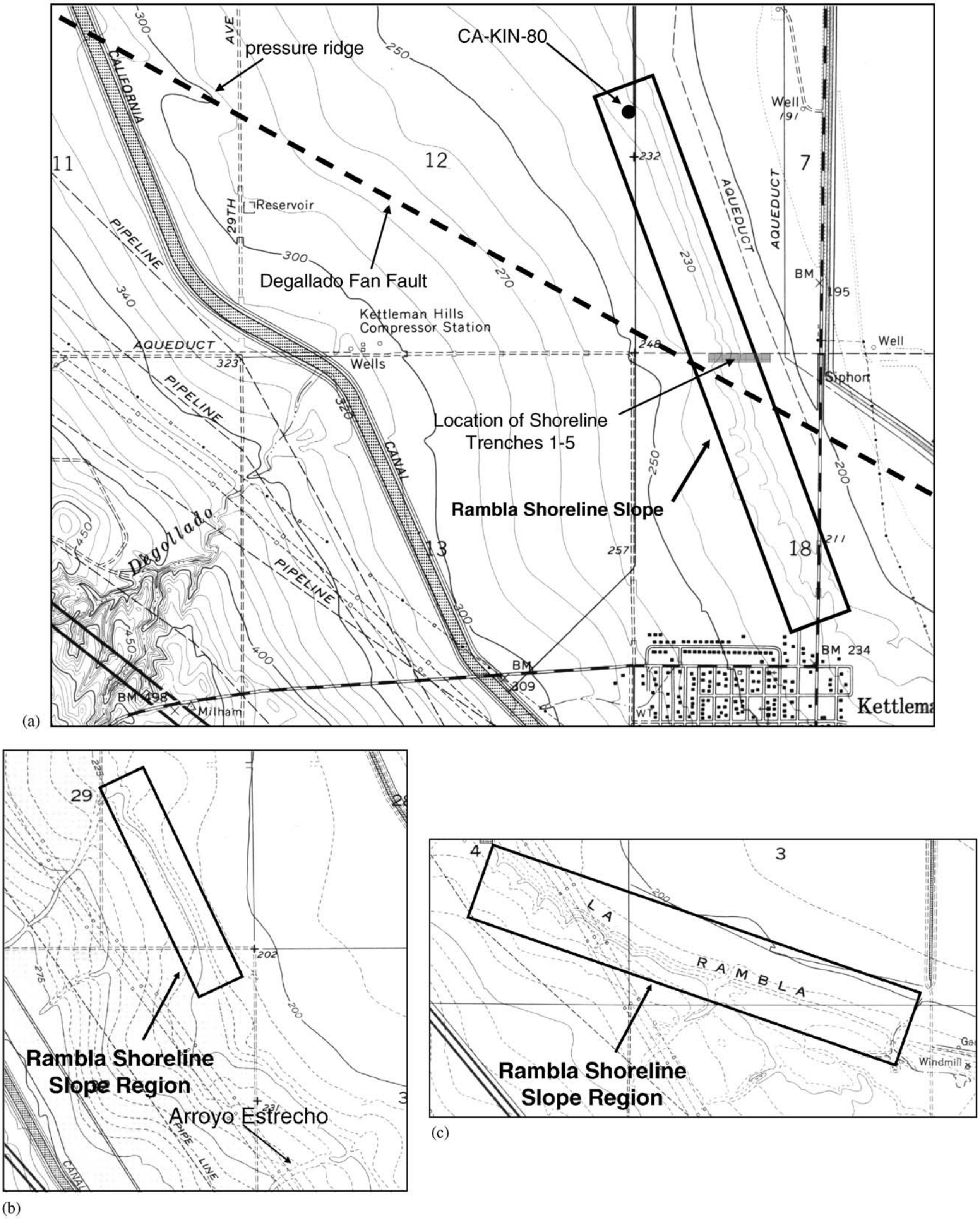


Fig. 2. Portions of 7.5′ topographic maps showing segments of Rambla highstand shoreline feature. (a) Northernmost segment of Rambla shoreline. Location of shoreline trenches 1–5 and archeological site CA-KIN-80, and the trace of the Degallado Fan Fault are also shown. (b) Portion of Los Viejos 7.5′ topographic map showing location of middle segment of Rambla shoreline. (c) Portion of Los Viejos 7.5′ topographic map showing location of southernmost segment of Rambla shoreline.

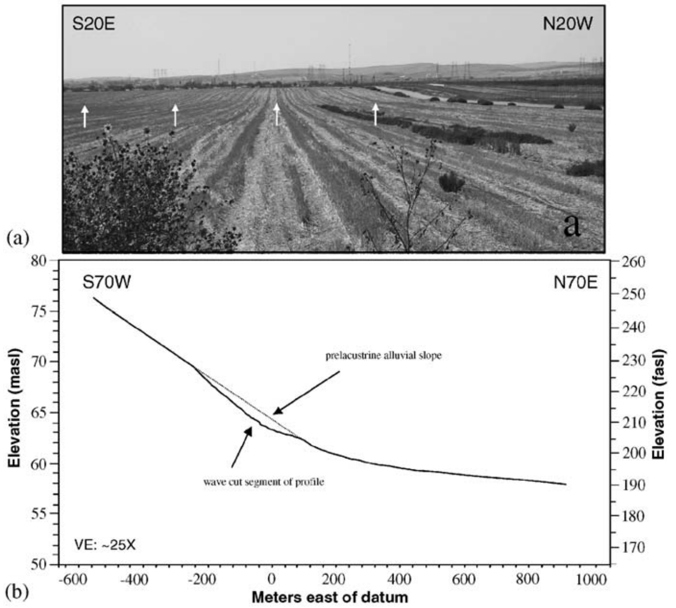


Fig. 3. (a) Photograph of northernmost segment of Rambla shoreline (view to SW). Kettleman Hills in the background. Base of steepest-slope portion of shoreline is indicated by arrows. (b) Topographic profile of Rambla shoreline. Feature is clearly eroded into pre-existing, uniform alluvial slope consistent with morphology discussed in Currey (1994). Profile runs through area of Trenches 1–5 (Fig. 2a). Vertical exaggeration ~25 × .

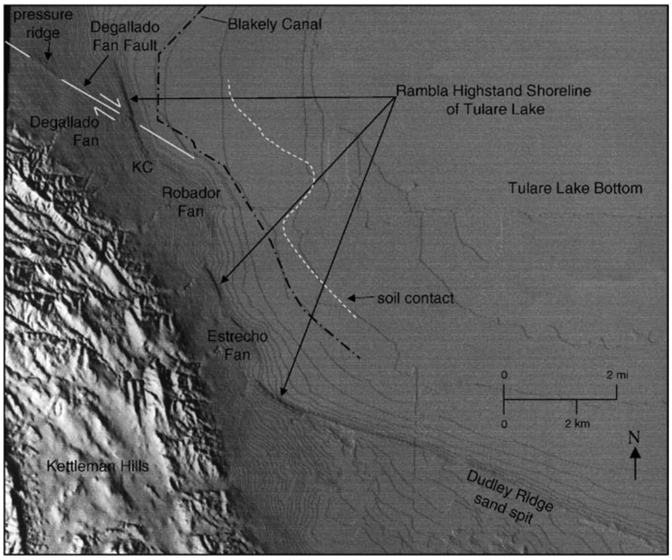


Fig. 4. Digital elevation model of study area and associated geologic features discussed in text. Degallado Fan fault is depicted in segments rather than a continuous line to avoid concealing evidence for its existence (the pressure ridge and offset shoreline). Soil contact is after Arroues and Andersen (1986). This contact separates lake bottom soils to the east from soils with coarser uppermost layers. Deflection of this contour basinward shows that alluvial fans extend farther out into lake basin than is apparent from the DEM alone.

Ridge. It also clearly illustrates the relationship of the Rambla shoreline feature with two prominent alluvial fans protruding into the Tulare Lake Basin from the Kettleman Hills. The larger fan is presently supplied by a stream occupying Arroyo Robador and the smaller fan is supplied by the Arroyo Estrecho stream. Both fans extend into the lake plain, especially the Robador Fan, as revealed by the eastward extension of lobes of soil types containing relatively coarse-grained materials (e.g., soil #126 of Arroues and Andersen, 1986) well out into the Tulare Lake Basin beyond the fan terminus suggested by the DEM image (Figs. 4 and 5).

Both the Robador and Estrecho alluvial fans are, for the most part, younger than the Rambla shoreline because their sediments have either covered or eroded much of this feature, resulting in the dissection of the shoreline into its three major segments. On the other hand, portions of the alluvial fans may have been active prior to one of the highstands that formed the Rambla shoreline. This is evidenced by two relatively subtle subsegments of the two more northerly segments, which show a deflection of the shoreline around the north end of the two alluvial fans (Fig. 4).

4.1.3. *Relationship of Rambla shoreline to the Degallado fan fault*

In Fig. 4, an elongate, N55W trending ridge cuts across the alluvial slope ~1.5 km north of the termination of Arroyo Degallado. This feature can also be observed on the USGS Kettleman Hills 7.5′ topographic map as deflected elevation contours in the northeast corner of Section 11, T22S, R18E, where it underlies the California Aqueduct. A slight right-lateral offset of the northern segment of the Rambla shoreline is almost exactly on trend with the aforementioned ridge. Based on these two observations, we interpret the ridge to be a local transpressional ridge due to recurrent right-lateral, strike-slip faulting. The fault is named the Degallado Fan fault because it transects the alluvial fan associated with Arroyo Degallado. The Rambla shoreline likely was developed prior to the latest slip events on this fault that apparently offset the shoreline several meters.

Although the Degallado Fan Fault passes within 100 m south of the shoreline trenches (Fig. 2a), no evidence of deformation was observed in any of the trenches. Thus, the fault zone must be localized to within a few tens of meters of its map trace.

4.2. *"190 ft" Clovis shoreline*

As discussed above, previous workers have suggested a stable shoreline of Tulare Lake based on the ubiquitous occurrence of Clovis-aged artifacts and Pleistocene megafauna in an elongate region parallel to the margins of the lake basin, north of Dudley Ridge at an elevation of 56–58.5 masl (185–192 fasl) (Fig. 1). Because much of the study area is located within this elevation range, particularly in the vicinity of the Blakeley Canal (Fig. 1), we investigated the possibility that this shoreline projected into the study area.

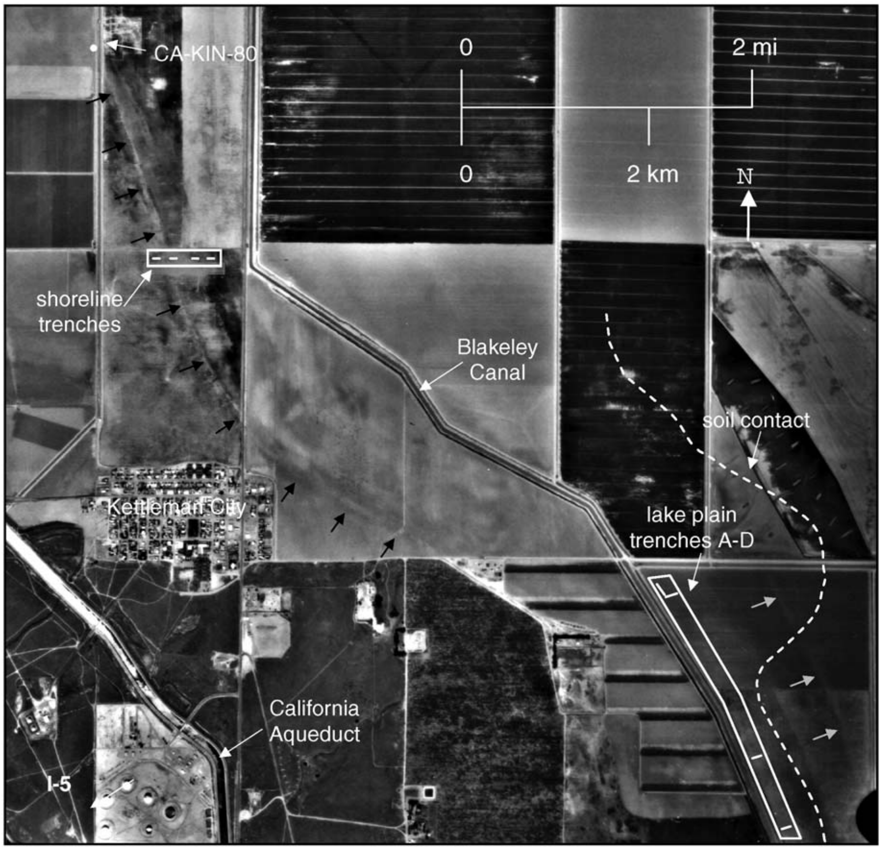


Fig. 5. Portion of NAPP 6915-254 aerial photograph showing main project area. Locations of all shoreline trenches and lake plain trenches A–D lie within rectangular regions outlined in white. Northern segment of Rambla shoreline is depicted by black arrows drawn perpendicular to shoreline. Gray arrows in SE corner of photo delineate a possible shoreline at the ~190 ft elevation associated with the abundant Clovis occupations found at the lake margin just north of Dudley Ridge (Fig. 1). Because this feature cuts through the alluvial fan margin indicated by the deflection in the soil contact (see text and Fig. 4), it, instead, must be much younger than the latest Pleistocene age of Clovis occupation.

We found no compelling evidence for such a shoreline in the mapping phase of this investigation. Several whitish streaks, similar to the signature of the Rambla shoreline, are observed in the aerial photographs at or near this elevation (e.g., see feature delineated by light gray arrows in the SE corner of Fig. 5). However, these features cut across the toe of the Robador fan, as defined by the outer contact of Soil Type #126 (Figs. 4 and 5), the last basinward soil with a relatively coarse-grained uppermost layer (Arroues and Andersen, 1986). If these are shoreline features, then they are clearly younger than the late Holocene sediments deposited by this fan and are too young to be associated with the hypothesized Clovis-aged lake-level stand. If a Clovis-aged shoreline exists in this area, then it would likely lie beneath the sediments of the alluvial fans emanating from the Kettleman Hills.

5. Trenching results

5.1. Relationship of trench locations to mapping results

The subsurface portion of the study was conducted in three areas. The first area consisted of five trenches (Trenches 1 through 5, heretofore referred to as the "shoreline" trenches) that were excavated in the vicinity of the northernmost segment of the Rambla shoreline feature (Fig. 2a). These trenches were typically 10 m-long and 2 m-deep. The elevations covered varied from 60 to 70 masl. Of these, all but Trench 1 were below the top of the wave-cut shoreline feature. Trench 1 was excavated into the sediments above the shoreline that represent the substrate materials, perhaps covered by a thin veneer of lacustrine beach deposits. Trenches 2 through 5 were dug into and just below the steepest slope of the shoreline to recover a potential record of lake sediments deposited at these high elevations during highstands. In addition, we inspected ~2.0 m of section exposed in a road-side ditch near the northernmost extent of the Rambla shoreline in order to discern the geological context of archeological site CA-KIN-80 (Gardner, 2003; Gardner et al., in press) that was exposed in the side of this ditch (Fig. 2a).

The second area was composed of four trenches (A–D) excavated into the toe of the Robador fan where the purported 190 ft (58 m) Clovis shoreline is possibly buried by a thin veneer of younger alluvial sediments at the toe of the fan (Figs. 4 and 5). Trenches A and D were located near the axis of this fan. Trench A was oriented parallel to the fan axis (perpendicular to potential shorelines) and Trench

D was oriented perpendicular to Trench A. Trenches B and C were oriented perpendicular to the shoreline but near the southern edge of the Robador Fan.

The third area contains Trenches E and F and DWR Test Pit #3 that were dug farther out into the lake basin (Fig. 1 and Gardner, 2003). These excavations, along with the trenches from the toe of the Robador fan, are referred to as the "lake plain" trenches. Collectively, they were investigated to provide a deep lake context for the stratigraphy associated with the trenches from the other two areas.

5.2. *Stratigraphy above the Rambla shoreline: distal alluvial fan sediments?*

Trench 1, which was dug into the sediments above the Rambla shoreline, could not be entered due to the uniformly sandy nature of its sediments and the associated danger of trench collapse. Three samples were collected from the edge of the trench down to a depth of 45 cm below ground surface. All three samples were well-sorted, very fine sands and silts with a color of 2.5Y 5-6/2. No lacustrine fossils (e.g., fish bones or *Anodonta* sp. shell) were found in the trench spoil. Inspection of the trench spoil and visual inspection down into the trench from the surface suggest that the top 45 cm of sediment is representative of the entire 2 m of section in the trench. Also, the deposits were observed to be massive in nature (i.e., no bedding). We interpret these sediments to have been deposited in a distal alluvial fan setting as sheet wash or perhaps eolian sediments.

5.3. *Stratigraphy of the Rambla shoreline trenches: three Holocene highstands*

The lacustrine sediments of the Rambla shoreline feature were deposited during a period that included three major highstands of Tulare Lake separated by intervals of nondeposition. The stratigraphy is described below and is summarized in Fig. 6. This composite stratigraphy is based primarily on a detailed description of Trench 2, the deepest trench containing the thickest section. The stratigraphy in Trenches 3, 4, and 5, which exposed sediments down to only Unit 7, were consistent with that described below.

5.3.1. *First highstand*

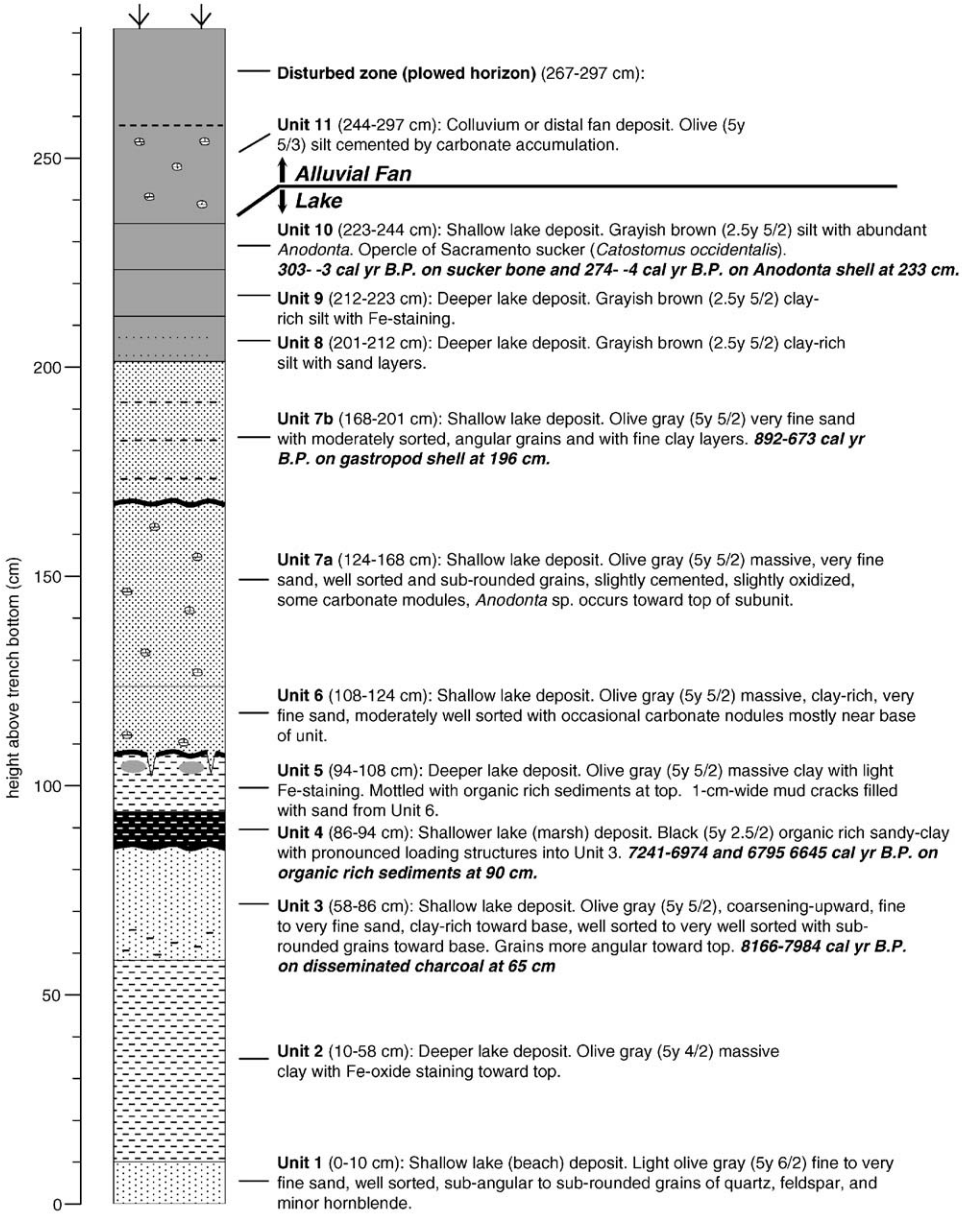
Unit 1 is a very well-sorted, fine sand consisting of subangular to subrounded grains of granitic minerals (e.g., quartz and feldspar with minor hornblende). Based on its lithology and its stratigraphic position below Unit 2, we interpret Unit 1 to represent a transgressive shore facies characterisitic of a beach deposit. Unit 2 is a relatively thick, massive, olive-gray colored clay layer. Fe-oxide staining occurs toward the top of this unit. It is likely to have been deposited under relatively deep water but the Fe-oxide staining in the top of the unit suggests that it was near the surface of the lake soon after deposition. Post-depositional exposure of Unit 2 to near surface conditions is consistent with the overlying Unit 3, an upward-coarsening sand layer that is interpreted to represent a regression at the end of the highstand corresponding to Unit 2. A sample of charcoal collected 7 cm above the base of Unit 3 yielded an age of 7250 ± 35 ^{14}C yr BP (7984–8166 cal yr BP).

5.3.2. *Second highstand*

Unit 5 represents the next interval of high lake. It is another massive clay that lies above an organic-rich, sandy clay (Unit 4). Two bulk, organic-rich sediment samples collected from the middle of Unit 4 were dated by two different radiocarbon facilities at 6190 ± 40 ^{14}C yr BP (6974–7241 cal yr BP) and 5900 ± 35 ^{14}C yr BP (6645–6795 cal yr BP). Unit 4 is interpreted as a marshy environment present when the water was still fairly shallow before the transgression indicated by Unit 5. The presence of organic-rich layers immediately below deeper water clays was also observed by Atwater et al. (1986) in cores from the Tulare Lake Basin. Unit 5 contained 1.0-cm-wide, sand-filled mud cracks that suggest lake level subsequently lowered to the point where Unit 5 was exposed subaerially. A return to overall shallower water conditions is also suggested by the gradual coarsening of grains beginning in Unit 6 and continuing up through Unit 7. Unit 7, nearly a meter thick, may even have been deposited subaerially as part of a distal alluvial fan, but the presence of articulated *Anodonta* sp. shell toward the top of Unit 7a and clay layers in Unit 7b suggest that Tulare Lake was at or above the elevation level of Unit 7 (61.3–62.1 masl) for at least a portion of its deposition, and was filled with cool, fresh water. Gastropod shell from within 10 cm of the top of Unit 7 yielded an age of 820 ± 40 ^{14}C yr BP (673–892 cal yr BP).

5.3.3. *Most recent highstand*

The third and final highstand observed in the Rambla shoreline trenches commenced with the top of Unit 7b and peaked during the deposition of Units 8 and 9, which are relatively fine-grained and clay-rich. Unit 10 is relatively coarse-grained but contains bones of Sacramento sucker (*Catostomus occidentalis*), a species commonly found in pools of clear, cool streams, lakes and impoundments (Page and Burr, 1991). This unit also contains *Anodonta* sp. shells., some of which are articulated. *Anodonta* sp. is a molluscan genus that favors muddy river bottoms (though they may be found in sands as well) or lakes with a high trophic level, but with some kind of current, and a diversity of fish that can be used in its reproductive cycle (Chamberlin and Jones, 1929). Together, these factors suggest that Unit 10 may also have been deposited in a lake and that the lake at this time was cool and fresh with some current. The uppermost unit, Unit 11, consists entirely of silt-sized grains partially cemented with calcium carbonate. Its environment of deposition is undetermined, though it is



Disturbed zone (plowed horizon) (267-297 cm):

Unit 11 (244-297 cm): Colluvium or distal fan deposit. Olive (5y 5/3) silt cemented by carbonate accumulation.

Unit 10 (223-244 cm): Shallow lake deposit. Grayish brown (2.5y 5/2) silt with abundant *Anodonta*. Opercle of Sacramento sucker (*Catostomus occidentalis*). ***303- -3 cal yr B.P. on sucker bone and 274- -4 cal yr B.P. on Anodonta shell at 233 cm.***

Unit 9 (212-223 cm): Deeper lake deposit. Grayish brown (2.5y 5/2) clay-rich silt with Fe-staining.

Unit 8 (201-212 cm): Deeper lake deposit. Grayish brown (2.5y 5/2) clay-rich silt with sand layers.

Unit 7b (168-201 cm): Shallow lake deposit. Olive gray (5y 5/2) very fine sand with moderately sorted, angular grains and with fine clay layers. ***892-673 cal yr B.P. on gastropod shell at 196 cm.***

Unit 7a (124-168 cm): Shallow lake deposit. Olive gray (5y 5/2) massive, very fine sand, well sorted and sub-rounded grains, slightly cemented, slightly oxidized, some carbonate modules, *Anodonta* sp. occurs toward top of subunit.

Unit 6 (108-124 cm): Shallow lake deposit. Olive gray (5y 5/2) massive, clay-rich, very fine sand, moderately well sorted with occasional carbonate nodules mostly near base of unit.

Unit 5 (94-108 cm): Deeper lake deposit. Olive gray (5y 5/2) massive clay with light Fe-staining. Mottled with organic rich sediments at top. 1-cm-wide mud cracks filled with sand from Unit 6.

Unit 4 (86-94 cm): Shallower lake (marsh) deposit. Black (5y 2.5/2) organic rich sandy-clay with pronounced loading structures into Unit 3. ***7241-6974 and 6795 6645 cal yr B.P. on organic rich sediments at 90 cm.***

Unit 3 (58-86 cm): Shallow lake deposit. Olive gray (5y 5/2), coarsening-upward, fine to very fine sand, clay-rich toward base, well sorted to very well sorted with sub-rounded grains toward base. Grains more angular toward top. ***8166-7984 cal yr B.P. on disseminated charcoal at 65 cm***

Unit 2 (10-58 cm): Deeper lake deposit. Olive gray (5y 4/2) massive clay with Fe-oxide staining toward top.

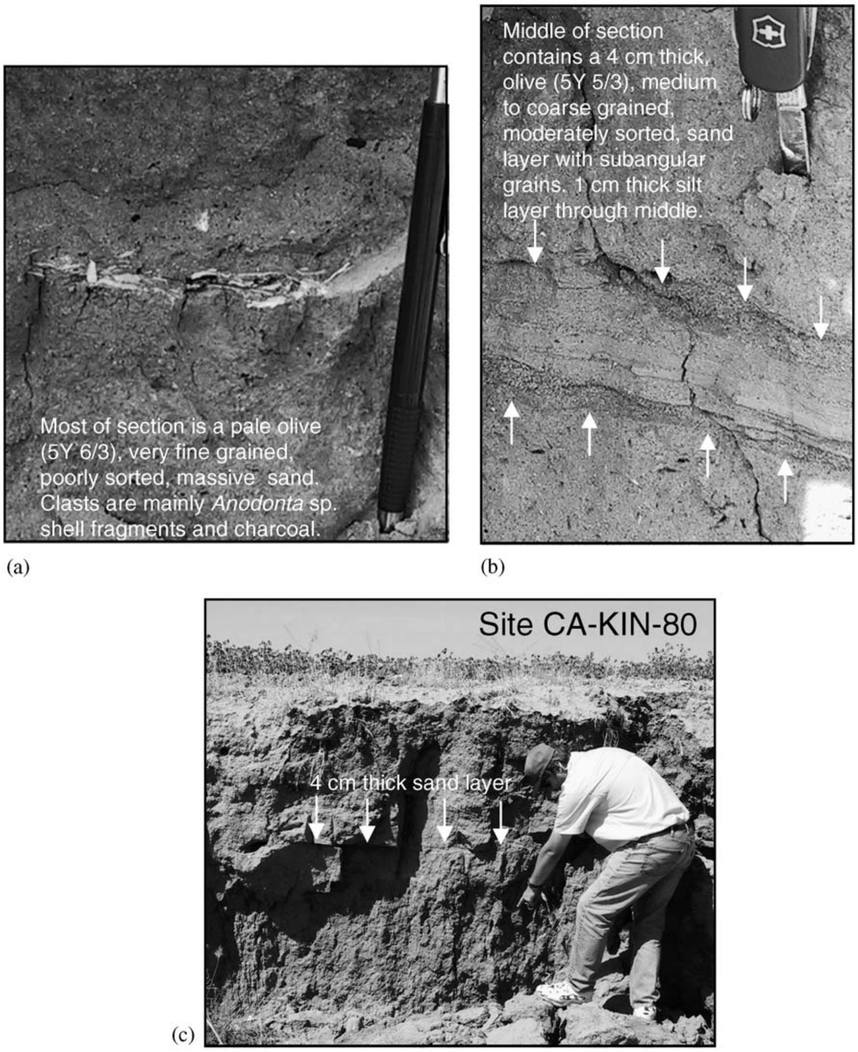
Unit 1 (0-10 cm): Shallow lake (beach) deposit. Light olive gray (5y 6/2) fine to very fine sand, well sorted, sub-angular to sub-rounded grains of quartz, feldspar, and minor hornblende.

Fig. 6. Stratigraphic description of units from Trench #2 dug into the slope segment of the Rambla shoreline wave-cut feature. Depth is measured relative to bottom of trench. Elevation at top of trench is 63 masl (206 fasl). Radiocarbon ages are shown in bold italics (also see Table 1). Unit 2, Unit 5, and Units 8–10 are interpreted to be deposited under relatively deep water (i.e., below wave base). Bold, wavy lines indicate dessication events.

not inconsistent with the distal alluvial fan environment favored for the sediments of Trench 1 (see above). The presence of discontinuous carbonate accumulation is indicative of incipient soil development. The lack of a well-developed soil is consistent with a young age for the most recent transgression, as suggested by the bounding radiocarbon ages shown near the top of Fig. 6. The lower bounding age is from near the top of Unit 7 (Section 5.3.2); the upper bounding age is constrained by radiocarbon dates of $180\pm50\,^{14}$C yr BP (−3–303 cal yr BP) and $100\pm50\,^{14}$C yr BP (−4–274 cal yr BP) from sucker bone and *Anodonta* sp. shell, respectively. These latter samples were collected from the middle of Unit 10. The top 30 cm of Unit 11 exhibits mixing and gouging of the sediments, probably due to agricultural tilling.

5.4. Stratigraphy of the Rambla shoreline ditch exposure (site CA-KIN-80)

At the archeological site CA-KIN-80, 190 cm of section was exposed in a ditch 1 km north-northwest of the shoreline trenches (Figs. 2a and 7). All but the top 30 cm of the sediments in this exposure consist of a massive, poorly sorted, very fine sand unit with abundant clasts of *Anodonta* sp. shell and charcoal (Fig. 8). A continuous 4.0-cm-thick, medium- to coarse-grained sand layer ran


Most of section is a pale olive (5Y 6/3), very fine grained, poorly sorted, massive sand. Clasts are mainly *Anodonta* sp. shell fragments and charcoal.

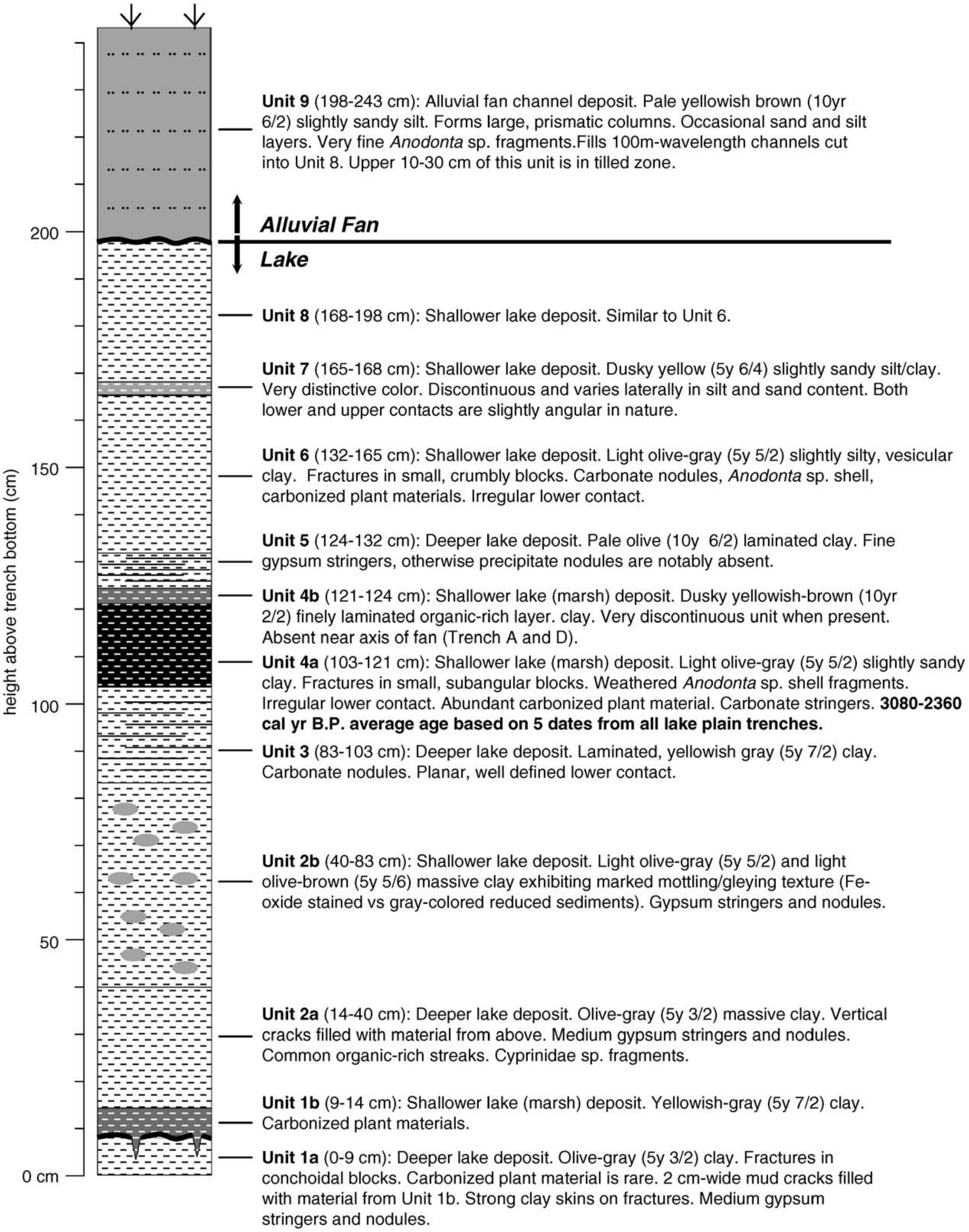
Middle of section contains a 4 cm thick, olive (5Y 5/3), medium to coarse grained, moderately sorted, sand layer with subangular grains. 1 cm thick silt layer through middle.

Fig. 7. Stratigraphy of CA-KIN-80 site: (a) 190 cm thick section is principally composed of poorly sorted, massive, very fine sands with abundant fragments of charcoal and *Anodonta* sp. shell. Upper 50 cm of this unit is in till zone; (b) continuous, 4-cm-thick medium to coarse sand found at 82–86 cm below the surface; and (c) photograph of entire section (R. Yohe for scale).

through the exposure ~85 cm below the surface. A fragmentary human distal metacarpal was found near the base at 177 cm (Gardner, 2003; Gardner et al., in press). The bone was dated at 4360 ± 70 ^{14}C yr BP (4817–5280). A shell fragment from 106 cm below ground surface yielded an age of 2880 ± 40 ^{14}C yr BP (2879–3157).

The Rambla shoreline is not well defined this far north and a major concrete irrigation canal separates this exposure from the main shoreline feature. Thus, the spatial relationship of the CA-KIN-80 stratigraphy relative to that of the Rambla shoreline trenches is unclear. With the exception of Trench 1, the deposits of the CA-KIN-80 exposure are generally coarser than those seen in the top 2 m of any of the trenches discussed previously. This suggests that the stratigraphy of the CA-KIN-80 exposure fits in with that of the top of the shoreline. If this is true, then much of the sedimentation responsible for the alluvial fan deposits in Trench 1 were deposited during the past 5000 years. This, in turn, implies that the present geomorphic expression of the Rambla shoreline has been formed by relatively recently wave erosion, perhaps in association with the uppermost transgression found in Trench 2, an event that occurred within the past ~700–900 cal yr BP (Fig. 6).

Except for the one through-going sand layer described above, the CA-KIN-80 sediments exhibited no bedding. This observation, combined with the ubiquitous presence of shell fragments and charcoal and, of course, the human bone fragment, all point towards the CA-KIN-80 sediments as an archeological midden. Given this interpretation and the aforementioned two radiocarbon dates, the midden was occupied at least intermittently throughout most of the Holocene after ~5000 cal yr BP. The sand layer running through the middle of the outcrop may represent a flooding event that occurred sometime between 1500 and 2000 cal yr BP based on the stratigraphic position of this sand layer relative to those associated with the two radiocarbon dates from this locality.



Unit 9 (198-243 cm): Alluvial fan channel deposit. Pale yellowish brown (10yr 6/2) slightly sandy silt. Forms large, prismatic columns. Occasional sand and silt layers. Very fine *Anodonta* sp. fragments.Fills 100m-wavelength channels cut into Unit 8. Upper 10-30 cm of this unit is in tilled zone.

Unit 8 (168-198 cm): Shallower lake deposit. Similar to Unit 6.

Unit 7 (165-168 cm): Shallower lake deposit. Dusky yellow (5y 6/4) slightly sandy silt/clay. Very distinctive color. Discontinuous and varies laterally in silt and sand content. Both lower and upper contacts are slightly angular in nature.

Unit 6 (132-165 cm): Shallower lake deposit. Light olive-gray (5y 5/2) slightly silty, vesicular clay. Fractures in small, crumbly blocks. Carbonate nodules, *Anodonta* sp. shell, carbonized plant materials. Irregular lower contact.

Unit 5 (124-132 cm): Deeper lake deposit. Pale olive (10y 6/2) laminated clay. Fine gypsum stringers, otherwise precipitate nodules are notably absent.

Unit 4b (121-124 cm): Shallower lake (marsh) deposit. Dusky yellowish-brown (10yr 2/2) finely laminated organic-rich layer. clay. Very discontinuous unit when present. Absent near axis of fan (Trench A and D).

Unit 4a (103-121 cm): Shallower lake (marsh) deposit. Light olive-gray (5y 5/2) slightly sandy clay. Fractures in small, subangular blocks. Weathered *Anodonta* sp. shell fragments. Irregular lower contact. Abundant carbonized plant material. Carbonate stringers. **3080-2360 cal yr B.P. average age based on 5 dates from all lake plain trenches.**

Unit 3 (83-103 cm): Deeper lake deposit. Laminated, yellowish gray (5y 7/2) clay. Carbonate nodules. Planar, well defined lower contact.

Unit 2b (40-83 cm): Shallower lake deposit. Light olive-gray (5y 5/2) and light olive-brown (5y 5/6) massive clay exhibiting marked mottling/gleying texture (Fe-oxide stained vs gray-colored reduced sediments). Gypsum stringers and nodules.

Unit 2a (14-40 cm): Deeper lake deposit. Olive-gray (5y 3/2) massive clay. Vertical cracks filled with material from above. Medium gypsum stringers and nodules. Common organic-rich streaks. Cyprinidae sp. fragments.

Unit 1b (9-14 cm): Shallower lake (marsh) deposit. Yellowish-gray (5y 7/2) clay. Carbonized plant materials.

Unit 1a (0-9 cm): Deeper lake deposit. Olive-gray (5y 3/2) clay. Fractures in conchoidal blocks. Carbonized plant material is rare. 2 cm-wide mud cracks filled with material from Unit 1b. Strong clay skins on fractures. Medium gypsum stringers and nodules.

Fig. 8. Stratigraphic description of units from lake plain Trenches A–D at distal end of Arroyo Robador alluvial fan (Fig. 4). Depth is measured relative to bottom of trench. Elevation at top of trench is 58 masl (190 fasl). Radiocarbon ages are shown in bold italics (also see Table 1). Units 1a, 2a, 3, 5, 7, and 8 are interpreted to be deposited under relatively deep water. Unit 9 is interpreted as a channel deposit associated with the progradation of the Arroyo Robador alluvial fan onto the lake plain. Bold, wavy lines indicate dessication events.

5.5. Stratigraphy of the lake plain trenches: deep lake facies

The stratigraphy in all of the lake plain trenches at the toe of the Robador fan (Fig. 4) was divided into nine correlative units. All but the top unit were clay-rich and contained fossils of aquatic fauna consistent with a freshwater lacustrine environment (Fig. 8). We therefore interpret that these deposits accumulated predominantly in quiet water under the surface of Tulare Lake. A discontinuous, organic-rich clay horizon in the middle of the section (~120 cm below surface) suggests at least one interval of shallower water, perhaps a marsh-like environment (Fig. 8). Furthermore, there is abundant evidence throughout the section of soil development (ped structures, clay skins on ped surfaces, vesicles), perhaps due to intermittent subaerial exposure. The common occurrence of vertical and polygonal drying cracks and gleying supports this hypothesis.

The uppermost unit in the lake plain trenches, Unit 9, was relatively coarse-grained and occupied broad, shallow, west-to-east trending channels (Figs. 8 and 9). This unit most likely represents alluvial deposition at the toe of the Robador fan. The top 30 cm of this uppermost unit shows the highly irregular lower boundary and disruption of sedimentary structures that is characteristic of agricultural tilling.

Not surprisingly, the stratigraphy farther out into the lake plain (Trenches E and F and DWR Pit #3; Fig. 1) was nearly identical to that of the lacustrine units from Trenches A through D. All units were clays. Stringers and nodules of gypsum (identified using X-ray diffractometer) were common in these units. As with the stratigraphy near the toe of the Robador fan, an organic-rich layer was often present (see Unit 4 in Fig. 8), although it was at a relatively shallower depth (~70 cm below the surface as opposed to 120 cm). In both cases the organic-rich units are found above units with relatively abundant *Anodonta* sp. shells, some of which were articulated. The total organic carbon content in this unit was 13% by mass, the highest measured in this study.

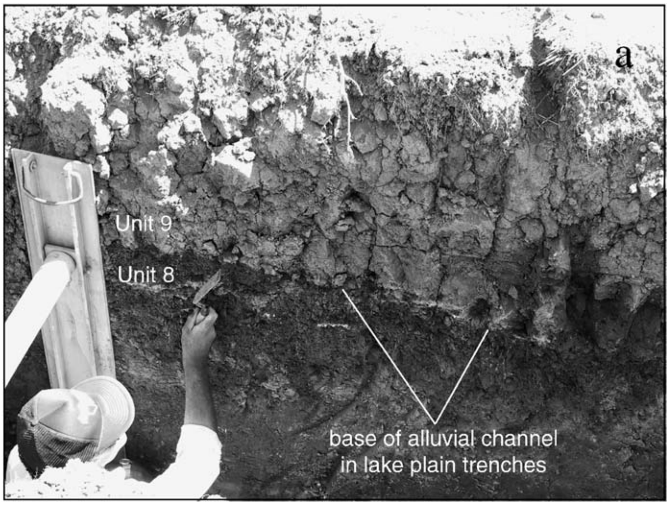


Fig. 9. Basal contact of alluvial silts near top of section in lake plain trenches from near the Blakeley Canal. Everything below this contact is interpreted to have been deposited in a lacustrine or marsh environment rather than in an alluvial fan setting.

The ~50 cm difference in depth between the organic-rich unit from the more basinward sites and that of Trenches A through D is easily explained by the additional ~50 cm of alluvial fan deposits found in these trenches. These deposits are not found in Trenches E and F and DWR Pit#3 because these sites are beyond the extent of the alluvial fans from the Kettleman Hills.

5.6. Summary of age control

The radiocarbon data are summarized in Table 1. In all trenches, radiocarbon dates from deeper units yielded older dates and, in the two cases where different materials were dated from nearly the same stratigraphic horizon, the radiocarbon analyses yielded consistent results from different materials. The organic-rich unit from Trenches A through F has consistent ages from both organic-rich sediment and shell. Also, the uppermost transgression in Trench 2 from the shoreline trenches has consistent dates from both fish bone and shell. Finally, the organic-rich sediments of Unit 4 in Trench 2 yielded the same date from two different laboratories.

Radiocarbon ages were converted to calibrated years using the Calib 5.0.1 software (Stuiver et al., 2005). In all cases, the 2-sigma distribution option was used in the conversions. In the case of a converted specific date, the range of dates within the 95% confidence window is reported (e.g., Table 1).

Only one horizon (Unit 4) is dated in the lake plain trenches. Its age (3609–2331 cal yr BP) is based on the full range of five calibrated ages from that unit corresponding to four different trenches (first five dates in Table 1). The average and standard deviation calculated from the five calibrated ages is 2810 ± 470 cal yr BP. The ages of the rest of the lake sediments in this section are estimated using the 0.038 cm/cal yr sedimentation rate for Tulare Lake bottom sediments of this age (referred to as the Chatom Silt by Atwater et al., 1986; Davis, 1999). The resultant oldest and youngest ages of the lake sediments in this section are ~5800 and ~550 cal yr BP, respectively.

6. Holocene lake-level history of Tulare Lake

6.1. Post-glacial to 10,700 cal yr BP: erosional event followed by aggradation

A large gap in the late Quaternary Tulare Lake records of Atwater et al. (1986) and Davis (1999) indicates an erosional event at the end of the Pleistocene. This event ended with the onset of deposition of lake bottom sediments at 11,800 cal yr BP (Davis, 1999). An abrupt change at ~10,700 cal yr BP from anomalously high to more typical sedimentation rates was interpreted by Davis

(1999) to represent a change from a rapid infilling of the lake associated with fan dam aggradation to an environment more typical of a geomorphically stable lake system influenced primarily by climate change.

6.2. 10,700–7800 cal yr BP: two early Holocene highstands

This interval consists of two highstands, the latter of which reached the maximum shoreline elevation of ~70 masl (Fig. 10). Evidence for these two highstands includes two peaks of pelagic algae (*Botryococcus* sp. + *Pediastrum* sp.) in the depocenter core (Fig. 1) which were interpreted by Davis (1999) to suggest open, deep water. The younger of the two peaks is coeval with the oldest highstand clay (Unit 2) found in the high shoreline trenches of this study (Figs. 6 and 10). The basal, well-sorted sand of this trench (Unit 1) was likely deposited in a beach setting during the transgression leading to the younger of these two early Holocene highstands.

The younger highstand lasted for ~1200 or more years, based on the thickness of Unit 2 and the typical deposition rates ($\sim 0.04\,\text{cm}/^{14}\text{C yr} = 0.038\,\text{cm/cal yr}$) of Tulare Lake bottom sediments reported by Atwater et al. (1986) and Davis (1999). This event ended with the regression below 61 masl represented by Unit 3 of the shoreline trenches, an upward-coarsening sand deposit. Oxidation stains in the upper part of Unit 2 are consistent with lake-level fall soon after its deposition. A radiocarbon age on disseminated charcoal at the base of Unit 3 indicates that this regression began at 8000–8100 cal yr BP (Fig. 10). This date, the 1.2 kyr duration of Unit 2, and the 9000 cal yr BP age of the older pelagic algae peak of Davis (1999) suggest that the lowstand between the two early Holocene highstands was a short-lived event.

6.3. 7800–5500 cal yr BP: lowstand followed by a middle Holocene highstand

In the record from the shoreline trenches, the time interval from 7800 to 5500 cal yr BP begins with a fall in lake level below 61 masl represented by the upward-coarsening sand of Unit 3 (see above). Unit 3 is ~1200 yr younger than the overlying Unit 4 (Figs. 6 and 10). Given this age difference and the interpretation of Unit 4 as a transgressive, shallow water deposit, lake level must have fallen below the elevation of the contact between these units during the time interval from 7800 to 7000 cal yr BP.

Beginning with the deposition of Unit 4, the lake rose above 61 m for at least 500 years, the time interval required for the deposition of Unit 5, a deepwater clay unit, at the sedimentation rate typical of Tulare Lake bottom sediments (Atwater et al., 1986; Davis, 1999). Mudcracks are

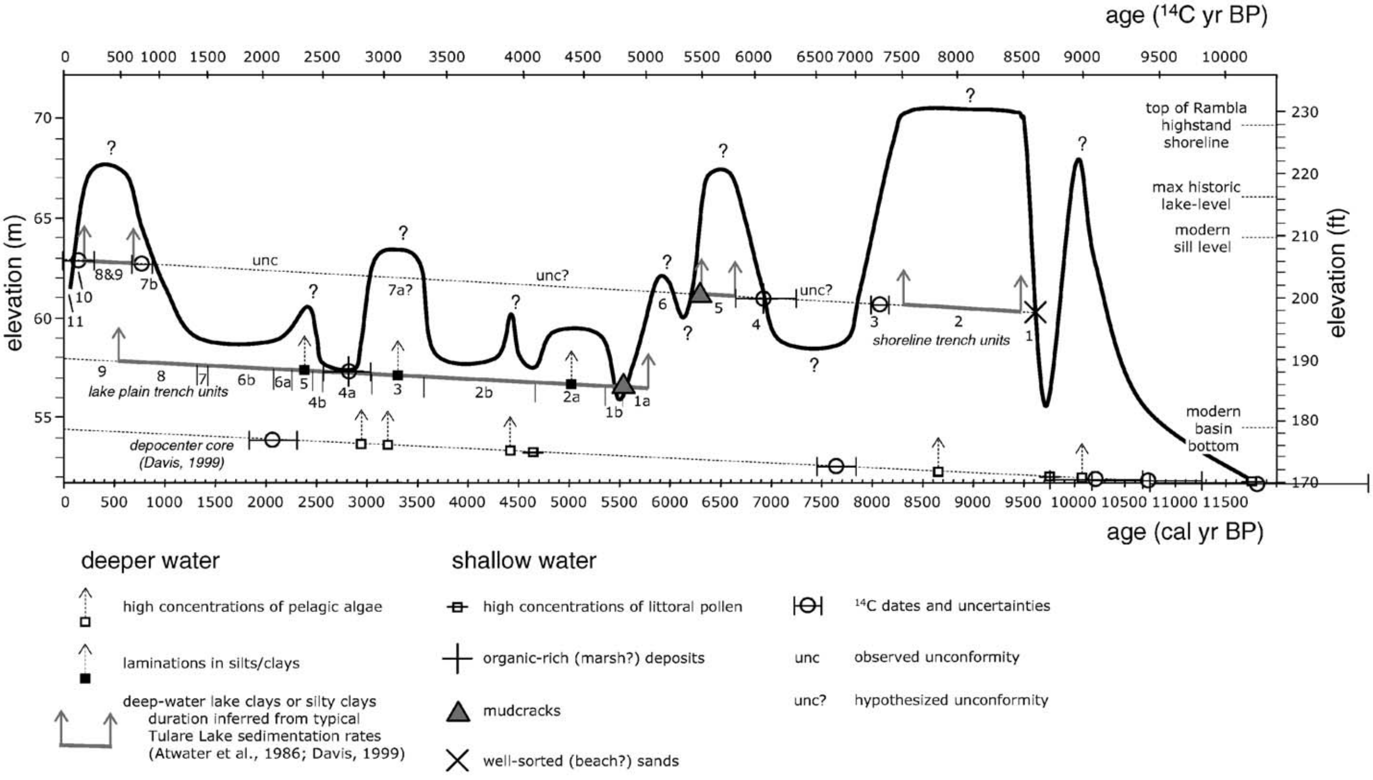


Fig. 10. Holocene lake-level history of Tulare Lake based on data from shoreline and lake plain trenches of this study (Figs. 5–9) and the depocenter core pollen record of Davis (1999). Lake level through time is indicated by bold line. The uncertainties shown for radiocarbon dates are the range of calibrated dates within the 95% confidence window except for date in Unit 4 of shoreline trenches which shows standard deviation calculated for the first five calibrated dates in Table 1.

found at the top of Unit 5. These are filled with Unit 6, a coarsening-upward sand. We interpret this sequence to represent a brief recession after the deposition of Unit 5 that was followed by a similarly brief return to high enough lake levels to allow the deposition of Unit 6. The latter deposit, a transgressive sand, then represents a terminal recession that ended an overall high lake-level interval in the middle Holocene that spanned from ~7000 to 5500 cal yr BP. The younger age limit is inferred from the estimated age of the top of Unit 1a, the lowest unit from the lake plain trenches (Figs. 8 and 10). Unit 1a is a blocky, gray clay deposit much like that of Unit 5 in the shoreline trenches. The age of the bottom of Unit 1a could not be estimated because it was below the bottom of its trench. Its uppermost age, however, was estimated at ~5500 cal yr BP based on linear extrapolation downward at 0.038 cm/cal yr from the calibrated radiocarbon date in an overlying unit. The top of Unit 1a contains mudcracks similar to those found in Unit 5 of the shoreline trenches. In this case, they represent a brief fall of Tulare Lake below the level of the lake plain trenches at the end of the middle Holocene highstand.

6.4. *5500–1000 cal yr BP: low amplitude lake-level fluctuations*

The record over this time period is mostly constrained by alternating lithologies in the lake plain trench sediments and the pollen record from the depocenter core of Davis (1999). Unit 2a (5400–4700 cal yr BP), Unit 3 (3600–3000 cal yr BP), and Unit 5 (2500–2300 cal yr BP) from the lake plain trenches are, for the most part, laminated, devoid of gleying structures (mottled mixtures including Fe-oxide stained sediments), and contain relatively few carbonate nodules. This suggests deeper water relative to the elevation of these units (57–58 masl). Because these features are more prominent in Units 3 and 5, we hypothesize that Tulare Lake was higher during the time periods corresponding to these units, perhaps above the level of the shoreline trenches (62–63 masl). This hypothesis is supported by prominent peaks in pelagic algae concentration that were found in the depocenter core (Davis, 1999) at approximately the same time as the probable age for Unit 3 (Fig. 10). The most likely corresponding deposit from the shoreline trenches is Unit 7a, a well-sorted, very fine sand that was likely a shallow water lake deposit, perhaps in a beach environment. This unit is separated from an almost identical Unit 7b by an angular unconformity. Unit 7a, the lower unit, differs from Unit 7b in that it is cemented weakly with a carbonate cement and contains abundant Fe-staining. Thus, it was probably exposed at the surface for a significant period of time prior to the deposition of Unit 7b.

A likely lowstand event that corresponds to the unconformity between Units 7a and 7b from the shoreline trenches is suggested by a dramatic drop in pelagic algae concentrations in the depocenter core (Davis, 1999) and a coeval, ubiquitous organic-rich marsh deposit (Unit 4) found in all the lake plain trenches (Fig. 8). The age of Unit 4 (~2800 cal yr BP) is approximately the same as that of the correlative event in the depocenter core (Davis, 1999).

6.5. *1000 cal yr BP to present. High lake levels and incursion of alluvial fans onto the lake plain*

During the past 1000 years, the surface of Tulare Lake rose above 63 m and stayed there long enough to deposit shoreline trench Units 7b, 8, 9, and 10. Units 8 and 9, together, comprise 22 cm of clay-rich silts. Presuming the typical sedimentation rate for Tulare Lake bottom sediments (~0.04 cm/yr), these units alone represent approximately 500 years of deposition. Given the upper and lower limits of the dates below and above these units (Table 1), this highstand must have commenced no later than 670 cal yr BP (1280 AD) and ended no earlier than 290 cal yr BP (1660 AD). Historical records show the lake rising to a level above the shoreline trenches several times in the nineteenth century (Atwater et al., 1986). Thus the upper part of Unit 10 was likely to have been deposited up until the time of irrigation-related stream diversion.

The trench sites in the toe of the Arroyo Robador alluvial fan (Figs. 4 and 8) began to receive alluvial deposits (Unit 9 channel deposits) sometime between 600 and 500 cal yr BP (1350 and 1450 AD). The timing of local alluvial fan progradation thus appears to be coeval with the lake-level rise described in the previous paragraph. This suggests that the climate change responsible for lake-level rise is not just restricted to the headwaters of the major Sierran rivers that feed Tulare Lake, but also reflects increases in the discharge of local streams.

7. Lake depth and marsh extent evidenced by selected algae, and marsh and aquatic plant pollen

The interpretations based mainly on the stratigraphic record that were presented in the previous section (Figs. 10 and 11a) are supplemented by additional examination of the pollen and algae record (Figs. 11b–d) that are based on raw data graciously provided by Owen Davis from his original data set (Davis, 1999). These data provide information regarding the water level, stability, and water chemistry of the marsh/lake from the basin bottom. First, Fig. 11b shows a ratio of the two most abundant algae, *Pediastrum* sp. and *Botryococcus* sp. These algae are characterized by very different water chemistry. Whereas *Pediastrum* sp. is found flourishing under more oligotrophic (fresh water) conditions, *Botryococcus* sp. is found under eutrophic (organic-rich water) conditions (Cohen et al., 2000). Thus, the ratio of *Pediastrum* sp. to *Botryococcus* sp. (Fig. 11b) is an indicator of water freshness. Second, shifting marsh composition as reflected in the relative predominance of sedge (Cyperaceae) and cat-tail (*Typha* spp.) pollen indicate changes in both water chemistry and stability of the marsh water level (Wigand, 1987; Cohen

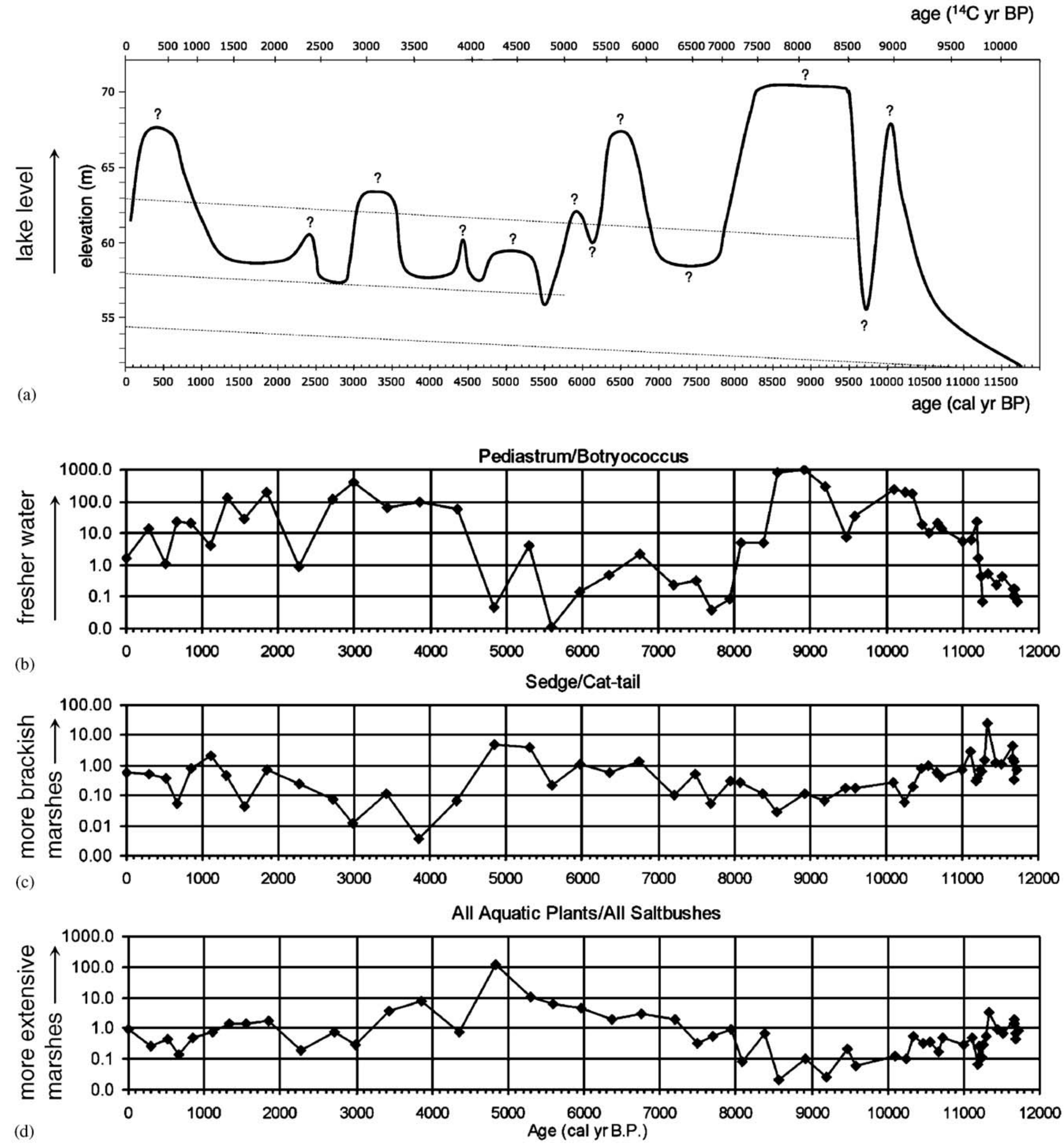


Fig. 11. Weighted ratios of major aquatic algae, and littoral, aquatic and terrestrial plant pollen reflecting lake and marsh dynamics in the Tulare Lake Basin. These are compared with the lake-level record reconstructed from stratigraphic trenches near Kettleman City. The ratios are weighted to reflect not only their relative proportions to other algae or pollen types, but also to reflect their abundance relative to the total terrestrial pollen abundance for each sample.

et al., 2000). Specifically, a higher ratio of sedge to cat-tail (Fig. 11c) implies marshes with relatively brackish waters. Finally, the proportion of aquatic plants relative to saltbushes (all Chenopodiaceae) reveals information regarding the extent of marsh in the Tulare Lake Basin with respect to the surrounding saltbush dominated basin slopes and flats (Fig. 11d).

In the early Holocene (11,000–8000 cal yr BP), increased abundance of *Pediastrum* sp. relative to *Botryococcus* sp. corresponds well overall to deeper lake intervals (Figs. 11a and b) after a period of time characterized by shallow marshes and/or ponds as indicated by all of the floral indicators including relatively high concentrations of both emergent and littoral aquatic plants. Maxima in the sedge/

cat-tail and aquatic plants/saltbush ratios in conjunction with a minimum in the *Pediastrum/Botryococcus* ratio infer a maximum extent of brackish water marshes in the middle Holocene (~5000 cal yr BP) after a gradual expansion of brackish water marshes starting at ~9000 cal yr BP (Figs. 11b–d). At their peak, organic production in these marshes would have been high as evidenced by maxima in absolute values of *Botryococcus* sp. The timing of maximum marsh extent coincides with overall low lake levels as indicated by the trench stratigraphy (Figs. 11a–d).

While the marsh was under expansion, a relative maximum in the *Pediastrum/Botryococcus* ratio from 7000 to 6500 cal yr BP, suggests that water conditions became slightly more oligotrophic. This supports the presence of a deeper lake as indicated by quiet water clay deposits found in the shoreline trenches, although the algae signal is subtler than one would expect given the >65 masl lake depth constrained by the trench data.

The return to fresher waters after the maximum marsh event commenced at ~4000 cal yr BP, according to all floral indicators (Fig. 11b–d). A spike in cat-tail (low sedge/cat-tail ratio) at ~4000 cal yr BP indicates a spurt of freshwater marsh expansion that likely is associated with a significant lake-level rise. This timing is a few hundred years earlier than the increase in lake level inferred from the trench stratigraphy (Figs. 10 and 11). The floral data also diverge from the trench stratigraphy in that the former suggests a fresh water event (high *Pediastrum/Botryococcus* ratio) from ~2000 to 1200 cal yr BP that is not seen unambiguously in the trench stratigraphy. These discrepancies will perhaps be reconciled by improved dating of both records. For example, the shoreline trenches contain a meter of fine-grained sediments between radiocarbon dates of ~7000 and 800 cal yr BP (e.g., Unit 7 of Fig. 6). As suggested in Fig. 10 at least some of these deposits may represent shallow water deposits at this high elevation and, because their age control is poorly constrained, some of these sediments could easily have been deposited during the 2000–1200 cal yr BP highstand indicated by the algae data.

The algae data is consistent with the high lake levels for most of the past several hundred years as inferred from the trench data (Fig. 11). Two peaks in the *Pediastrum/Botryococcus* ratio suggest that the highest lake levels occurred in two phases, one centered at ~800 cal yr BP and the other at ~250 cal yr BP.

8. Implications for Holocene climate change

As discussed previously, the geomorphological "fan dam" component of control on the level of Tulare Lake (Atwater et al., 1986) is likely to operate on a time scale much greater than 10^3–10^4 yr; thus, the Holocene lake-level history of Tulare Lake should primarily be a record of climate change in the drainage basin. Because the greatest source of recharge results from precipitation in the headwaters of the Kings, Kaweah, Tule, and Kern Rivers, the lake-level curve in Fig. 10 should be mostly dependent on precipitation change in the central and southern Sierra Nevada.

The principal results, based on both the trench stratigraphy and the floral analyses presented herein and in Davis (1999), are summarized as follows. There were seven to eight discernable fluctuations in the surface elevation of Tulare Lake over the past 11,500 yr (i.e., one per ~1500 yr). At least three of the highstands, and possibly as many as five, surpassed the 60–63 masl elevation of the shoreline trenches (Figs. 10 and 11a). Because the Rambla shoreline modifies the surface of the Robador alluvial fan, at least one of these Holocene highstand events was likely to have risen as high as the top of this shoreline feature (~70 m).

Lake level was generally higher during the early Holocene (prior to ~6000 cal yr BP). The oldest, well constrained highstand ended ~8200 cal yr BP and may have lasted for >1000 years. The age of a subsequent, briefer middle Holocene highstand peaked at 6500 cal yr BP. Two middle- to late-Holocene highstands possibly rose to the elevation of the shoreline trenches and lasted from 4000 to 2700 cal yr BP and 2000–1200 cal yr BP, respectively, the latter based principally on the pollen and algae data shown in Fig. 11b–d). The youngest highstand lasted for a period of several hundred years ending ~100 cal yr BP and may have peaked twice near 800 and 250 cal yr BP. Alluvial fan progradation into the lake as far out as the lake plain trenches commenced approximately at the same time as the youngest highstand. At least three major lowstands (<58 masl) occurred, probably of relatively short duration. The ages of the lowstands are centered at the following times: ~9700, 5400, and 2600 cal yr BP.

In a general way, the Tulare Lake record reflects the climatic pattern of the Holocene derived from other records in the intermontane western US. That is: (1) a moist early Holocene prior to ~8500 cal yr BP; (2) a dry middle Holocene; (3) a moist Neopluvial period between ~4500 and 2800 cal yr BP followed by a strong drought; (4) an episode of wetter, though late spring or summer shifted rainfall between ~1900 and 1100 cal yr BP; and (5) two episodes of wetter climate during the last 1000 cal yr BP (Wigand and Rhode, 2002).

More regionally, the major climate events inferred from the Tulare Lake record are compared to those of other records from localities in the southwestern US (Fig. 12). These records are more or less proximal to the southern Sierra drainage source for Tulare Lake. Included in this comparison are lacustrine records from Lake Elsinore (Kirby et al., 2005), pluvial Lake Mojave (Enzel et al., 1992), and a combined record from Owens and Pyramid lakes (Benson et al., 2002). The records in Fig. 11 are portrayed in a manner to focus on events associated with high precipitation/evaporation (P/E) ratios (black bars) to facilitate comparison with the Lake Mojave pluvial history. Pluvial Lake Mojave was, for the most part, an ephemeral playa lake during the Holocene; thus, its record is mainly

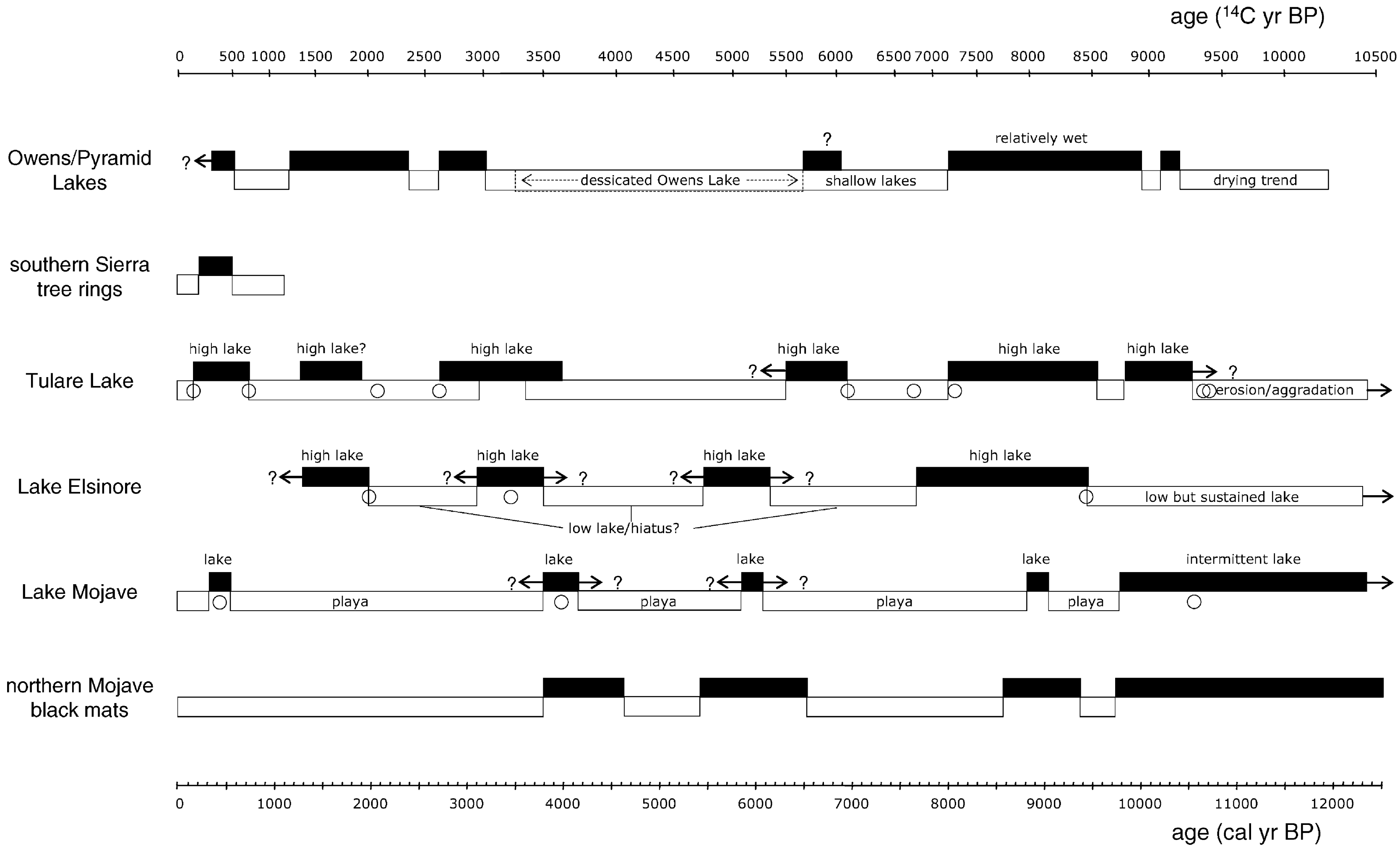


Fig. 12. Representative Holocene climate records from the southwestern US. Wet events were emphasized because of the clipped nature of the Mojave record with respect to dry climates (see associated discussion in text). The records are arranged by the location of their respective precipitation source areas. From top to bottom, they represent regions progressively southward and/or eastward. Owens/Pyramid record is after Benson et al. (2002) and Benson (2004). The tree ring record is based on a reprocessing of the Graumlich (1993) record by Benson et al. (2002). Lake Elsinore record is after Kirby et al. (2005) and Lake Mojave record is after Enzel et al. (1992) and Wells et al. (2003). Black mats record reflects major peaks where ^{14}C age probability is >0.01 as calculated by Wigand (2003) using results from Mehringer and Warren (1976), Mehringer and Sheppard (1978), and Quade et al. (1998). Radiocarbon dates are represented by open circles on the records with sparse age control.

sensitive to climate events with enough effective moisture to leave a record of lacustrine sediments. Fig. 11 also includes a record of precipitation based on tree rings from the source area of Sierran streams feeding Tulare Lake (Graumlich, 1993; Benson et al., 2002) and a record showing relatively high (< 0.01) ^{14}C age probabilities for spring (aka, black) mats (from Quade et al., 1998; Wigand, 2003). In all cases, the definition of relative conditions applies only for the Holocene. That is, for all records that extend back into the Pleistocene, high P/E conditions shown here are, in fact, low P/E conditions when compared to conditions in the Pleistocene.

In the earliest part of the Holocene ($>$10,000 cal yr BP), the records are somewhat inconsistent. Tulare Lake probably exhibited high lake levels only toward the very end of this period when the concentration of pelagic algae peaked in the record from the depocenter core of Davis (1999). This is similar to the conditions and timing exhibited in the Pyramid/Owens lakes record. In contrast, the pluvial Lake Mojave and spring mat records reflect relatively wet conditions for most of the early Holocene up to 9000–8500 cal yr BP. Lake Elsinore, which shows evidence for a sustained but low level lake during this time period, seems to fall somewhere in between.

Relatively wet conditions are indicated by all records from ~10,000 to 8000 cal yr BP and perhaps a few hundred years later than that for Owens Lake based on precise dates on nearshore tufas at relatively high elevations (Bacon et al., in press). These conditions are represented by one, relatively short-lived lacustrine episode in Lake Mojave. All other lacustrine records point to long-lived lakes at perhaps their deepest Holocene levels.

One brief wet episode, observed in all of the records, punctuates an otherwise dry interval that lasted for at least a few thousands of years in the middle Holocene after ~7500 cal yr BP. The maximum age of this wet episode in the Tulare Lake record is constrained at ~7000–6400 cal yr BP by two radiocarbon dates from the shoreline trenches (Fig. 6 and Table 1). The thickness of clay-rich deposits associated with this highstand suggests that the lake persisted for at least several hundreds of years. Prominent features in proxies that indicate higher lake levels for 300–500 years appear at the end of the third climatic interval of Benson et al. (2002; see also Benson, 2004), approximately at the same time as the Tulare Lake highstand. The records from Lake Mojave, Lake Elsinore and the spring mat record also show this feature but at a slightly younger age. In the former two cases, these younger ages are based on linear interpolations between far-removed radiocarbon ages. Further dating of the Elsinore and Mojave records are thus required in order to test the regional correlatibility of this event, an event which potentially corresponds with a dramatic shift to wetter climate at ~6500 cal yr BP (~5500 ^{14}C yr BP) observed from the Plateau of eastern Washington to the northern Mojave Desert in records of paleovegetation, spring peats, and drowned trees (Wigand and Rhode, 2002). Although its initial dramatic increase declined somewhat after a few decades, the effects of this wet event lingered for several hundred years, before drier conditions returned.

All the lacustrine records in Fig. 11 exhibit a middle Holocene dry interval centered at ~5000 cal yr BP. The end of this interval varies between 4000 and 3000 cal yr BP. In the Pyramid/Owens record, this boundary marks the onset of a late Holocene interval characterized by overall wetter conditions. This result is consistent with a plant macrofossil study of Little Lake, California, by Mehringer and Sheppard (1978) and the results of several other studies summarized in Benson et al. (2002). The three other lacustrine records in Fig. 12, however, suggest a return to wetter conditions several hundred years sooner.

The exact duration of the event varies from record to record, but the Pyramid/Owens, Tulare Lake, and Lake Elsinore records all point to wetter conditions during a time interval centered around ~2000–1600 cal yr BP. Notably, this event is missing in the Lake Mojave and Northern Mojave black mat records.

With the exception of the black mat records, all of the records in Fig. 11 for which there is coverage show a wetter period during the past 1000 years. At Tulare Lake, this event commences as much as a few hundred years earlier than the rest of the records. However, if one averages the age of this event over all of the records, the timing is consistent with that of the Little Ice Age (e.g., Ruddiman, 2001).

9. Implications for paleoindian sites around Tulare Lake

In theory, Clovis-aged shorelines built on the alluvial fans originating in the Kettleman Hills would have provided an ideal habitat along the western margin of Tulare Lake. The sandy deposits of the alluvial fans may have provided a well-drained living surface on the margins of a large lake with abundant food resources and materials for manufacturing shelters, as well as for making matting, basketry, and clothing. However, both sets of trenches investigated herein, including those dug into the Rambla highstand shoreline feature, contained younger lacustrine sediments. Hence, any such ideal habitats for Clovis-aged occupations are either buried by younger deposits in this area or have been eroded.

Clovis-age deposits (or, more likely, an unconformity representing an erosional surface at this time) would be found approximately 1 m deeper than the bottom of Rambla shoreline Trench 2. Accessing this horizon would thus require a trench ~3.5 m deep. The correlative horizon in the lake plain trenches would be encountered at a depth of ~5 m or more. Thus the surface elevation at the lake plain trench locality would have been at an elevation of ~53 masl, significantly below the 56–58.5 masl elevation proposed for the surface of Tulare Lake during the Clovis occupation (Riddell and Olsen, 1969; Wallace and Riddell, 1988; West et al., 1991; Fenenga, 1993). This implies that this location would have been submerged under a lake or marsh and that the shoreline at this time would have lain considerably further inland and has since been covered by younger fan deposits from the Kettleman Hills.

The occupants of archeological site CA-KIN-80 likely lived on top of the Rambla highstand feature for a time period that started as early as 5000 cal yr BP and ended as late as ~1000 cal yr BP. Notably, the elevation of the surface of Tulare Lake would typically have been ~10 m lower than CA-KIN-80 for most that time interval (Fig. 10). This would have required a walk of at least a few hundred meters to access the lakeshore. It is apparent, therefore, that these Native Americans opted to live at CA-KIN-80 for reasons other than immediate proximity to the lake, perhaps such as the superior vantage point, more abundant breezes and fewer insect pests offered at the top of the Rambla shoreline.

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