Lake levels for the past 19,000 years from the TL05-4 cores, Tulare Lake, California, USA: Geophysical and geochemical proxies

Ashleigh B. Blunt

Ashleigh.blunt@gmail.com

Robert M. Negrini*

robnegrini@gmail.com

*Department of Geological Sciences, California State University, Bakersfield, 9001
Stockdale Highway, Bakersfield, CA 93311
1 661 654-2185*

**Corresponding Author.*

Abstract

Geochemical and geophysical proxy data from the TL05-4 lake-plain cores of Tulare Lake, California, are reported on here representing most of the past 19,000 years. The new record consists of carbon/nitrogen ratios, total organic carbon (TOC), nitrogen (N), total inorganic carbon (TIC), grain size, and magnetic susceptibility analyses from samples taken at 1-cm intervals (~45 yr/sample). Age control is provided by 22 radiocarbon dates. The first part of the record (~19.0-14.5 cal ka BP) consists of elevated sand and silt percentages and higher sedimentation rates interpreted as elevated runoff associated with melting of the Tioga-age Sierra Nevada ice cap. The TIC was undetectable and TOC and N were low suggesting low productivity in a relatively sterile, freshwater lake. From 14.5-10.3 cal ka BP, the deposits consisted of 50% clay and 50% silt with TIC and TOC extremely low, which is consistent with a stable, low productivity lake. From 10.3-7.5 cal ka BP, an initial pulse of fining upward sand gave way to increased clay deposition that suggests a lake transgression to a stable highstand, coeval with the deep water event found in previously published records of Tulare Lake and other lakes from central and southern California, including Owens Lake and Lake Elsinore. A

few-hundred-year duration spikes in TIC centered at 8.0 cal ka BP is suggestive of evaporating lake conditions toward the end of this early Holocene highstand. Tulare Lake dropped quickly to a relative low at 7.5 cal ka BP, but then lake level increased steadily until 3.0 cal ka BP. High amplitude fluctuation in almost all proxies occurs from 2.5 to 1.8 cal ka BP at the end of the record, suggesting that this time interval was characterized by rapid fluctuations in lake level. Tulare Lake levels during the Holocene vary in conjunction with sea surface temperature (SST) records from the Ocean Drilling Program (ODP) Site 1017 located off the coast of central California, which suggests that variations in SSTs throughout the Holocene drove changes in precipitation in the Sierra Nevada and hence, Tulare Lake level. Since historic lake-level histories have been shown to be directly related to stream discharge from the Sierra Nevada, this observation will be integral in forecasting future decadal-scale changes in southern San Joaquin Valley water supply due to anticipated climate change.

1. Introduction

Tulare Lake is located in the San Joaquin Valley of central California, one of the world's foremost agricultural regions, between the Coast Ranges and the Sierra Nevada (Fig. 1). Over the past 19,000 years Tulare Lake has fluctuated by several tens of meters in response to regional climate change and changes in elevation of the sill formed at the northern end of the lake by alluvial fans from the Sierra Nevada and Coast Ranges (Fig. 1) (Atwater et al., 1986; Davis, 1999; Negrini et al., 2006). The relative lake level history of Tulare Lake is an important source of data toward understanding paleoclimate change in western North America following the last glacial maximum.

Davis (1999) produced a record of late Quaternary climate change for the Tulare Lake region based on the palynology of a depocenter core and provided conclusions on relative lake level during the late Pleistocene and Holocene. Negrini et al. (2006) refined this study using shoreline and lake-plain trenches to constrain absolute elevations and dates of lake levels throughout the Holocene. The study reported here builds on the previous two by providing an improved chronology (22 radiocarbon dates) and much higher resolution

sampling (one sample per cm = one sample per <50 y) for the latest Pleistocene and late Holocene using geochemical and geophysical proxies for relative lake level.

This refined lake level history has the potential to constrain decadal- to centennial-scale forecasts of water resource variations in the San Joaquin Valley, forecasts at time scales relevant to water management policy decisions. Of further relevance is the fact that Tulare Lake level has been linked closely with the composite discharge of southern Sierra Nevada streams as established by water balance modeling (Harding, 1949; Atwater et al., 1986) wherein the 30 years of historical lake-level records (1850-1880) prior to drainage diversion were modeled accurately based on stream discharge data for the same time period. Furthermore, understanding the lake-level history of Tulare Lake over the past 15,000 years is important toward understanding early Paleo-Indian occupation of North America. High concentrations of Clovis-age and younger artifacts are found in an areally restricted, elongate region that is parallel to the southern margin of the lake basin and at an elevation of 56-58.5 masl (Riddell and Olsen, 1969; Wallace and Riddell, 1988; West et al., 1991; Fenega, 1993). The locations of associated occupation sites were proposed to have been the result of a stable and low surface elevation of Tulare Lake during the “Clovis Drought” of Haynes (1991) at 12.9 cal ka BP and into the Holocene. The testing of this hypothesis has proved difficult largely due to agricultural disturbances that have disrupted or destroyed stratigraphic relationships.

2. Regional Setting

2.1. Modern Climate

As defined by the Köppen Climate Classification System, Tulare Lake is currently a semi-arid steppe characterized by low relative humidity, sporadic rainfall, and potential evapotranspiration that exceeds average rainfall (Köppen, 1936; Peel et al., 2004). Mean annual temperatures are 16.5-17.5°C (62-63.5 °F). Summers have mean high temperatures of 33-37 °C (91-98 °F) and mean low temperatures of 15-17 °C (59-63 °F). Mean high temperatures in the winter are within 12-17 °C (54-63 °F) and winter mean

low temperatures are within 1-5 °C (34-41 °F). Mean annual precipitation is 19.3-21.8 cm (7.6-8.6 in). The wettest months are October to March when 85-92% of rainfall occurs. Northwest and west-northwest winds with speeds of 5-25 kmph (3-15 mph) are common (Preston, 1981). Low precipitation and high temperatures produce evaporation rates of standing water of at least 1m (3.3ft)/yr, which exceeds annual precipitation rates by almost an order of magnitude (Atwater et al., 1986), thus runoff from the Sierra Nevada is required to produce a perennial lake. The western Sierra Nevada is characterized by warm, dry summers and cool, wet winters. Summer temperatures average 20.4°C (68.7 °F) and winter temperatures average 4.1°C (39.4°F). Annual precipitation averages between 81-163 cm (32-64 in) with 90% occurring between November and May. Snowfall comprises between 25 and 40% of precipitation and averages from 184-402 cm (72-158 in) annually.

2.2. Geological Setting

Tulare Lake is located in the San Joaquin Valley of California between the Kettleman Hills of the Coast Ranges and the Sierra Nevada (Fig. 1). Although currently dry due to agriculture diversion, historical data shows that Tulare Lake was the largest fresh water lake in the US by surface area (1600 km²) west of the Great Lakes with a maximum depth of 12 meters. Tulare Lake is fed by the Kings, Kaweah, Tule, and Kern Rivers the headwaters of which are in the Sierra Nevada (Fig. 1). The ephemeral streams emanating from the Kettleman Hills to the west did not significantly affect lake level historically (Atwater et al., 1986). Nonetheless, at the north end of Tulare Lake, the alluvial fans of Los Gatos Creek and the Kings River meet in the valley and formed a sill during the last glacial maximum (MIS2) and effectively transformed the area into a closed basin lake system (Atwater et al., 1986).

The sediments of Tulare Lake are primarily silt and clay. West of the Tulare Lake beds, between the lake bed and the Kettleman Hills, the lake deposits are overlain and/or intercalated with alluvial fan deposits formed by ephemeral streams (Negrini et al., 2006).

3. Methods

Two adjacent, multidrive cores, TL05-4A (36.0066094, -119.936270) and TL05-4B (36.0065750, -119.9362444), were obtained from within 100 m of Lake Plain Trench A, the location of which is shown in Fig. 5 of Negrini et al. (2006) (Fig. 1). TL05-4A consisted of ten drives and reached a depth of 15.1 m below ground surface level (mbgs). TL05-4B consisted of nine drives and extended to 11.7 mbgs.

The top three drives of TL05-4A (0.33-4.40 mbgs) and the second drive of TL05-4B (1.08-2.45 mbgs) were split, described, digitally photographed, and sampled at a 1-cm interval (N=440) for all analyses described below unless otherwise stated. Drive 2 of TL05-4B provided coverage for an unrecovered 64-cm long section of TL05-4A. Magnetic susceptibility was used to correlate individual cores and construct a composite core.

Twenty-two bulk organic carbon samples were collected for AMS ^{14}C dating. Samples for radiocarbon dating were collected every 20-40 cm from core TL05-4A and every 15-20 cm from core TL05-4B. Samples were processed and analyzed at the University of California, Irvine Keck Carbon Cycle AMS Laboratory or the University of Arizona AMS Laboratory. All dates were calibrated using CALIB 6.0 and the INTCAL09.14c data set (Stuvier and Reimer, 1993; Reimer et al., 2009).

Grain size was determined using a Malvern Mastersizer 2000 laser diffraction, grain-size analyzer. Sediment samples were soaked in deionized water at least 24 hours and sieved to <1 mm. Grains larger than 1 mm were rarely found and never accounted for more than a few milligrams. Two methods of analysis were employed: 1) a splitter aliquot was utilized to reach ideal laser obscuration, as discussed in Sperazza et al. (2004), and 2) settled grains were extracted via pipette from samples vigorously stirred and allowed to settle for 1.5 minutes. The latter method was designed to better identify the grain size of

the coarse fraction whose corresponding peaks would otherwise be convolved with the rest of the grain-size distribution.

Magnetic susceptibility was measured at 1 cm intervals with a Bartington MS2/ MS2B magnetic susceptibility meter/sensor combination. Meter readings were multiplied by 1E-06 to yield dimensionless cgs units of volume-normalized susceptibility.

Total inorganic carbon (TIC) for core TL05-4A was determined at CSU Bakersfield using a UIC model 5020 Carbon Coulometer CM150 after the TIC was liberated from the sample in the form of CO₂ gas in a UIC CM5230 Acidification Module. One hundred milligram samples were ground and dried at 105 °C for at least 24 hours, placed into silicone cups and acidified. The TIC for core TL05-4B was analyzed at the University of Minnesota Limnological Research Center Core Facility (LacCore) using the same methodology and equipment as with the samples run at CSU Bakersfield. In both cases, instrument sensitivity was 1 µg C or, given typical sample sizes of 100 mg, ~10 ppm. Sample reproducibility was better than 1%, both within and between laboratories.

Total carbon (TC) and nitrogen were determined using a Costech 4010 Elemental Analyzer. Ten mg samples were ground, dried at 105 °C at least 24 hours, placed into tin cups, and combusted within the elemental analyzer to determine mass percent TC and N with sensitivities down to 10 ppm. Total organic carbon (TOC) was determined by subtracting TIC results from TC results. TOC and N were then used to determine C/N ratios, which were converted to molar ratios after McFadden et al. (2005).

4. Results

4.1. Age Control

Two radiocarbon dates (TL04A-2-50-52 and 04B-2-100-102) were rejected due to stratigraphic inversions (e.g. older over younger) (Table 1). A two-part age model was constructed minimizing the sum of the squared residuals for exponential ($r^2=0.872$; $n=14$; $p=0.0001$) and 2nd order polynomial ($r^2=0.952$; $n=6$; $p=0.0002$) curves from the remaining twenty AMS ¹⁴C dates (Fig. 2). Based on the model, the sediments in the cores

range in age from approximately 19.0-1.8 cal ka BP. The sedimentation rates vary from 11.7–122.6 yr/cm with a mean of 42.9 yr/cm. Expressed in cm/yr, sedimentation rates vary from 0.012-0.086 cm per year with a mean of 0.032 cm/yr.

The bulk radiocarbon ages (Fig. 2; Table 1) may overestimate the actual age by as much as a few hundred years due to possible incorporation of reworked organic matter. Previously published dates on organic matter (2.75 ± 0.113 ^{14}C ka BP) were essentially the same as that (2.74 ± 0.040 ^{14}C ka BP) from an *Anodonta* shell obtained from the same horizon sampled in a set of trenches adjacent to the coring site (Unit 4a of the lake plain trench of Negrini et al., 2006). This observation suggests that the bulk organic matter age offsets are similar to that of the lake reservoir effect associated with dates on the freshwater mussel shells. Because *Anodonta* live in relatively fresh water lakes and streams, dates on their shells likely require relatively small lake reservoir corrections (Ingram, 1948), a presumption consistent with 0.340 ± 0.020 ka offset between shell and charcoal dates from the nearby Buena Vista Lake bed reported by Culleton (2006). Furthermore, sediments in the studied interval of the TL05-4 cores contain an average of <1% total inorganic carbon, an observation that is consistent with a small lake reservoir effect.

Six of the twenty AMS ^{14}C dates used in the age model for the TL05-4 cores in the present study fall within the 18-10 ka time interval interpreted by Davis (1999) to be missing from the Tulare Lake record due to an unconformity. Because no obvious lithologic features commonly associated with unconformities are present in the TL05-4 cores in the corresponding depth range, and because the unconformity hypothesis is based on only one anomalously old radiocarbon date (Fig. 2 of Davis, 1999), we reject this hypothesis in favor of the continuous sedimentation throughout this interval as indicated by the chronology in Fig. 2 of this article. We note that the youngest portion of the age model (5.0-1.8 cal ka BP) may be several hundred years younger than suggested by the model because the first sample TL05-4A-1-82-85 (see Table 1) is considerably older than the next three stratigraphically lower samples.

4.2. Core Descriptions

The composite stratigraphy of Drives 1-3 of TL05-4A and Drive 2 of TL05-4B is described from the bottom of Drive 3 to the top of Drive 1 below and summarized in Fig. 3. Overall, grain size was silt to clay reflecting the prevalence of a lacustrine setting. The bottom 27 cm of the core (429-407 cm) is composed of fining upward olive to olive-gray silts to medium grained sands. Thick olive to olive-gray clay-rich silts with frequent iron staining comprise the majority of the latest Pleistocene sediments in Units 1-6 (407-272 cm). The bottom of the Holocene section consists of Units 7-13 (272-103 cm) which are comprised of dark grayish-brown to light olive-brown clay-rich silt to silty-clay units with abundant gypsum stringers and occasional iron staining (Unit 10; 187-183 cm). Unit 14 (79-64 cm) extends to 2.5 cal ka BP and consists of laminated, light olive-brown (2.5Y 5/4) silty clay to fine grained sand. Unit 15 (64-51 cm), which extends through 2.3 cal ka BP, consists of dark grayish-brown (2.5Y 4/2) mottled clays and silts with gypsum stringers and nodules. Fluctuating dark grayish-brown (2.5Y 4/2) clays, silts, and sands comprise the sediments of Unit 16 which extend upward in age to ~1.8 cal ka BP. The top unit (Unit 17), spanning a depth range from 33-0 cm, is separated from the younger units by a sharp contact. It consists of coarser-grained sediments up into the medium-sand range.

4.3. Geochemical and geophysical measurements

4.3.1 Laser granulometry and the designation of zones 1-6

Mean bulk grain size (Fig. 4a) is near the silt/clay boundary for most of the record. The grain size of the coarse fraction (Fig. 4b) is initially ~240 μm at 18.8-18.0 cal ka BP and drops to 10-20 μm throughout the remainder of the Pleistocene. Within the Holocene there are several grain-size excursions in the coarse fraction that approach or even exceed 100 μm .

The sand, silt, and, clay percentages were used to identify six zones (Fig. 4c). Zone 1 (19.0-18.0 cal ka BP) is highly sand dominated (Fig. 4c). Within Zone 2 (18.0-14.4 cal ka BP), silt decreases and clay increases steadily until they each comprise 50% each of the sediment. The relative amount of silt and clay remains the same through Zone 3 until its termination at 10.3 cal ka BP. Clay content reaches a maximum of 60% throughout a plateau that defines most of Zone 4 from 10.3-7.5 cal ka BP. An asymmetric, fining-upward peak in sand percentage to 20% occurs at the beginning of Zone 4. An increase/decrease in silt/clay of ~20% each occurs at 7.5 cal ka BP after which overall grain size gradually decreases through Zone 5 until silt and clay percentages again become equal at 3.0 cal ka BP. This is followed by a period of rapid, high amplitude fluctuations in sand, silt, and clay percentages until the top of the record at 1.8 cal ka BP (Zone 1).

4.3.2 Magnetic susceptibility

Magnetic susceptibility (χ) is generally highest during the latest Pleistocene with peak Pleistocene values of $\sim 1\text{E-}5$ cgs units within Zone 3 (Fig. 4d). After the onset of the Holocene, χ steadily decreases to a minimum of less than $1\text{E-}6$ cgs units. Thereafter it quickly rises to a plateau centered around $5\text{E-}6$ cgs with relative maxima of $8\text{E-}6$ cgs at 4.0 and 3.2 cal ka BP. Finally, χ reaches its highest values of $>2\text{E-}5$ cgs units twice at 2.5 and 2.1 cal ka BP. These two, high frequency peaks are separated by a distinct minimum down to $2\text{E-}6$ cgs units at 2.3 cal ka BP.

4.3.3 Carbon and Nitrogen geochemistry

The TIC, TOC, N, and C/N levels were low throughout the latest Pleistocene with TIC essentially undetectable; TOC is typically $<1\%$, N is typically $<0.2\%$; and C/N is <10 (Fig. 4e-h). These values remained similar until approximately 8.0 cal ka BP where frequent high amplitude variations in TIC, TOC, and C/N up to 3%, 3%, and 50, respectively, occurred throughout the remainder of the Holocene. The TIC remained very low until the early middle Holocene except for a few-hundred-year-long spike

centered at 8.0 cal ka BP. Thereafter, TIC is relatively high at >2%. In Zone 6, high amplitude, high frequency oscillations in TIC are exactly out of phase with similarly high-frequency variations in C/N and grain-size (Fig. 4a-c, e, h). The data from the overlapping part of the TL05-4A-2 and TL05-4B-2 drives shown in Fig. 4 generally agree very well. An exception is the TOC% data (Fig. 4f), which are lower for the B drive by ~0.5-1% between 6.5 and 5.0 cal ka BP. The associated C/N data are also lower (Fig. 4f). As a result, only changes in TOC% of more than 1% will be considered to be significant.

5. Interpretations and Discussion

The results presented above suggest varying lacustrine environments throughout the past 19,000 years represented by the TL05-4 cores. The lone exception is that of the alluvial fan deposits in the top 33 cm (Unit 17), which are separated from the rest of the section by an angular unconformity mapped in adjacent trenches (Fig. 8-9 of Negrini et al., 2006). The five lacustrine environments of deposition are as follows:

5.1. Latest Pleistocene discharge from glacial outwash: 19.0-14.5 cal ka BP; Zone 1,2

At the beginning of the record (Zone 1), from 19.0-18.0 ka, the sediments of the TL05-4 core contain 65-90% sand, decreasing significantly over a thousand years or so to a silt-dominated sediment with little or no sand (Fig. 4). Magnetic susceptibility was near peak values at this time suggesting a dominance of detrital sources for the lake sediments (Gale and Hoare, 1991; Evans and Heller, 2003; Rosenbaum and Heil, 2009). The TIC% was negligible as were TOC%, N%, and C/N. Collectively, these data suggest a freshwater (low TIC%), shallow, and unproductive (low TOC% and N%) lake, dominated by coarse-grained, terrigenous detritus (high χ) with relatively little detrital organic matter (low C/N) (Cohen, 2003). From 18.0-14.5 cal ka BP (Zone 2), silt was the dominant grain size reaching a maximum of 80%. Clay increased steadily at the expense of silt until the sediment consisted of equal parts silt and clay at 14.5 cal ka BP. During this transition out of a silt-dominated lake phase, TIC% remained undetectable. As silt

steadily decreased starting at the middle of Zone 2, concurrent slight rises in TOC% and N% up to 1.5% and 0.15%, respectively, suggest increasing productivity in the lake, or perhaps, less dilution of lacustrine organic matter by silt. A slightly elevated C/N to >10 during this time interval is consistent with increased transport of terrestrial vegetation into the total mix of organic matter possibly due to an increasingly less barren post-glacial (i.e., warmer) landscape, but this C/N value is still well within the threshold for lacustrine vegetation (Meyers and Lallier-Vergès, 1999). Increased productivity could be due to increased visibility in the water column as the percentage of glacial flour decreased and/or higher temperatures in the lake and surrounding landscape.

This above interpretation for the 19.0-14.5 cal ka BP sediment interval (Zones 1 and 2) is consistent with outwash, first sand and then silt-sized glacial flour, transported via the four major Sierra Nevada rivers flowing into Tulare Lake. The headwaters of all of these rivers originate in regions formerly occupied by the Sierra Nevada ice cap at its ~23 ka MIS2 maximum extent (Martinson et al., 1987). The cessation of the outwash by the end of Zone 2 suggests that bulk of the melting was completed by 14-15 cal ka BP. This timing is consistent with that cited in Gillespie and Zehfuss (2004). The timing of a decrease in sedimentation rates at ~15.0 cal ka BP (Fig. 2) also supports this hypothesis.

5.2. Stable, freshwater lake conditions throughout the Pleistocene-Holocene Transition: 14.5-10.3 cal ka BP; Zone 3

Zone 3 is characterized by uniformity in all proxies. Sediment size is dominated by equal parts silt and clay with essentially no sand component. TIC% is negligible, TOC% and N% are low (1%) suggesting an unproductive lake. Magnetic susceptibility is at a relative high suggesting that terrigenous input dilutes whatever organics might be present. Because C/N is low, the terrigenous input appears to be devoid of organic matter.

The uniformity shown throughout the Pleistocene-Holocene transition in the Tulare Lake record contrasts the variability shown by records of Younger Dryas glaciation in southern California (e.g., Owen et al., 2003) and by other records of lakes from the region (Fig. 1),

including Swamp Lake (Street et al., 2012), Owens Lake (Bacon et al., 2006; Orme and Orme, 2008; Reheis et al., 2014), and Lake Elsinore (Kirby et al., 2013). In the latter two cases, lake-level change is apparently timed in tune with archetypical millennial-scale change observed throughout the northern hemisphere at that time (i.e., the Older Dryas, Bølling-Allerød, and Younger Dryas events). The lack of consistency between these four records at this time is either due to the failure of the proxies at one or more of the lakes to reliably represent changes in catchment basin environment or geography-related variability in the response of separate regions to latest Pleistocene millennial-scale climate drivers (e.g., Kirby et al., 2013). Notably, the Tulare Lake drainage basin, principally the west side of the Sierra Nevada south of 37.1° N, is distinct geographically from the others. Swamp Lake and Owens Lake receive their water from farther north in the Sierra Nevada; Lake Elsinore, in the Peninsular Range in southern California, is more southerly and proximal to the Pacific Ocean.

5.3. Lake-level maximum in the early Holocene: 10.3-7.5 cal ka BP; Zone 4

The early Holocene at Tulare Lake is characterized by a plateau in clay percentage that persists for more than 2000 years. At the onset of Zone 4 an asymmetric peak in sand percent marks a fining upward sand that is interpreted to be a transgressive sand at the beginning of this highstand. The end of the highstand is marked by a 3% peak in TIC that may signal the onset of evaporation as the lake rapidly drops in elevation. The timing of this long-lived highstand during the early Holocene is consistent with that shown in the record of Negrini et al. (2006) based on sediments exposed in “shoreline trench” excavations on the west side of the Tulare Lake basin, WNW of the TL05-4 cores (Fig. 5a). We note that the TL05-4 core record improves our knowledge of the timing of this highstand because that of the previous work was based upon only one radiocarbon-dated horizon on a charcoal fragment found at the top of a 0.5 meter-thick clay layer coupled with the presumption of a 0.038 cm/yr sedimentation rate for that clay layer, a rate suggested by that of deep water clays in Tulare Lake found by Davis (1999). Unlike the late Pleistocene, the mean grain size of the coarse fraction throughout the entire Holocene part of the record frequently contains high-amplitude (~100 µm), high-frequency peaks

suggesting a contribution to the discharge into this lake in the form of significant storm events (e.g., Kirby et al., 2012).

5.4. Middle Holocene regression followed by recovery to deep lake conditions: 7.5-3.0 cal ka BP; Zone 5

The middle Holocene begins with a significant, rapid drop in lake level indicated by the sharp decrease in clay% observed at 7.5 cal ka BP. Subsequently, a steadily increasing clay percentage at the expense of silt throughout the remainder of this 4500 year interval indicates a return to deep lake conditions by 3.0 cal ka BP. Increasing volatility in most other proxies suggests an increased level of storm activity contributing to the discharge into the lake. Combined with the long highstand earlier in the Holocene (Zone 4), this lake-level history bears a strong resemblance to a Swamp Lake discharge proxy record and the lake-level record from Owens Lake (Fig. 5b-d) and to two other lakes in southern California (Kirby et al., 2012). This is in contrast to the disparate behavior of these lakes during the Pleistocene-Holocene transition, suggesting a common climate driver for the southwestern United States throughout the Holocene.

5.5. High variability in lake conditions during the late Holocene: 2.5-1.8 cal ka BP; Zone 6

The top of the record consists of an ~700 year interval from 2.5 to 1.8 cal ka BP characterized by rapid, high amplitude changes in all lake-level proxies. High stream discharge occurred toward the beginning of this interval as suggested by coarse grain size, and high magnetic susceptibility. The TIC% was low at this time and the lake was not very productive (low TOC% and N%). High C/N values (>40) indicate that whatever organic matter was present was brought in by high discharge events. A few hundred years later (2.2 cal ka BP), the environment switched to one where fine grains were deposited, terrigenous input was low (low coarse fraction grain-size, low κ , and low C/N), and TIC was nearly always >1%. We interpret this sequence to represent an early, storm-driven, high lake episode followed by a shallow water marsh environment. The final interval at

the top of the record reverted to the deposition of coarser grains, high $\delta^{13}C$, and higher TIC%, though C/N remained low (<10).

6. Conclusions

6.1. Influence of the melting Sierra Nevada ice cap during the late Pleistocene

Conditions in Tulare Lake during the late Pleistocene appear to be driven by dynamic clastic input from the melting of the Sierra Nevada ice cap, the evidence for which is sandy outwash followed by silt-sized glacial flour and elemental geochemistry suggesting freshwater and sterile conditions (undetectable TIC, low TOC, and N). Post-glacial conditions during the latest Pleistocene, in contrast, resulted in static rather than dynamic clastic input into a still sterile, freshwater lake, the evidence for which is homogenous granulometry and no change in the elemental geochemistry from earlier.

6.2. Pacific sea surface temperatures drive post-glacial precipitation in the Sierra Nevada

Variations in the depth of Tulare Lake through time are implied primarily by changes in the clay% because finer grains are usually deposited in deeper lake environments. A deeper Tulare Lake, in turn, is linked to increased discharge from the Sierra Nevada through the hydrologic balance models of Harding (1949) and Atwater et al. (1986). During the Holocene, in the absence of a significant ice cap, stream discharge is likely linked to precipitation in the Sierra Nevada. Thus we make the connection from Tulare Lake sediment clay% to precipitation.

The Holocene Tulare Lake level-Sierra Nevada precipitation record shown here, is consistent with the previous work in the basin (Fig. 5a, d) based on trench exposures and the pollen record of a depocenter core (Davis, 1999; Negrini et al., 2006). The clay% proxy for lake level-precipitation also bears resemblance to records from Owens (Bacon et al., 2006) and Swamp (Street et al., 2012) Lakes, two lakes also fed by precipitation that falls in the nearby Sierra Nevada, though from farther north in the central rather than southern Sierra Nevada (Fig. 5b-d). The Owens Lake record is primarily based on shoreline evidence from outcrops, thus it directly reflects lake level. The Swamp Lake

record consists of a myriad of geochemical, geophysical, and geobiological proxies. Of these, C/N is plotted here as an indicator of the relative input of terrestrial vs. lacustrine organic matter, thus discharge into the lake and, hence, lake level. This assertion is supported by a demonstrated correlation of paleo-C/N values with those from modern plant matter (Fig. 3 of Street et al., 2012) and the fact that the Swamp Lake watershed is relatively small and uncomplicated much like that of Lower Bear Lake in the California Transverse Ranges (Kirby et al., 2012), which has a C/N record that accurately reflects lake level and regional climate change.

The Tulare Lake record most notably bears remarkable resemblance to variations in sea surface temperatures (SSTs) from offshore California during the Holocene (Fig. 5). Because the levels of these lakes are ultimately dependent on the discharge of streams coming from the Sierra Nevada (e.g., Atwater et al., 1986), this result strongly suggests that Pacific SSTs exerted the dominant control on Holocene precipitation in the Sierra Nevada and therefore, stream discharge.

6.3. Implications for central California water resources due to anthropogenic climate change

The SST record shown in Fig. 5e represent the temperatures associated with the California Current which, though affected on an annual to decadal time scale by high frequency climate variations, such as ENSO and the PDO, responds more or less linearly to the long-term anthropogenic global warming signal (Field et al., 2006) of 0.8 C° over the past century. The major drop in Tulare Lake of ~10 m in elevation (Fig. 5a) at ~7.5 cal ka BP corresponds to a change in SST of at least 2 C°. In turn, the change in total discharge from the Sierra feeding Tulare Lake that corresponds to a drop in lake level from ~70 to ~60 masl would be ~6 km³/y (~five million acre•ft/y) (Atwater et al., 1986). Presuming a linear relationship as a point of departure, and thus scaling down to the 0.8 C° change in SST over the past century, the Tulare Lake basin should have seen an increase in discharge over this time of ~2.4 km³/y (two million acre•ft/y). This is a difficult number to reconcile given the current state of drought in the American Southwest, including the southern and central Sierra Nevada. One explanation for this is

that the average time represented by each sample in the Tulare Lake record is ~50 years, too long a time to capture an analogous Holocene drought lasting less than a decade. Second, this discrepancy supports the modeling results of Sewall and Sloan (2004) and Sewall (2005), who used a fully coupled Earth system model wherein SSTs were raised in the absence of Arctic sea ice. Their results demonstrated that a large region of the western US including California will experience a decrease in precipitation in response to rising SSTs rather than the increase in precipitation suggested, at least for the central and southern Sierra Nevada, by the Tulare Lake record. This discrepant result suggests, in turn, that the sign of the response of precipitation in the western US to changes in SST varies dependent on boundary conditions, specifically, the volume of Arctic sea ice. It remains to be seen whether the effect of increasing SSTs will eventually overtake the effect due to the shrinking Arctic sea ice a century or more from now after the sea ice is completely gone (Knies et al., 2014).

6.4. Implications for Clovis-age Sites around Tulare Lake

In theory, the alluvial fans extending from the Kettleman Hills would have made an ideal location for Clovis-age settlements. The sandy fan deposits would have provided a well-drained location in close proximity to food and other resources. The sediment depth in the TL05-4 cores corresponding with the oft-cited age of Clovis occupations (13.5-13.0 cal ka BP) is ~3 mbgs, which places Clovis-age shorelines at approximately 55 masl, slightly lower than the 56-58.5 masl elevation previously suggested for this time (Wallace and Riddell, 1988; West et al., 1991; Fenega, 1993). As discussed above, Tulare Lake was characterized by deep, colder waters from 14.0-12.0 cal ka BP, throughout the entire Clovis period. Thus, the 56.0-58.5 masl elevation was likely well under water at this time and could not have served as settlement sites for Clovis peoples. However, there is a section of 12 cm of unrecovered core from the bottom of one of the core drives that, were it recovered, would have represented 13.1-12.2 ka cal, a time interval which includes the “Clovis Drought” discussed by Haynes (1991). Because sands are often lost at the base of core drives due to their unconsolidated nature, this break in the record could conceivably have contained coarse-grained, nearshore sediments indicating lower lake-level conditions during this time. Additionally, differential subsidence due to

modern groundwater withdrawal may have resulted in the lower than expected relative depth of the Clovis-age sediments on the western Tulare Lake margin.

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Figure Captions

Figure 1. Map of Tulare Lake and surrounding area. Tulare Lake drainage basin is outlined by bold dashed line. Filled circle near the northwestern margin of Tulare Lake shows the location of the TL05-4 cores taken adjacent to trenches upon which the previous study of Tulare Lake is based (see also Fig. 5 of Negrini et al., 2006). Inset shows location of Swamp Lake (SL), Owens Lake (OL), Lake Elsinore (LE), and ODP Site 1017 which are all referred to in the text.

Figure 2. Calibrated radiocarbon dates from the TL05-4A and -4B cores. Error bars correspond to 2-sigma range of output from CALIB 6.1/INTCAL09 ^{14}C calibration (Reimer et al., 2009). Cross symbols point to samples not used in chronology model due to age inversion.

Figure 3. Composite stratigraphic section of TL05-4 cores. Depth is measured in centimeters relative to ground surface level (58 masl).

Figure 4. Geophysical and geochemical proxies from TL05-4 cores. The TL05-4A core data are shown by solid black line, TL05-4B data by dashed grey line except for Figure 4c which is a composite of data from both cores. Zones 1-6 are defined principally by sand/silt/clay percentage in Figure 4c. Vertical, bold grey line segments at both end of

Zone 3 in Figure 4c separate lake regimes as defined in text. EOD = environment of deposition. χ = volume normalized magnetic susceptibility, TIC = total inorganic carbon, TOC = total organic carbon, N = nitrogen, C/N = carbon nitrogen ratio and is expressed as a molar ratio.

Figure 5. Lake-level/stream discharge records for three lakes filled with water draining from the central and southern Sierra Nevada. a) Tulare Lake level-stream discharge history based primarily on trench exposures (Davis, 1999; Negrini et al., 2006). b) Outcrop-based record for Owens Lake (Bacon et al., 2006; Orme and Orme, 2008; Reheis et al., 2014). c) Swamp Lake carbon/nitrogen record (Street et al., 2012). d) Tulare Lake level-stream discharge history from this study based on clay percent. e) Alkenone-based sea-surface temperature estimates from ODP Site 1017 core (Seki et al., 2002).

Figure 1

Figure 1

Figure 2

Figure 4) Composite stratigraphic description of cores TL05-4A and TL05-4B. Depth is measured relative to ground surface level, which is 58 masl.

Figure 4

Figure 4

Figure 5

Table

Sample Name	Lab #	Depth Interval (cm)	Depth (cm)	¹⁴ C Age BP	±	Cal yr BP Mean	Cal yr 2σ
TL05-4A-1-82-85	UCI36682	76-79	77.5	3110	30	3342	3256-3392
TL05-4B-2-11-14	AA100123	110-113	111.5	2655	40	2771	2736-2849
TL05-4B-2-21-24	AA100124	120-123	121.5	2695	52	2807	2741-2888
TL05-4B-2-40-42	AA100125	139-141	140.0	3038	42	3257	3141-3361
TL05-4B-2-55-57	AA100126	154-156	155.0	3509	42	3779	3687-3893
TL05-4A-2-26-32	UCI36684	163-169	166.0	4585	20	5310	5287-5322
TL05-4A-2-37-39	AA100117	174-176	175.0	5708	57	6502	6397-6656
TL05-4B-2-81-84	AA100127	180-183	181.5	5232	45	5988	5912-6032
TL05-4A-2-50-52	UCI36692	187-189	188.0	7665	30	8447	8403-8522
TL05-4B-2-100-102	AA100128	199-201	200.0	4275	43	4847	4811-4922
TL05-4B-2-118-120	AA100129	217-219	218.0	7366	51	8186	8040-8322
TL05-4B-2-132-134	AA100130	230-232	231.0	6357	51	7295	7235-7418
TL05-4A-2-95-97	UCI36685	232-234	233.0	8020	25	8896	8857-9008
TL05-4A-2-101-103	AA100118	238-240	239.0	7408	51	8250	8157-8364
TL05-4B-2-144-146	AA100131	243-245	244.0	7521	54	8341	8277-8411
TL05-4A-2-113-117	AA100119	250-254	252.0	7682	70	8479	8380-8592
TL05-4A-2-131-134	AA100120	268-271	269.5	9750	72	11171	11066-11306
TL05-4A-2-144-147	AA100121	281-284	282.5	9995	82	11497	11237-11817
TL05-4A-3-12-17	AA100122	303-308	305.5	10907	73	12782	12605-12971
TL05-4A-3-20-24	UCI36686	313-317	315.0	12665	25	15011	14642-15228
TL05-4A-3-54-60	UCI36687	345-349	347.0	13040	30	15719	15181-16346
TL05-4A-3-100-104	UCI36691	390-394	392.0	14525	40	17687	17370-17940