

Last glacial maximum and Holocene lake levels of Owens Lake, eastern California, USA

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Received 25 February 2005; accepted 6 October 2005

Abstract

Stratigraphic investigations of fluvio-deltaic and lacustrine sediments exposed in stream cuts, quarry walls, and deep trenches east of the Sierra Nevada in Owens Valley near Lone Pine, California have enabled the reconstruction of pluvial Owens Lake level oscillations. Age control for these sediments is from 22 radiocarbon (¹⁴C) dates and the identification and stratigraphic correlation of a tephra, which when plotted as a function of age versus altitude, define numerous oscillations in the level of pluvial Owens Lake during the latest Pleistocene and early Holocene. We have constructed a lake-level altitude curve for the time interval ~27,000 cal yr BP to present that is based on the integration of this new stratigraphic analysis with published surface stratigraphic data and subsurface core data. Pluvial Owens Lake regressed from its latest Pleistocene highstands from ~27,000 to ~15,300 cal yr BP, as recorded by ~15 m of down cutting of the sill from the altitudes of ~1160 to 1145 m. By ~11,600 cal yr BP, the lake had dropped ~45 m from the 1145 m sill. This lowstand was followed by an early Holocene transgression that attained a highstand near 1135 m before dropping to 1120 m at 7860–7650 cal yr BP that had not been recognized in earlier studies. The lake then lowered another ~30 m to shallow and near desiccation levels between ~6850 and 4300 cal yr BP. Fluvial cut-and-fill relations north of Lone Pine and well-preserved shoreline features at ~1108 m indicate a minor lake-level rise after 4300 cal yr BP, followed by alkaline and shallow conditions during the latest Holocene. The new latest Quaternary lake-level record of pluvial Owens Lake offers insight to the hydrologic balance along the east side of the southern Sierra Nevada and will assist regional paleoclimatic models for the western Basin and Range.

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1. Introduction

Owens Valley is an approximately 15–40 km wide and 200 km long complex graben in the southwestern Great Basin in eastern California. The valley lies adjacent to the eastern Sierra Nevada which forms one of the principal rain shadows in the western US (Fig. 1). The valley has a drainage area of ~8450 km² bounded by the crests of the Sierra Nevada Range to the west, White-Inyo Mountains to the east, and the Coso Range to the south and east. The northern extent of the watershed reaches north of Bishop near Long Valley, Adobe Valley and occasionally Mono basin during extreme pluvial times (Reheis et al., 2002), but presently is limited by a drainage divide that separates

Mono basin and the Volcanic Tableland to the north (Hollett et al., 1991) (Fig. 1). Crests of the Sierra Nevada and White-Inyo Mountains rise more than 3000 m above the floor of Owens Valley, with Mt. Whitney (alt. 4417 m) rising ~3280 m above the town of Lone Pine to the west.

The depocenter of the valley, which underlies Owens Lake playa within the southern portion of the valley, is a graben formed by prominent normal faults of the Sierra Nevada frontal fault system and the oblique-normal Inyo-White Mountains fault zones. The latest high stand of the lake, controlled by a spillway at 1145 m near Haiwee Reservoir, formed a water body at least 50 km long and 80 m deep (Gale, 1914; Smith and Bischoff, 1997) (Fig. 2). Owens Valley is generally steep-sided and flat-bottomed; thus, at 10 m below the sill altitude of 1145 m only 7% (40 km²) of the lake bottom is exposed. About 40–45 km² is exposed with each 10 m of lowering in lake level to the current playa bottom at ~1085 m (Mensing, 2001) (Fig. 2).

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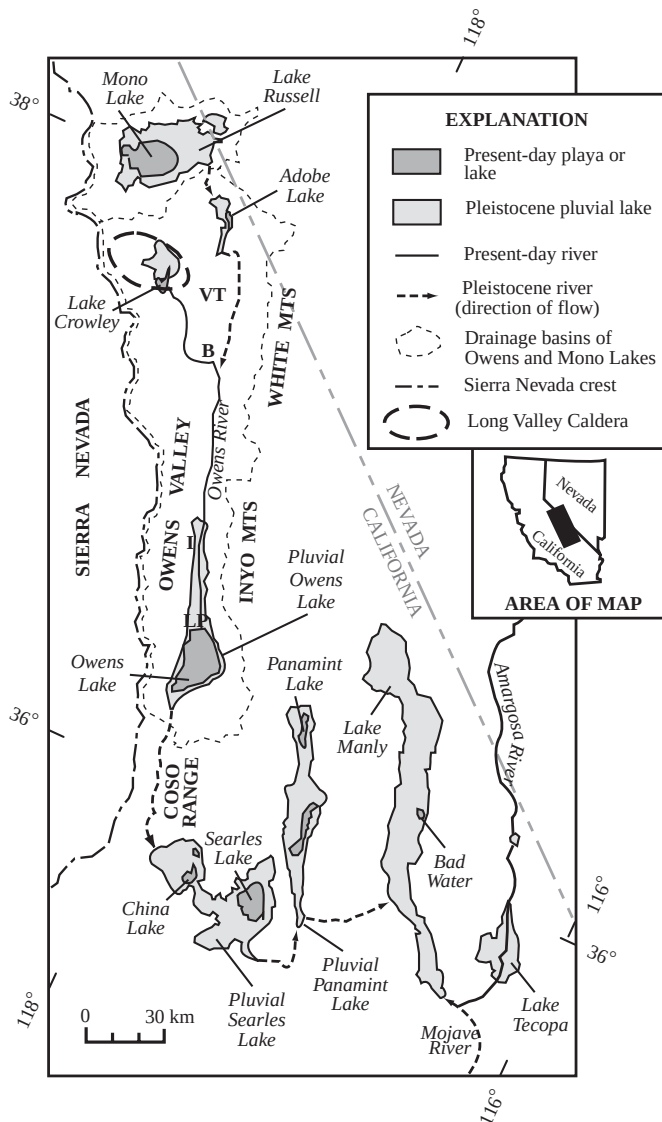


Fig. 1. Map of present day and pluvial Owens Lake, and other lakes hydrologically connected upstream and downstream from it during pluvial periods of the Pleistocene. B, Bishop; I, Independence; LP, Lone Pine; VT, Volcanic Tableland (figure modified from Smith and Bischoff (1997)).

During much of the middle and late Quaternary, Owens Lake was a perennial freshwater lake that periodically overflowed into a chain of lakes occupying one or more of four successively lower-altitude basins (Gale, 1914; Smith and Street-Perrott, 1983; Smith and Bischoff, 1997; Smith et al., 1997) (Fig. 1). The Owens River drainage system supplied most of the water to the lower chain of lakes, although at times pluvial Lake Russell in Mono basin has intermittently overflowed to become the northernmost lake in the drainage system (Lajoie, 1968; Smith and Street-Perrott, 1983; Reheis et al., 2002) (Fig. 1). In this paper, we use the term pluvial to mean a climatic regimen of sufficient duration to be represented in the physical or organic record, and in which the precipitation/evaporation ratio results in greater net moisture available for water bodies

and organisms than is available in the same area today or in the preceding regimen (Flint, 1971).

The highest identified shorelines without numerical age control within Owens Valley are located at an altitude of ~ 1180 m in the southern margin of Owens Lake basin (e.g., Hollett et al., 1991; Beanland and Clark, 1994). During the latest Pleistocene, at sill altitudes between ~ 1160 and 1145 m, pluvial Owens Lake filled the southern ~ 90 km of the valley north to about the location of Independence, covering more than ~ 700 km² (Smith and Street-Perrott, 1983; Orme and Orme, 2000) (Fig. 2). During the middle and late Holocene, Owens Lake was mostly a shallow, highly saline closed-basin lake (Benson et al., 1997; Smith et al., 1997; Li et al., 2000).

In 1872 AD, Owens Lake was a perennial closed-basin lake that covered more than 256 km² having a historical maximum lake level at ~ 1096 m and a water depth of 14.9 m (Gale, 1914). Major water diversions in Owens Valley began in 1921 AD with the construction of the Owens River-Los Angeles aqueduct that transports Owens River water more than 320 km to the south for distribution (Hollett et al., 1991). Owens Lake first began depositing salts onto the lake floor in 1921 AD because of these diversions, and by around 1931 AD, Owens Lake had desiccated and become a playa (Smith et al., 1997).

1.1. Previous stratigraphic investigations in southern Owens Valley

The Quaternary lacustrine history of southern Owens Valley has previously attracted stratigraphic investigations, with one of the earliest by Smith and Pratt (1957). More recently, sediment cores have documented the timing and qualitative changes of latest Quaternary lake-level fluctuations based on attributes such as isotopic, geochemical, mineralogical, and sedimentological, along with ostracode, diatom, and pollen biological proxy climatic indicators (e.g., Newton, 1991; Benson et al., 1996, 1997, 2002; Smith et al., 1997; Smoot, 1998; Forester, 2000; Li et al., 2000; Mensing, 2001; Bischoff and Cummins, 2001). Although sediment core proxy data are useful in detecting changes in a paleolake system, core data alone do not provide any indication of the surface altitude of a paleolake level, except during desiccation when evaporite minerals or evidence of a soil are present.

Stratigraphic and geomorphic data from shoreline deposits and associated features presented by Orme and Orme (1993, 2000), Smith (1997a), Stone et al. (2000), and Bacon (2003), combined with sediment cores of Benson et al. (1997, 2002) and Smith et al. (1997) document an open-basin lake during the latest Pleistocene and a closed-basin lake during the Holocene. These studies demonstrate that pluvial Owens Lake water levels fluctuated throughout the latest Pleistocene and Holocene, mostly within the basin at altitudes much above the playa, yet below the overflow sill at 1145 m. All but one of these studies were completed after the paleoseismic investigation on the Owens Valley fault

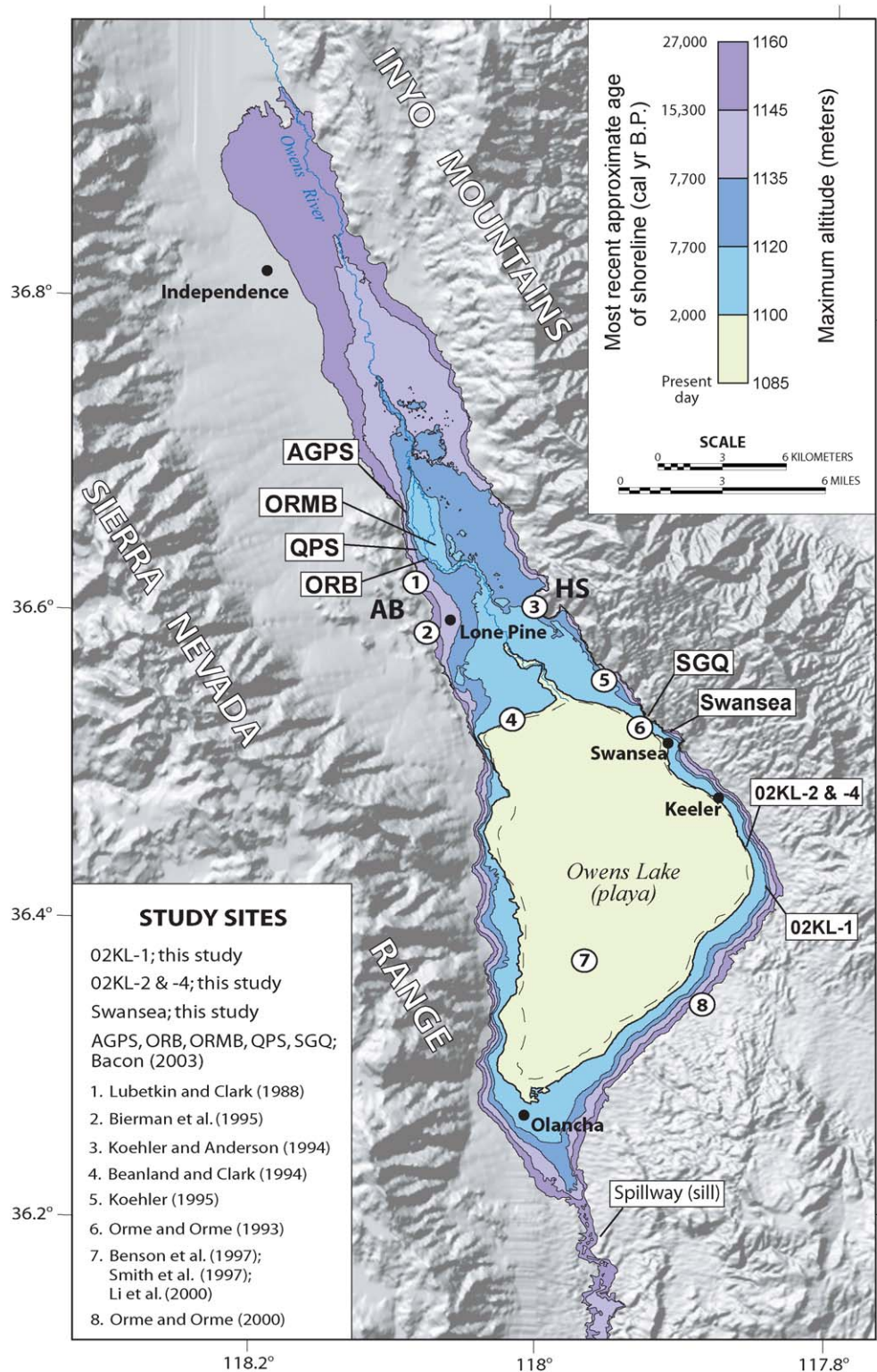


Fig. 2. Shaded relief map of southern Owens Valley. Different colored contours represent the ages of the most recent prominent highstands and recessional shorelines of Owens Lake during the latest Quaternary. Study sites discussed in text are shown: Alabama Gates paleoseismic site (AGPS); Quaker paleoseismic site (QPS); Owens River bluffs exposure (ORB); Owens River meander belt borehole site (ORMB); and Swansea gravel quarry (SGQ) tephra locality; AB, Alabama Hills; HS, Haystack.

zone by [Beanland and Clark \(1994\)](#), who inferred Holocene ages of several individual strand lines with corresponding altitudes below the sill.

In this study, we present a comprehensive lake-level curve for Owens Lake between 27,000 cal yr BP and the present using new numerical ages and stratigraphic

correlations combined with stratigraphic, geomorphic, and sediment core data from previous work (Fig. 3). Altitudes are mainly derived from 1:24,000 topographic maps, total-station and leveling surveys, and global positioning system (GPS) (Tables 1–3). We consider the wide range of different methods used to measure or estimate altitudes to have a vertical accuracy that ranges from <1 to 5 m.

We also present the age and altitudes of specific lake levels based on the sequence stratigraphy of latest Pleistocene to early Holocene fluvio-deltaic and lacustrine sediments of pluvial Owens Lake near Lone Pine (Figs. 2 and 3). Sequence stratigraphic analyses are based on the subdivision of a sedimentary section into hierarchies of strata that together form geometric packages which are defined and characterized by bounding and internal surfaces of erosion or non-deposition (sequence boundaries) (e.g., Einsele, 2000). The stratigraphic analysis includes a description of ~1.5 km of Owens River bluffs (ORB) exposed along the west bank of the river, the Owens River meander belt (ORMB) borehole site, and the Swansea gravel quarry (SGQ) that exposes a tephra (Fig. 2). In addition, we report on the results from seven trenches and four pits at the Alabama Gates (AGPS) and the Quaker paleoseismic sites (QPS) that were originally excavated to provide stratigraphic context for a paleoseismic investigation on the Owens Valley fault zone near Lone Pine (Bacon, 2003; Bacon et al., 2003), but that also provide important new stratigraphic constraints for the altitudes of the latest lake levels (Fig. 2).

1.2. Age control and correlations

We present 22 new radiocarbon (^{14}C) dates as well as one new tephra correlation analyzed by A.M. Sarna-Wojcicki, US Geological Survey, Menlo Park, California (Tables 1 and 2) and integrate these data with published ^{14}C dates (Table 3). These numerical dates constrain the age of both subaqueous deposits and subaerial shoreline features. Accelerator mass spectrometry (AMS) and conventional ^{14}C dates were obtained on charcoal, tufa, shells, and bulk organic carbon. Conventional ^{14}C dates reported in this study and prior studies have been converted to calibrated years before present (cal yr BP) using the CALIB v 5.0.1 program (Stuiver and Reimer, 1993) with the INTCAL04 data set (Reimer et al., 2004) for dates younger than ~20,000 yr BP (Tables 1 and 3 and Fig. 3). Furthermore, conventional ^{14}C dates reported in this study and prior studies that are older than ~20,000 yr BP were calibrated using ^{230}Th – ^{234}U and ^{14}C ages of corals after Bard et al. (1998) (Tables 1 and 3 and Fig. 3). Where conventional dates from published data lacked an uncertainty at $\pm 1\sigma$, we infer a standard error ± 60 yr BP in an effort to best present a calibrated age. Many of the ^{14}C dates contain multiple intercepts when calibrated, thereby providing multiple calibrated ages with different probabilities. The preferred intervals shown in bold in Tables 1 and 3 represent the range of calibrated ages at $\pm 2\sigma$ that includes

the y-intercept of the conventional radiocarbon age. The calibrated range of ages at $\pm 2\sigma$ and the intercept between the conventional ^{14}C ages are plotted to construct the lake-level curve.

Stratigraphic and geomorphic data are compiled from Orme and Orme (1993, 2000), Beanland and Clark (1994), Koehler and Anderson (1994), Bierman et al. (1995), Koehler (1995), Smith et al. (1997), Li et al. (2000), and Bacon (2003) (Fig. 3). Sediment core data from Benson et al. (1997), Smith et al. (1997), and Li et al. (2000) are also integrated with the shoreline data (Fig. 3). The altitude of each sediment core data point is approximated by comparing the reported age with a corresponding depth (altitude) using the graphic log of core OL-92 in Smith (1997). Age control of sediment cores is derived from AMS ^{14}C on carbonate and humate. Li et al. (2000) reported the ages of lacustrine sediment based on the correlation to paleomagnetic secular variations, because of uncertainties in the reservoir age estimation of Owens Lake, and are also shown on the lake-level curve. Organic-rich sediment (humate) that bound sediment hiatuses (unconformities and/or facies changes) provide ^{14}C dates that are interpreted by Smith et al. (1997) as proxy indicators of a change from deposition in deep-water to moderate- or shallow-water within a closed-basin lake. Sediment hiatuses in cores appear as frosted quartz grains, coarse sand, oolites or rubified clay with prismatic soil structure, all indicators of shallow to dry lake conditions (Benson et al., 1997; Smith et al., 1997). In addition to sediment hiatuses, the variation of $\delta^{18}\text{O}$ values from the sediment core record indicates changes in evaporation of the Owens Lake system (Benson et al., 1997). During a wet period, the volume of a closed-basin lake increases, which typically drives the $\delta^{18}\text{O}$ value in the lake to decrease, whereas during a dry period the $\delta^{18}\text{O}$ value in the lake increases as the lake shrinks (Benson et al., 2002); thus constraining the direction of lake-level oscillations in the absence of surface data.

It has been demonstrated that tufas (e.g., Bischoff et al., 1993) and shells (e.g., Brennan and Quade, 1997) in certain environmental conditions are unsuitable for numerical dating by the radiocarbon method, because tufas and shells are susceptible to contamination with older carbon. Also, Benson (1994) explains how reservoir corrections need to be applied to ^{14}C dates from tufa in lake systems. We acknowledge the uncertainty in dating tufa carbonates and shells, which may provide artificially older ^{14}C ages, but used with additional supporting ^{14}C dates from charcoal in addition to stratigraphic relations, may still offer reliable ages.

1.3. Uncertainties with altitude correlations across Owens Lake basin

Owens Valley is a region of active tectonism (Savage and Lisowski, 1995), with most of the study sites located on the valley bottom or graben block and bounded by the Owens Valley fault and Inyo Mountains fault blocks and

Table 1
Radiocarbon dates on charcoal, organic sediment, shell, and tufa from sites of this study in southern Owens Valley

Sample number and material dated	Sample location and altitude (m)	Radiocarbon date ^a (yr BP)	$\delta^{13}\text{C}/\delta^{12}\text{C}$ (‰)	Calibrated date ^b (cal yr BP)	Depositional environment
Beta-158755 ^c (Radiometric-shell)	Swansea-01; K-1 1128	9870 ± 90	−2.3	11,650–11,130; 11,700–11,670	Fluvial
Beta-166887 ^c (Radiometric-tufa)	02 KL-1; near Keeler 1124	16,320 ± 90	+ 3.5	19,600–19,230; 19,800–19,670	Lacustrine (shore to nearshore)
Beta-166888 ^c (Radiometric-tufa)	02 KL-2; near Keeler 1111	11,320 ± 70	+ 2.2	13,320–13,080	Lacustrine (shore to nearshore)
Beta-166889 ^c (Radiometric-shell)	02 KL-4C; near Keeler 1111	20,680 ± 120	−2.8	24,520–24,240 ^d	Lacustrine (shore to nearshore)
Beta-166890 ^c (Radiometric-tufa)	02 KL-4E; near Keeler 1111	10,970 ± 70	+ 2.2	13,050–12,840	Lacustrine (shore to nearshore)
USGS-WW4044 ^c (AMS-shell)	02 KL-4B; near Keeler 1111	21,300 ± 100	0	25,320–24,980 ^d	Lacustrine (shore to nearshore)
USGS-WW4045 ^c (AMS-tufa)	02 KL-4B; near Keeler 1111	14,805 ± 40	0	18,190–17,690; 18,470–18,320	Lacustrine (shore to nearshore)
USGS-WW4782 ^c (AMS-shell)	Swansea-1-17-04 1128	13,340 ± 40	0	16,220–15,480	Lacustrine (shore)
Beta-163551 ^c (AMS-charcoal)	OR-2B; ORB 1113	9990 ± 40	−22.1	11,620–11,270; 11,690–11,680	Delta plain (marsh to mud flat)
Beta-163552 ^c (AMS-organic sediment)	OR-2A; ORB 1113	10,480 ± 40	−26.1	12,200–12,190; 12,320– 12,240; 12,670–12,340	Delta plain (marsh to mud flat)
Beta-163553 ^c (AMS-organic sediment)	OR-4; ORB 1112.5	9560 ± 40	−25.4	11,090–10,730	Delta plain (marsh to mud flat)
Beta-163554 ^c (AMS-charcoal)	T2; AGPS 1121.8	9060 ± 40	−23.9	10,260–10,180	Delta plain (marsh to spring)
Beta-163555 ^c (AMS-organic sediment)	T2; AGPS 1121.8	9030 ± 60	−25.4	10,070–9920; 10,290– 10,120; 10,370–10,360	Delta plain (marsh to spring)
Beta-163556 ^c (AMS-organic sediment)	T4; QPS 1116.8	9160 ± 50	−25.2	10,440–10,230; 10,490–10,460	Delta plain (marsh to mud flat)
Beta-163557 ^c (Radiometric-organic sediment)	T4; QPS 1116.8	9680 ± 50	−25.1	10,860–10,790; 10,970– 10,860; 11,030–11,000; 11,220–11,070	Delta plain (marsh to mud flat)
Beta-163558 ^c (AMS-charcoal)	T4; QPS 1116.8	9920 ± 50	−24.7	11,410–11,230; 11,500– 11,430; 11,600–11,530	Delta plain (marsh to mud flat)
Beta-163500 ^c (AMS-charcoal)	T4; QPS 1116.8	9300 ± 60	−25.3	10,610–10,280; 10,660–10,620	Delta plain (marsh to mud flat)
Beta-163561 ^c (Radiometric-tufa)	T5; QPS 1120.5	7910 ± 60	−3.2	8820–8600; 8980–8820	Lacustrine (shore to nearshore)
Beta-168599 ^c (Radiometric-tufa)	P4; QPS 1114.5	6910 ± 60	−1.2	7650–7620; 7860–7650; 7920–7900	Lacustrine (shore)
Beta-168600 ^c (AMS-charcoal)	P4; QPS 1111.5	12,580 ± 60	−27.8	15,120–14,400	Delta plain (marsh to mud flat)
Beta-168601 ^c (AMS-charcoal)	P4; QPS 1111.5	12,590 ± 60	−28.2	15,130–14,420	Delta plain (marsh to mud flat)
Beta-168602 ^c (AMS-charcoal)	P4; QPS 1111.5	12,730 ± 60	−27.7	15,270–14,750	Delta plain (marsh to mud flat)

Note: Radiometric and accelerator mass spectrometry (AMS) dates provided by Beta Analytical Inc., Miami, FL, USA or Jack McGeehin, US Geological Survey, Reston, Virginia; ORB: Owens River bluffs exposure; AGPS: Alabama Gates paleoseismic site; QPS: Quaker paleoseismic site.

^aRadiocarbon date $\pm 1\sigma$ using Libby half-life of 5568 years.

^bRadiocarbon date is calibrated at $\pm 2\sigma$ using CALIB v 5.0.1 program (Stuiver and Reimer, 1993) with the INTCAL04 data set (Reimer et al., 2004); bold range includes the y -intercept and is the range shown in Fig. 3.

^cRadiocarbon dates from this study.

^dConventional radiocarbon date is calibrated (cal yr BP) after Bard et al. (1998).

^eRadiocarbon dates from Bacon (2003).

Table 2

Major oxide composition and correlation of a tephra from the Swansea gravel quarry near Lone Pine, Owens Valley

Sample	SiO ₂	Al ₂ O ₃	FeO	MgO	MnO	CaO	TiO ₂	Na ₂ O	K ₂ O	Total
Swansea gravel quarry OL-SW-1 (all glass) T470-9										
Mean (<i>n</i> = 23)	71.72	12.16	0.951	0.024	0.053	0.538	0.051	3.624	4.555	93.67
Std. dev.	0.43	0.10	0.066	0.010	0.029	0.028	0.033	0.103	0.105	0.60

Tephra layer exposed at the Swansea gravel quarry at an altitude ~1125 m. Tephra has a homogenous, compositionally tight mode, and matches best with Holocene tephra from the Mono Craters in Mono basin. Best matches are to tephra samples in the age range 1100–1200 ¹⁴C yr BP, but the greater part of the Holocene time span, from about 560 to 7000 ¹⁴C yr BP cannot be excluded, because there is a Holocene tephra layer with similar composition that is ~6900 ¹⁴C yr BP. The tephra at the Swansea gravel quarry is located ~20 m below the sill altitude of Owens Lake basin, therefore the tephra is likely within the older range of ages because it is overlain by younger beach barrier gravels that appear to extend to ~1135 m. The tephra is inferred to correlate with the oldest age of ~6900 ¹⁴C yr BP (7830–7670 cal yr BP^a) from the Mono Crater series.

Note: Original analytical data from electron-microprobe analysis of volcanic glass shards separated from tephra layer and correlation of tephra, which is based on the calculation of similarity coefficients using selected oxides, are presented in Bacon (2003). Shards were analyzed using the JEOL8900 (use of trade names by the US Geological Survey does not represent endorsement of the product) instrument. *N* = number of shards analyzed for each sample. Varying fluids account for differences in totals from 100%. Electron-microprobe analyses performed by J. Walker and tephra identification analyses performed by A.M. Sarna-Wojcicki, US Geological Survey, Menlo Park, California in 2001.

^aCalibrated age of tephra is in calendar years after Reimer et al. (2004).

associated fault zones (Pakiser et al., 1964). Owens Valley contains several active normal and oblique fault zones that generate large magnitude earthquakes that can cause wide spread subsidence and uplift. Several shorelines of different ages are deformed where they extend across or are near fault zones (Carver, 1970; Beanland and Clark, 1994; Bacon, 2003). For example, the magnitude $7\frac{1}{2}$ – $7\frac{3}{4}$ Owens Valley earthquake in 1872 AD, created a seismic seiche (tsunami) as well as laterally shifted the position of the eastern shoreline of Owens Lake hundreds of meters to the west, raising the western shoreline ~1 m in altitude (Ventura Signal, 1872; Meyer, 1977; Smoot et al., 2000).

Paleoseismic investigations on the Owens Valley fault zone near Lone Pine by Bacon (2003) provide minimum estimates for the amount of vertical deformation in the valley during the latest Quaternary. Geomorphic features and sediments deposited prior to the penultimate event at 9300 ± 300 cal yr BP are vertically deformed as much as 2.5 m. In addition, sediments and features deposited or formed during the time between the penultimate and 1872 AD earthquakes are vertically displaced ~1 m. These displacements are considered a minimum, because it is not clear how much subsidence or uplift is distributed within southern Owens Valley during earthquakes on the Owens Valley fault zone or on other faults that bound the valley, nor is it clear how much differential uplift has occurred due to isostatic rebound since the last significant highstands. In addition to ground deformation affecting the original altitude of sediments and features, the natural variability in the height of constructional beach features in Lahontan basin were within 2.5 m in altitude when spatially compared to shoreline features of the same lake level (Adams and Wesnousky, 1998). This range would be smaller for Owens Lake basin because of its lesser size. The reported altitudes shown on the lake-level curve have not been corrected because of the uncertainties in the original

altitude of sediments and shoreline features, which likely have been affected by the processes discussed above.

2. Latest Quaternary Owens Lake level curve

2.1. 27,000–15,800 cal yr BP

The highest latest-Pleistocene shoreline complex with numerical age control is located at an altitude of ~1160 m in southern Owens Valley (Fig. 2), where it is characterized by moderately to well-preserved beach ridges and wave-cut notches. Published lake-level data from Owens Valley are sparse, and three previous studies with ¹⁴C control constrain the age of shoreline features at this altitude. The ~1160 m shoreline has yielded a 26,250–23,230 cal yr BP ¹⁴C date on lithoid tufa-cemented beach gravel at an altitude of ~1156 m near Lone Pine (Lubetkin and Clark, 1988) (Table 3 and Figs. 2 and 3). The altitude of the dated beach gravel is considered a minimum because construction of the Los Angeles aqueduct has removed ~2–3 m of the upper section of the shoreline record at the site. A maximum altitude for this shoreline of ~1160 m is dated to ~24,230–23,730 cal yr BP from shells within beach ridge sediments from a site along the southern margin of Owens Lake basin (Orme and Orme, 2000) (Table 3 and Figs. 2 and 3). Furthermore, dung from packrat middens at an altitude of ~1155 m at Haystack east of Lone Pine date between 27,130 and 20,560 cal yr BP (Koehler and Anderson, 1994) (Table 3 and Figs. 2 and 3). The age and preservation of the packrat midden constrain the position of a lake level below 1155 m as recently as ~20,560 cal yr BP. Although it appears that there is overlap with the ¹⁴C dates and altitudes from each of the three studies, it is possible that the altitude estimate of ~1155 m for the packrat midden is incorrect as much as 5 m because it was probably approximated from a 1:24,000-scale topographic

Table 3

Compilation of radiocarbon dates on charcoal, organic sediment, shell, and oolites from previous investigations in southern Owens Valley

Reference and material dated	Sample location and altitude (m)	Radiocarbon date ^a (yr BP)	Calibrated date ^b (cal yr BP)	Depositional environment
Li et al. (2000) Historical	Owens playa 1096	NA (130)	NA	Lacustrine (shore) ^c
Li et al. (2000) (PSV)	Owens playa 1082	915 ± 135 ^d	NA	Dry (< Li & Mg) ^c
Beanland and Clark (1994) Artifact	Northern Owens Lake 1100	~2000 ^f	NA	Lacustrine (shore) ^c
Bierman et al. (1995) (radiometric-charcoal)	Near lone pine 1030–1150	4030 ± 60	4330–4300; 4370–4350; 4390–4390; 4660–4400 ; 4710–4670; 4810–4760	Alluvium (alluvial fan) ^c
Benson et al. (1997) (AMS-organic sediment)	Owens playa 1081	5870 ± 60* to 4040 ± 60*	6850–6820; 6800–6530; 6520–6500 to 4820–4750; 4730–4410	Shallow (erosional; sand) ^c
Smith et al. (1997) (AMS-oolites)	Owens playa 1080	5100 ± 60*	5670–5660; 5690–5680; 5950–5710 ; 5990–5970	Shallow (erosion; oolites) ^c
Orme and Orme (1993) (radiometric-shell)	Northern Owens Lake 1120	9600 ± 60*	11,170–10,750	Lacustrine (shore) ^c
Benson et al. (1997) (AMS-organic sediment)	Owens playa 1079.5	9700 ± 60*	10,970–10,790; 11,030– 11,000; 11,240–11,070	Dry (δ ¹⁸ O content) ^c
Orme and Orme (1993) (radiometric-shell)	Northern Owens Lake 1100	10,000 ± 60*	11,720–11,260 ; 11,750–11,730	Lacustrine (shore) ^c
Beanland and Clark (1994) (radiometric-charcoal)	AGPS 1122	10,190 ± 70	11,430–11,410; 11,530– 11,500; 11,550–11,540; 12,150–11,600	Delta plain (marsh to spring) ^c
Benson et al. (1997) (AMS-organic sediment)	Owens playa 1079	10,450 ± 60*	12,650–12,120	Dry (soil) ^c
Orme and Orme (1993) (radiometric-shell)	Northern Owens Lake 1116	10,940 ± 60*	12,990–12,820	Lacustrine (shore) ^c
Koehler (1995) (radiometric-shell)	Northern Owens Lake 1097	11,400 ± 60	13,380–13,150	Lacustrine (shore to nearshore) ^c
Benson et al. (1997) (AMS-organic sediment)	Owens playa 1078	11,280 ± 60*	13,280–13,070	Dry (δ ¹⁸ O content) ^c
Orme and Orme (1993) (radiometric-shell)	Northern Owens Lake 1123	11,450 ± 60*	13,420–13,200	Lacustrine (shore) ^c
Smith et al. (1997) (AMS-organic sediment)	Owens playa 1077	12,000 ± 60*	14,000–13,740	shallow (sand) ^c
Orme and Orme (1993) (radiometric-shell)	Northern Owens Lake 1126	12,200 ± 60*	14,210–13,880	Lacustrine (shore) ^c
Benson et al. (1997) (AMS-organic sediment)	Owens playa 1076	12,850 ± 60*	15,460–14,940	Dry (δ ¹⁸ O content) ^c
Orme and Orme (1993) (radiometric-shell)	Northern Owens Lake 1138	13,000 ± 60*	15,690–15,070	Lacustrine (shore) ^c
Benson et al. (1997) (AMS-organic sediment)	Owens playa 1073–1075	15,510 ± 60* to 13,430 ± 60*	18,920–18,700 to 16,370–15,590	Shallow (soil; sand) ^c
Koehler and Anderson (1994) (radiometric-dung)	Northern Owens Lake 1155	22,900 ± 270 to 17,680 ± 150	27,130–26,990 ^g to 21,220–20,560	Terrestrial (packrat midden) ^c
Orme and Orme (2000) (radiometric-shell)	Eastern Owens Lake 1160	20,000 ± 60*	24,230–23,731	lacustrine (shore) ^c
Lubetkin and Clark (1988) (radiometric-tufa)	Near Lone Pine 1156	21,000 ± 1300	26,250–23,230 ^g	Lacustrine (shore) ^c

Note: PSV: paleomagnetic secular variations; NA: not applicable; AMS: accelerator mass spectrometry; AGPS: Alabama Gates paleoseismic site;

*Indicates assumed uncertainty of ±60 yr BP, because reported conventional date lacked one.

^aRadiocarbon date at ±1σ.^bRadiocarbon date is calibrated at ±2σ using CALIB v 5.0.1 program (Stuiver and Reimer, 1993) with the INTCAL04 data set (Reimer et al., 2004); bold range includes the y-intercept and is the range shown in Fig. 3.^cDepositional environment interpreted from stratigraphic evidence.^dAge is determined from paleomagnetic secular variations.^eDepositional environment interpreted from proxy indicators in sediment cores.^fEstimated age on native American artifact.^gRadiocarbon date is calibrated (cal yr BP) after Bard et al. (1998).

map. In contrast, if the altitude estimate is correct, the difference of altitudes between similar aged study sites could be attributed to vertical deformation. The packrat midden study site on the southern Inyo Mountains block near Lone Pine could be vertically deformed and down-dropped relative to the Owens Valley fault zone located ~5 km to the east, providing an estimate for the position of a lake level between 1155 and 1160 m.

In addition to shoreline and terrestrial evidence for the age of the highstand lake, articulated mussels (*Margaritifera* sp.) in living position with a ^{14}C date of 24,520–24,240 cal yr BP occur at ~1111 m altitude south of Keeler, providing a minimum constraint on lake altitude at that time (Table 1 and Figs. 2 and 3). Sediment that filled the in situ articulated mussels contain the ostracode faunal association of *Candona caudata* and *Cytherissa lacustris* to the exclusion of other species; this occurrence indicates a cold fresh water lake with limited seasonal variability and therefore, full glacial conditions (R. Forester, written comm., 2001). Also, from the same altitude, but from a nearby site near Keeler, other in situ mussels (*Margaritifera* sp.) partly encrusted with tufa in a sandy substrate provided a ^{14}C date of 25,320–24,980 cal yr BP (Table 1 and Figs. 2 and 3). These paleontological relations indicate the water level of the lake was above 1111 m altitude and that it may have lowered from its highstand for a brief period from ~25,300 to 24,200 cal yr BP (Fig. 3). Many varieties of aquatic molluscan fauna grow their shells in waters with an initial ^{14}C deficiency and as a result, yield artificially older ^{14}C ages (Brennan and Quade, 1997). Changes in the reservoir effect in Owens Lake basin are not established, so we do not apply a reservoir correction, but instead interpret the ^{14}C ages of the mussels as a maximum estimate of their time of death (e.g., Briggs et al., 2005).

In addition to ^{14}C dates from mussels, two dates from tufa constrain the lake level during a pluvial time. Tufa encrusting basaltic beach cobbles at an altitude of ~1124 m in the southeastern part of the basin yield a ^{14}C date of 19,600–19,230 cal yr BP (Table 1 and Figs. 2 and 3). Furthermore, tufa encrusting the mussel shell dated at ~25,000 cal yr BP yields a ^{14}C date of 18,190–17,690 cal yr BP, thereby providing confidence in the ^{14}C dates because the tufa has a younger age, as would be expected (Table 1 and Figs. 2 and 3).

Between ~27,000 and 15,800 cal yr BP, the lake-level curve is poorly constrained because of sparse lake-level indicators. However, proxy indicators from sediment cores, such as $\delta^{18}\text{O}$ and total inorganic carbon (TIC), can be used to indicate the probable existence of a relatively deep freshwater lake that may have been punctuated by at least two periods of a closed-basin lake (Benson et al., 1996, 1997; Smith et al., 1997). Evidence in sediment cores for a closed lake, and even a desiccation event, includes possible sub-aerial features such as a 1–3 mm thick lag deposit of frosted quartz grains between ~18,920 and 15,590 cal yr BP (Benson et al., 1997) (Table 3 and Fig. 3). The observed 3700 yr long sediment hiatus in this interval from sediment

cores, which is inferred to represent a desiccation event by Benson et al. (1997) and/or shallow lake conditions, partially overlaps with the interval of time of a possible lake-level lowering suggested by tufa precipitation near Keeler from ~19,480 to 17,740 cal yr BP (Fig. 3).

Additionally, probable low lake levels during this time corroborates the ^{14}C ages on shells from shoreline deposits dated by Orme and Orme (2000) that represent possible lowstands below ~1160 m between ~19,300 and 14,700 cal yr BP which are not shown on Fig. 3. We acknowledge the uncertainties in the ages of the materials dated that constrain the lake-level curve, but the apparent overlap of the time of low lake levels likely represents the occurrence of moderate fluctuations below the overflow sill altitude between 27,000 and 15,800 cal yr BP. These fluctuating water levels apparently did not lower enough to precipitate carbonate during this interval of time, because core OL-90 records the occurrence of maximum rock flour and low percentage of carbonate during this period, implying moderate to overflowing lake conditions (Bischoff and Cummins, 2001).

2.2. 15,800–11,000 cal yr BP

Shoreline data from beach ridges and barriers indicates the lake level of pluvial Owens Lake oscillated between ~15,800 and 11,000 cal yr BP, and at times was punctuated by minor and brief transgressions of varying durations (Orme and Orme, 1993). Sediment core data also reveal the presence of sharp facies changes during this time period in the form of two sand horizons (Benson et al., 1997; Smith et al., 1997) and two extremely dry events indicated by $\delta^{18}\text{O}$ data (Benson et al., 1997) that together suggest drops in lake level that are within the age resolution of the ends of five highstands, which are indicated by shoreline data (Table 3 and Fig. 3). According to shoreline data alone, pluvial Owens Lake significantly receded with an overall drop in altitude of ~38 m between ~15,300 and 11,400 cal yr BP (Orme and Orme, 1993) (Fig. 3).

The lower of the two latest Pleistocene highstand shorelines in southern Owens Valley is located at or near the overflow sill altitude of 1145 m (Carver, 1970; Smith and Street-Perrott, 1983; Lubetkin and Clark, 1988; Orme and Orme, 1993, 2000) (Fig. 2). Beach ridges, wave-cut notches, and broad terraces of this shoreline complex are more common than the higher shoreline features at ~1160 m. A minimum age for the 1145 m highstand comes from ^{14}C dates on shells within the highest beach barrier sediments at ~1138 m near Swansea that are 15,690–15,070 cal yr BP (Orme and Orme, 1993) (Table 3 and Figs. 2 and 3). Also, disarticulated and broken mussel shells (*Margaritifera* sp.) collected at an altitude of ~1128 m within well-imbricated beach barrier gravels at Swansea yielded an AMS date of 16,220–15,480 cal yr BP (Table 1 and Figs. 3 and 5). The mussels from Swansea at ~1128 m were probably deposited during a transgression

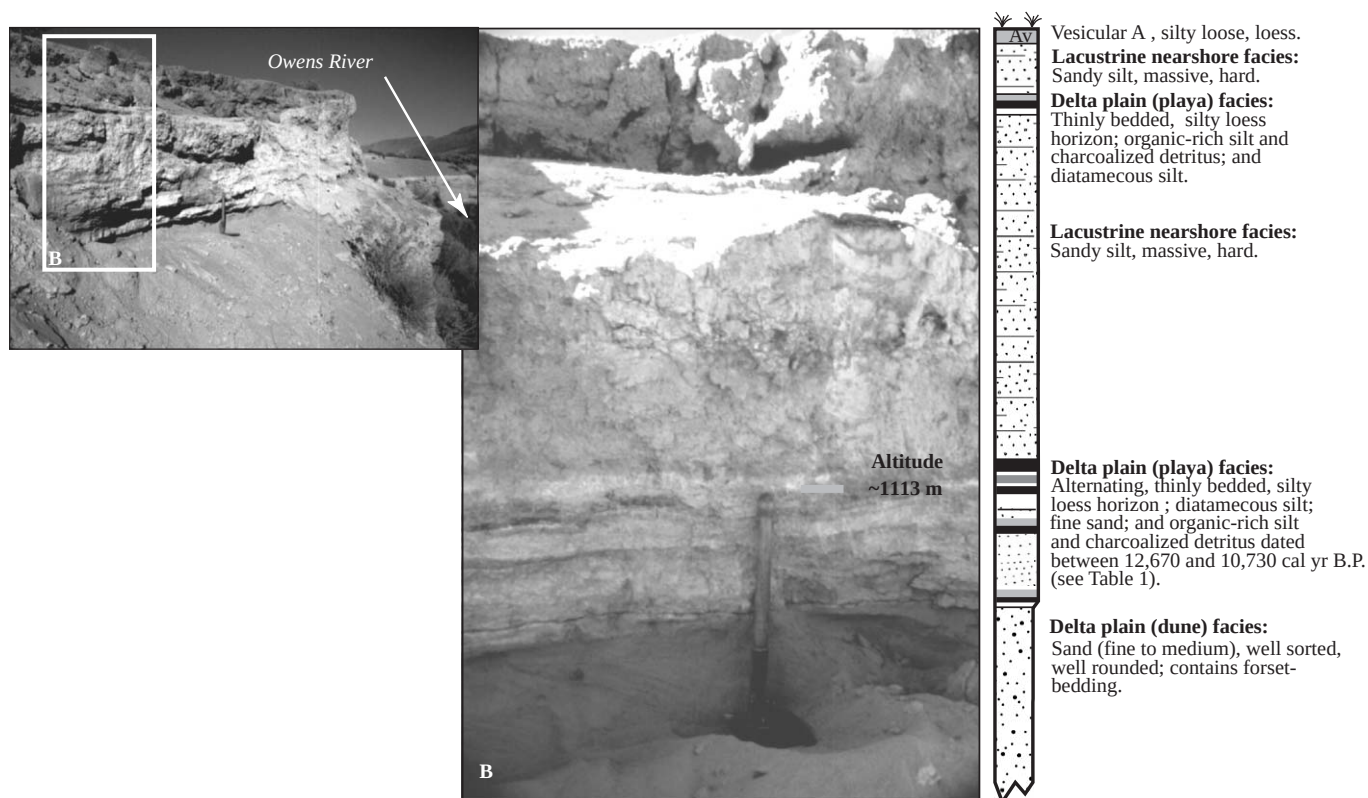


Fig. 4. Photographs and stratigraphic column of interbedded lacustrine nearshore sandy silt sediments with delta plain, playa and eolian sediments exposed at the Owens River bluff (ORB) exposure along the west bank of the Owens River (see Fig. 2 for location). Several ^{14}C dates at an elevation of $\sim 1113\text{ m}$ are from charcoaled woody debris, which constrain the age and position of Owens Lake water levels (ORB; Table 1 and Fig. 3). Alternating sandy silt sediments of a lacustrine nearshore facies are part of a transgressive sequence that occurred after $\sim 10,730\text{ cal yr BP}$ and attained an altitude greater than $\sim 1116\text{ m}$.

that attained an altitude above 1138 m prior to $\sim 15,300\text{ cal yr BP}$ (Fig. 3).

Additional corroborative evidence supporting the brief oscillating lake levels during this interval comes from the Quaker paleoseismic site (Fig. 2). This site exposes a terrestrial depositional environment at 1111.5 m in Pit P4 (Bacon, 2003) indicating the lake was below this altitude (Fig. 3). From this site, three AMS radiocarbon samples of well-preserved charcoaled fragments of willow (*Salix* sp.) that appear to have been transported and deposited in a marsh or mud flat (playa) environment, indicate an age range of $15,270$ to $14,400\text{ cal yr BP}$ (Table 1). Soon after, the lake level apparently rose to an altitude of 1126 m at $14,210$ – $13,880\text{ cal yr BP}$ based on dated shells in beach sediments (Orme and Orme, 1993; Table 3), which was followed by a significant lowering indicated by sandy facies in sediment cores dated to $14,000$ – $13,740\text{ cal yr BP}$ (Smith et al., 1997; Table 3).

During a subsequent lake-level oscillation, which was followed by a brief lake level high that reached $\sim 1123\text{ m}$ at $13,420$ – $13,200\text{ cal yr BP}$ (Orme and Orme, 1993; Table 3), tufa at $\sim 1111\text{ m}$ near Keeler dates to $13,320$ – $13,080\text{ cal yr BP}$ (Table 1 and Figs. 2 and 3). The age of the tufa that is presumed to have formed at or below wave-base is within the uncertainties of the age of shoreline sediments at

$\sim 1123\text{ m}$ of Orme and Orme (1993) that are $\sim 12\text{ m}$ higher in altitude. This regressive lake level reached an altitude of $\sim 1097\text{ m}$ at $13,380$ – $13,150\text{ cal yr BP}$ based on a ^{14}C date on bivalve shells (*Anodonta californiensis*) from an assemblage in the northeastern basin (Koehler, 1995) (Table 3 and Figs. 2 and 3). A regressive and low lake level at this time is supported by $\delta^{18}\text{O}$ proxy data in cores of Benson et al. (1997) that indicate dry conditions at $13,280$ – $13,070\text{ cal yr BP}$ (Table 3 and Fig. 3). Also, during a subsequent lake-level transgression, lacustrine conditions near $\sim 1111\text{ m}$ are suggested by the presence of algal or stromatolitic colonial tufa south of Keeler that yielded a ^{14}C date of $13,050$ – $12,840\text{ cal yr BP}$ (Table 1 and Figs. 2 and 3). The tufa is well-preserved with concentric growth rings, and bowl-shaped with flat upper surfaces resembling in situ tufa heads of Newton and Grossman (1988), implying formation at or below wave-base. The age of the tufa heads that are presumed to have formed below wave-base coincides with $12,990$ – $12,820\text{ cal yr BP}$ shoreline sediments at $\sim 1116\text{ m}$ of Orme and Orme (1993) that are 5 m higher in altitude (Table 3 and Fig. 3).

Evidence for low lake levels between ~ 1100 and 1122 m from $\sim 12,600$ to $10,000\text{ cal yr BP}$ is from the indication of two dry intervals in sediment cores (Benson et al., 1997), from beach barrier sediments (Orme and Orme, 1993), and

from marsh, spring, and playa sediments representing subaerial conditions at sites near Lone Pine (Beanland and Clark, 1994; Bacon, 2003) (Tables 1 and 3 and Figs. 2 and 3). During this interval, the lake level appears to have significantly dropped because cores reveal rubified color and prismatic cracking implying soil development at 12,650–12,120 cal yr BP (Benson et al., 1997) (Table 3 and Fig. 3). This low lake level was followed by a transgression that reached 1100 m at 11,720–11,260 cal yr BP (Orme and Orme, 1993) (Table 3 and Fig. 3).

These low lake levels are supported by the existence of terrestrial facies of a delta plain depositional environment at an altitude of ~1113 m along the ORB exposure (Figs. 2 and 3). The bluffs exposure exhibits a delta plain depositional environment consisting of interbedded sand dune facies with thinly bedded and alternating organic-rich, diatomaceous, and wind-blown silty horizons representing marsh to playa facies dated between ~12,670 and 10,730 cal yr BP (Table 1 and Figs. 3 and 4). Furthermore, the delta plain sediments are overlain by a succession of lacustrine nearshore facies and interbedded marsh to playa facies of the delta plain, which represent at least two lake-cycles above ~1113 m after ~10,730 cal yr BP (Figs. 3 and 4).

Within this interval and at higher altitudes, marsh and/or spring deposits are exposed at altitudes from ~1117 to 1122 m at the Alabama Gates (Trench T2) and Quaker (Trench T4) paleoseismic sites that indicate terrestrial conditions from ~11,400 to 10,120 cal yr BP (Bacon, 2003; Table 1 and Figs. 2 and 3), as well as a ^{14}C date of 12,150–11,600 cal yr BP from an altitude of 1122 m at the Alabama Gates site (Beanland and Clark, 1994; Table 3 and Figs. 2 and 3). Two AMS ^{14}C samples from Trench T2 of the Alabama Gates site are of charcoaled plant fibers and bulk organic sediment from the base of a fining upward sequence of silty peat to organic-rich silt to clay and fine sand (Bacon, 2003). The organic-rich silt to clay sample contains numerous seeds and rhizome fragments of bulrush (*Scirpus* sp.) and pondweed (*Potamogeton* cf. *gramineus*), flora indicative of freshwater springs, ponds, and marshes. The AMS analyses of this deposit in Trench T2 provide dates of 10,290–10,120 and 10,260–10,180 cal yr BP (Table 1 and Fig. 3). In Trench T4 of the Quaker site, two samples of charcoal within an organic-rich silt horizon representing a marsh to mud flat (playa) setting yields ^{14}C dates of 11,410–11,230 and 10,610–10,280 cal yr BP and two bulk samples of organic sediment have ^{14}C dates of 11,220–11,070 and 10,440–10,230 cal yr BP (Table 1 and Fig. 3).

In addition, a well-preserved gastropod-bearing bed at ~1128 m near Swansea, which is at the upper contact of gravelly sediment that is sedimentologically characteristic of a fluvial deposit, is bounded by lacustrine gravel beach facies (Fig. 5). The gastropod-bearing bed contains abundant adult and juvenile forms that date to 11,650–11,130 cal yr BP (Table 1). The fluvial deposit consists of very poorly sorted and well-rounded to sub-

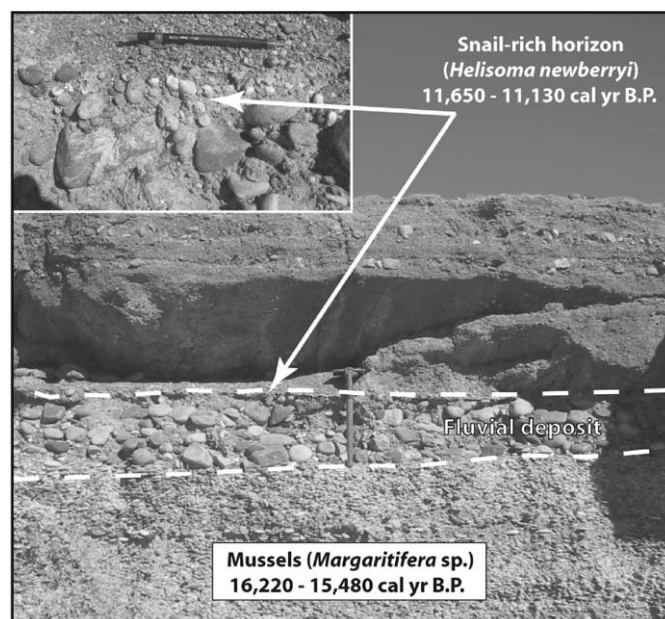


Fig. 5. Photograph of gravel quarry near Swansea. Image shows ~40 cm thick gravelly fluvial deposit interbedded between barrier beach sands and gravels at an altitude of ~1128 m. Top of fluvial deposit contains a thin, shelly horizon of well-preserved gastropods (*Helisoma newberryi*) dated to 11,650–11,130 cal yr BP. The barrier gravels below the fluvial deposit contain disarticulated mussels (*Margaritifera* sp.) that yielded a ^{14}C date of 16,220–15,480 cal yr BP. The stratigraphic relations at this site indicate fluctuating water levels at or after ~15,800 cal yr BP, a fluvial environment prior to ~11,200 cal yr BP, which was followed by a water level as high as ~1128 m after ~11,200 cal yr BP. (Note: ~0.5 m high shovel for scale.)

rounded cobbles. The cobbles are equant and compositionally distinct from the bounding horizons. The matrix consists of sandy to gravelly sediment. Gastropod shells are fresh, intact, have pigment and are well exposed within a ~5 cm thick shelly horizon at the upper contact of the deposit (Fig. 5). The shells appear not to have been redistributed or significantly reworked, based on their degree of preservation. The shells are mostly the large planorbid snail (*Helisoma (carinifex) newberryi*) with lesser occurrences of the smaller planorbid snail (*Helisoma (vorticifex) newberryi*), which both live in large perennial freshwater lakes and permanent streams (Miller, 1989).

The gastropod-rich fluvial bed is underlain by beach gravels dated at ~15,800 cal yr BP and overlain by younger cross-bedded beach pea gravels (Table 1 and Fig. 5). Both overlying and underlying beach deposits are distinctly well-sorted and consist of well-rounded clasts, but the two deposits sharply contrast in their average clast size, shape and composition, likely reflecting different beach facies and provenience source areas to this part of the shoreline, which completely changed in the time interval preceding and following the deposition of the fluvial, gastropod-bearing horizon. The lower beach deposit consists of greenish-gray weathering, strongly imbricated, ~2–3 cm sized, oblate-shaped clasts (Fig. 5), whereas the overlying beach deposit consists of reddish weathered equant to sub-equant, pea-sized (~0.3–0.7 cm) gravel and sand.

Orme and Orme (1993) reported the age of shoreline sediments at 1120 m near Swansea to be 11,170–10,750 cal yr BP based on shells, which does not agree with the lake-level curve for this same period as presented (Fig. 3). As discussed earlier, a reservoir correction is not established in Owens Lake basin, therefore we interpret the dated shells from our study, as well as those from other studies, such as the 11,170–10,750 cal yr BP date at ~1120 m of Orme and Orme (1993), as maximum estimates of their time of death. There are at least two explanations for the disagreement of the reported age of sediments at 1120 m with the lake-level curve: (1) the ^{14}C ages are older than the shoreline sediments they date because of uncertainties in the reservoir correction, and that the sediments were deposited during a later transgression or (2) the ^{14}C dates are correct and indicate a brief lake-level oscillation at 11,170–10,750 yr BP that reached an altitude of ~1120 m (Fig. 3).

2.3. 11,000–7650 cal yr BP

Soon after the lowest lake level at 1100 m, the ratio $\delta^{18}\text{O}$ in core samples (Benson et al., 1997) indicates a dry interval at 11,240–11,070 cal yr BP before a latest Pleistocene and early Holocene transgression of pluvial Owens Lake (Fig. 3). During this transgression, the lake had complex lake-level fluctuations between ~1100 and 1135 m that deposited shore, nearshore, and fluvio-deltaic sediments over subaerial deposits and constructed shoreline features between ~11,000 and 7650 cal yr BP. The lake-level curve for this time interval is from sequence stratigraphy analysis at the SGQ tephra locality, the ORB exposure, and the Alabama Gates and Quaker paleoseismic sites (Figs. 2 and 3).

The tephra exposed at the SGQ is a 0.5–6.0 cm thick pure tephra at ~1125 m that is interbedded between gravelly beach barrier sediments that appear to extend to an altitude as high as ~1135 m (Bacon, 2003) (Fig. 6). The barrier sediments that underlie the tephra are inferred to correlate to nearby deposits dated between ~15,300 and 13,300 cal yr BP by Orme and Orme (1993). This correlation is based on the range of altitudes and close proximity to exposures of shells sampled by Orme and Orme (1993) within nearby beach barrier sediments. Moreover, the tephra is overlain by a stacked sequence of an alluvial or nearshore sandy deposit and gravelly barrier sediments that represents an oscillation in lake level above 1125 m (Fig. 6). The tephra best matches a series of Holocene tephtras from the Mono Craters in Mono basin that date from about 7830 to 560 cal yr BP (A. Sarna-Wojcicki, written comm., 2001; Sarna-Wojcicki, 2000; Table 2). Because the tephra is interbedded with shoreline sediments that occur between ~10 and ~20 m below the overflow level altitude, the tephra is inferred to correlate to the oldest tephtras from the Mono Craters series. This assignment is further supported by other sites near Lone Pine of Bacon (2003) that do not show evidence of lake levels

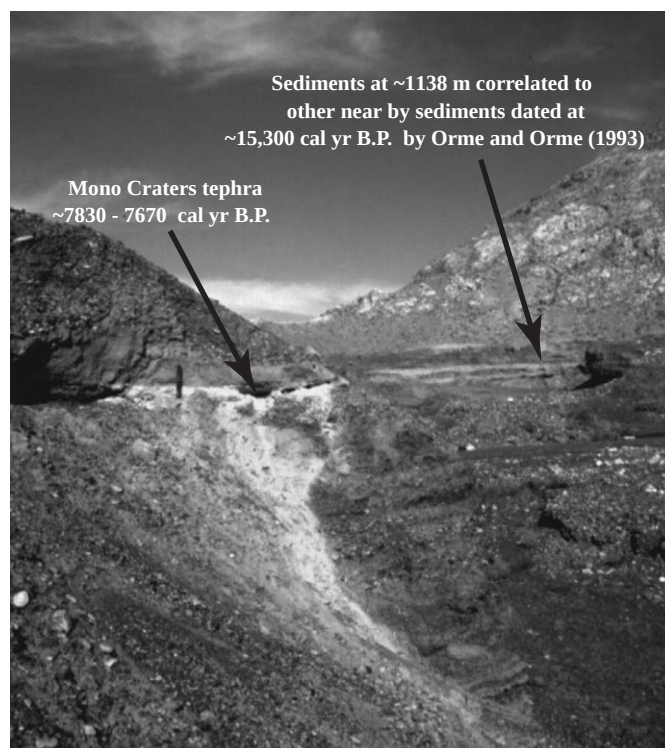


Fig. 6. Photograph of the Swansea gravel quarry tephra locality. Tephra is underlain by beach barrier gravels correlated at ~15,300 cal yr BP and overlain by a stacked sequence of silty sand alluvial deposit and beach barrier gravels at an altitude of ~1125 m. The tephra is correlated to a Mono Craters eruption at 7830–7670 cal yr BP. This site provides an age constraint for an early Holocene highstand in southern Owens Valley just after 7830–7670 cal yr BP that appears to have attained an altitude as high as ~1135 m. (Note: Knife for scale.)

younger than 7860–7650 cal yr BP above 1120 m. Furthermore, local stratigraphic evidence support a lake level above 1128 m that occurred after ~11,240 cal yr BP from the site where shells in fluvial and barrier sediments were directly dated in this study (Figs. 3 and 5). Based on the stratigraphy and tephrochronology at the SGQ and other sites nearby, the Holocene highstand of pluvial Owens Lake reached an altitude of ~1125 m that likely reached as high as ~1135 m shortly after 7830–7670 cal yr BP (Table 2 and Figs. 2 and 3). Geomorphic evidence of this lake level is from the presence of erosional shoreline features consisting of wave-cut notches and platforms at an altitude of 1135 m east of Keeler, located 5–15 km southeast of the SGQ (Beanland and Clark, 1994; Strandline C). Beanland and Clark (1994) infer that the wave-cut features at 1135 m near Keeler formed <7000–2000(?) yr ago, based on the correlation to poorly constrained Holocene glaciations in the Sierra Nevada (e.g., Burke and Birkeland, 1983). Founded on the tephra correlation at the SGQ (Fig. 6) and degree of preservation, these features likely were constructed around 7830–7670 cal yr BP.

Stratigraphic and geomorphic evidence from the Alabama Gates and Quaker paleoseismic sites, ~18 km north-west of the tephra locality and Keeler, provide evidence for

nearshore depositional environments between ~10,200 and 8650 cal yr BP in Trenches T2 and T5, respectively (Bacon, 2003). The stratigraphy in Trench T2 at the Alabama Gates site supports the existence of a lake level above 1127 m, with the presence of nearshore sediments deposited over spring and/or marsh peat at an altitude of ~1122 m after ~10,200 cal yr BP (Fig. 3). Geomorphic evidence at the site indicates that wave-cut notches and platforms are also located at altitudes between 1128 and 1136 m (Bacon, 2003). Stratigraphy in Trench T5 at the Quaker paleoseismic site exhibits lacustrine sediments and tufa precipitation at an altitude as high as 1121 m implying a higher lake level after 8820–8600 cal yr BP, based on a ^{14}C date from tufa (Table 1 and Fig. 3).

The 7830–7670 cal yr BP early Holocene highstand documented at the SGQ appears to have attained an altitude of 1135 m for a brief period prior to a ~15 m regression. This regression apparently stabilized and formed an abrasion platform, eroded older sediments, and constructed a beach ridge at an altitude of ~1120 m at the Quaker paleoseismic site (Bacon, 2003) (Figs. 2 and 3). The age of the 1120 m beach ridge is estimated from the correlation of tufa-bearing sediments from a foreshore beach facies exposed in Pit P4. The tufa materials in Pit P4 at an altitude of 1114.5 m resulted in a ^{14}C date of 7860–7650 cal yr BP, which is a similar age to the tephra from Swansea (Table 1). The tufa ^{14}C date of ~8650 cal yr BP from Trench T5, which is underlain by undated deposits that correlate to deposits dated at ~11,400 to 10,200 cal yr BP in Trench T4, support the tufa age of the 1120 m beach ridge (Bacon, 2003). Based on tephra correlation at the SGQ and ^{14}C date from tufa materials of the beach ridge at the Quaker paleoseismic site, the early Holocene highstand of pluvial Owens Lake appears to have attained the altitudes of 1120 and 1135 m around 7860–7650 cal yr BP (Fig. 3).

At a similar altitude to the 1120 m beach ridge at the Quaker paleoseismic site is a shoreline feature at an altitude of 1122 m that is located to the south near Olancho (Beanland and Clark, 1994; Strandline D) (Fig. 2). Beanland and Clark (1994) infer that this strandline formed <7000 to 2000 yr ago. The altitude of Strandline D is close to the altitude of the 7860–7650 cal yr BP beach ridge at the Quaker paleoseismic site. The ~2 m difference in altitude between the two features is within the range of natural variability in crest heights of shoreline landforms (Adams and Wesnousky, 1998). It is plausible that the strandline at 1122 m documented by Beanland and Clark (1994) formed during the same relatively stable lake level that constructed the beach ridge at the Quaker paleoseismic site.

2.4. 7650–4300 cal yr BP

Regression of pluvial Owens Lake continued after the construction of the 7860–7650 cal yr BP beach ridge at an altitude of 1120 m (Fig. 3). Lake level lowered to altitudes that permitted subaqueous erosion of the lake bottom. This erosion is responsible for discontinuities in the Owens Lake

core record that date back to the ~9500 cal yr BP horizon (Smith et al., 1997). Radiocarbon dates on oolites and on humate that are in unconformable contact with sand horizons indicate near-desiccation and shallow water levels between 6520 and 4410 cal yr BP (Benson et al., 1997, 2002; Smith et al., 1997) (Table 3 and Fig. 3). During this same interval, alluvium was deposited in the channel of the Owens River ~30 km south of the sill of Owens Lake basin in Rose Valley, which dammed the southern part of the channel to form Little Lake. Radiocarbon dates on basal sediment in a core from Little Lake provide an extreme minimum age of overflow from pluvial Owens Lake at 5900–5640 cal yr BP (Smith et al., 1997).

2.5. 4300 cal yr BP to present

Lake level is inferred to have increased after ~4300 cal yr BP, because cores lack relatively shallow lake-level indicators between 4300 cal yr BP and 1000 yr BP (Benson et al., 1997; Li et al., 2000) (Fig. 3). A maximum lake level during this interval, and below ~1114 m, is indicated by the sequence of cut-and-fill relations observed at the ORMB north of Lone Pine (Figs. 2, 3, and 7). Boreholes drilled on the highest preserved surface of a fluvial terrace at an altitude near ~1114 m indicate the terrace surface is underlain by a 4 m package of bedded fluvial sands and silts that are in unconformable contact with deep-water lacustrine clayey silts. The lacustrine sediment is inferred to be greater than 15,000 cal yr BP because they occur stratigraphically below younger dated deposits exposed along nearby bluffs of the Owens River (Figs. 2, 7, and 8). These stratigraphic relations suggest that the sharp contact represents a ravinement (erosion from fluvial entrenchment) formed in response to the lower lake levels between ~6520 and 4410 cal yr BP. During a subsequent rise in base level, the Owens River north of Lone Pine apparently responded by aggradation of ~4 m associated with a rise in lake level. The age of the fill terrace at ~1114 m is less than 7860–7650 cal yr BP based on cut-and-fill relations of latest Pleistocene and early Holocene age strata exposed along bluffs of the Owens River, within nearby paleoseismic trenches, and sediment core data (Figs. 2, 3, and 7).

This fill terrace likely formed in response to a transgression that stabilized at an altitude of ~1108 m, suggested by the presence of a prominent beach ridge and wave-cut notches at the southern margin of Owens Lake (playa) (Beanland and Clark, 1994; Strandline E). Beanland and Clark (1994) infer that this strandline formed <7000–2000 yr ago. We speculate that the fluvial terrace and strandline formed after ~4300 cal yr BP. The beginning of this transgression roughly coincides with a ^{14}C date of 4460–4400 cal yr BP from Bierman et al. (1995) who dated part of an alluvial fan associated with Lone Pine Creek that is located between an altitude of 1130 and 1150 m near Lone Pine, which is not considered a maximum age for the alluvial fan (Table 3 and Figs. 2 and 3). Fan development at this time may be synchronous with aggradation of the

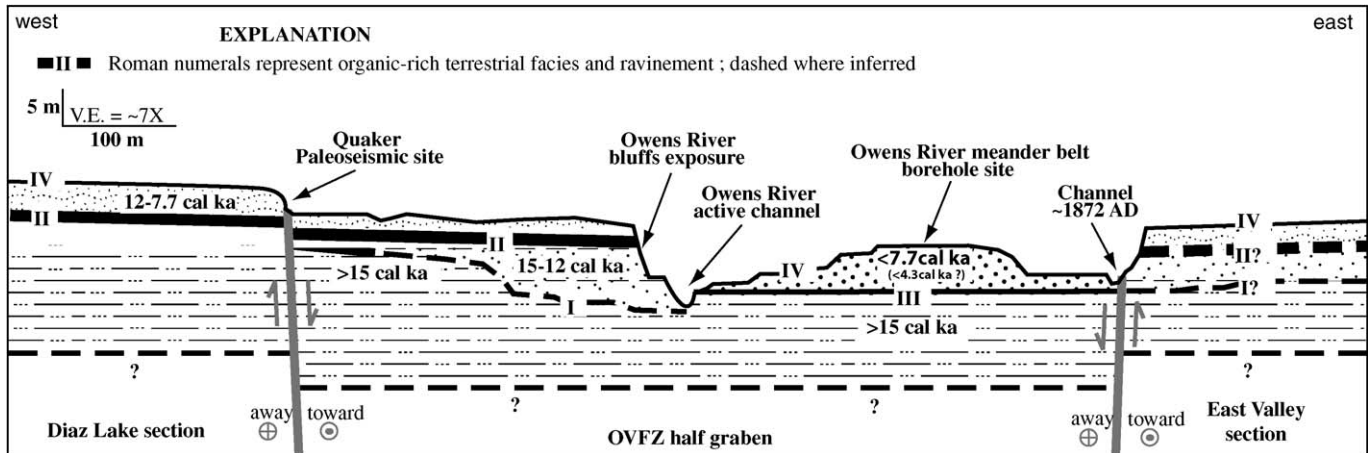


Fig. 7. Schematic geologic cross-section along a composite east–west transect across the Quaker paleoseismic site, the Owens River bluffs exposure, the Owens River meander belt borehole site, and the eastern margin of the meander belt. The schematic cross-section shows prominent cut-and-fill relations within fluvio-deltaic and lacustrine valley fill sediments along with the structural orientation of the Owens Valley fault zone half-graben. The faults of the half-graben are the Diaz Lake section (main trace) and the East Valley section of Bryant (1988). Roman numerals denote at least four spatially continuous ravinements within this part of Owens Valley near Lone Pine. The different ravinements are related to base-level changes associated with latest Quaternary Owens Lake water levels. The age of ravinements I and II are constrained by the age of strata exposed at the Quaker paleoseismic and Owens River bluffs exposure sites. The age of ravinement III is correlated, based on cut-and-fill relations at the Owens River borehole site and sediment core data. Ravinement IV is the active ravinement surface near Lone Pine (view looking north, up valley).

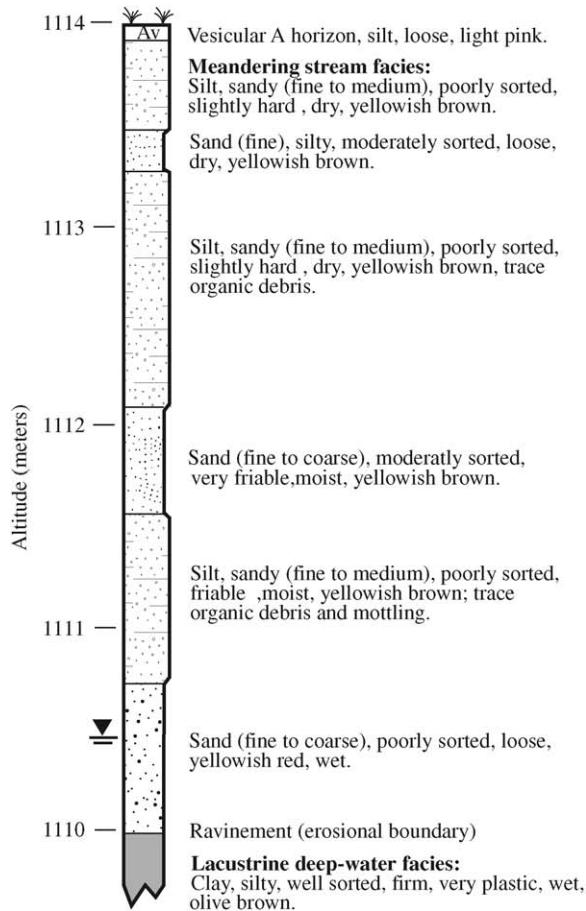


Fig. 8. Stratigraphic column and photograph of the borehole site within the Owens River meander belt (ORMB) north of Lone Pine. Column shows three sequences of normally graded sands and silts representing deposition in a meandering stream environment that overly an erosional boundary (ravinement III on Fig. 7) cut into lacustrine deep-water clay and silt. Photograph of the low gradient meander belt of the Owens River and hand-auger. View to the south, down Owens Valley towards Owens Lake playa.

Owens River and construction of a prominent beach ridge and wave-cut notches in Owens Lake basin during a time of relatively wetter conditions when compared to the earlier period between ~6520 and 4410 cal yr BP (Fig. 3).

A regression after aggradation of the Owens River is implied by ~10 m of incision within the meander belt between the Alabama Gates paleoseismic site and Owens Lake (playa) (Fig. 2). The late Holocene incision formed a sequence of cut terraces into post 4300 cal yr BP fluvial sediments and exposed a lacustrine and fluvio-deltaic stratigraphic section along the margins of the meander belt that dates back to older than ~12,500 cal yr BP (Fig. 7).

Besides incision near Lone Pine, a drop in lake level is indicated by the lowest suite of prominent beach ridges and wave-cut notches that encompass Owens Lake (playa) at an altitude of 1096–1100 m (Fig. 2). These shoreline features are inferred to have formed <7000(?) yr ago to ~1872 AD (Beanland and Clark, 1994; Strandline F). A native American artifact from one of the higher beach ridges at ~1100 m is estimated to be a few thousand years old, which provides a poorly constrained minimum age for the feature (Beanland and Clark, 1994) (Table 3 and Figs. 2 and 3). Between 1000 and 730 yr BP, sediment cores provide evidence for highly saline and alkaline lake conditions that imply relatively low lake levels during an effectively dry climate corresponding to the Medieval Climatic Anomaly (a warm period in northern Europe) that was followed by relatively wet climate and higher lake levels from 730 to 670 yr BP (Li et al., 2000) (Table 3 and Fig. 3). The period between 670 and ~135 yr BP (1872 AD) is characterized as fluctuating with lake depths that range from <10 m to the historical maximum of 14.9 m with a lake level at 1096 m (Li et al., 2000) (Fig. 3). Around 1921 AD, Owens Lake first began depositing salts onto the lake floor when the lake surface was at an altitude of ~1086 m because of source water diversions that began nearly eight years prior. By 1931 AD, Owens Lake had desiccated and become a playa (Smith et al., 1997).

2.6. Response of the Owens River to latest Quaternary lake-level changes

During the latest Quaternary, dramatic shifts in climatic conditions initiated base-level changes of the Owens River that responded by creating a sequence of cut-and-fill terraces down the axis of Owens Valley near Lone Pine (Fig. 7). Within the ORMB, vertical bluffs oriented nearly north-south through the ~1116 m playa surface expose ~10 m thick section of latest Pleistocene to early Holocene fluvio-deltaic and lacustrine sediments adjacent to the modern channel of the river. Middle to late Holocene fluvial sediments are inset to the older strata exposed along the bluffs within the meander belt. The Diaz Lake (main trace) and East Valley sections of the Owens Valley fault zone half graben, largely control the distribution of latest

Quaternary sediments north of Lone Pine (Bacon, 2003) (Fig. 7).

There are at least four spatially continuous ravinements within this part of Owens Valley that formed during periods of subaerial exposure (Fig. 7). Ravinement I represents a brief period of marsh or mud flat (playa) conditions at an altitude of ~1112 m around ~14,800 cal yr BP that was followed by a sequence of cut-and-fill (Figs. 3 and 7). Ravinement II signifies a period of marsh conditions from ~12,600 to 10,000 cal yr BP above an altitude of ~1112 m during a major regression of pluvial Owens Lake (Figs. 3 and 7). Shoreline and nearshore sediments associated with an early Holocene highstand at 7860–7650 cal yr BP overlie ravinement II. A significant regression after 7860–7650 cal yr BP, likely from ~6520 to 4410 cal yr BP, formed ravinement III that was followed by aggradation of the river at ~4300 cal yr BP (Figs. 3 and 6). The latest incision within the meander belt is related to an overall regression of latest Holocene and historic Owens Lakes, which is inferred to have occurred after ~3000 cal yr BP and is the active ravinement surface IV in the valley (Fig. 7).

3. Synthesis of the Owens Lake level curve

3.1. Last Glacial Maximum

During the interval 30,500–15,000 yr BP, the Sierra Nevada had the most intense and prolonged glacial advance in the last 79,000 yr (Bischoff and Cummins, 2001). At this time, pluvial Owens Lake attained a lake level of ~1155–1160 m as recently as ~20,600 cal yr BP. The lake level lowered ~13 m to the Owens Lake basin sill altitude of ~1145 m in ~11,000 to 7700 yr, which was characterized by relatively stable overflowing lake levels that were punctuated by oscillating lower ones. The sill altitude probably lowered to its present altitude by a combination of erosion by overflow and uplift associated with local faults and volcanism within the Coso Range. Packrat midden records at Haystack near Lone Pine record the departure of trees and shrubs, such as Joshua tree (*Yucca brevifolia*) and bitterbrush (*Purshia tridentata*) and the first occurrence of cliffrose (*Purshia glandulosa*) between ~23,300 and 20,600 cal yr BP, suggesting a decrease in temperature, but the disappearance of bitterbrush supports a slight decrease in effective moisture (Koehler and Anderson, 1995). Packrat middens in the Alabama Hills near Lone Pine record Pinyon-Juniper woodland to about 21,000 cal yr BP and Rocky Mountain Juniper to about 19,100 cal yr BP when woodlands were succeeded by sage brush (Koehler and Anderson, 1994). The succession of sage brush in the valley after ~19,100 cal yr BP is a time when pluvial Owens Lake apparently began a regression (Fig. 3). During this interval, pluvial Searles Lake, the next consecutive basin downstream of Owens Lake basin, as well as Lake Russell located upstream in Mono Lake basin (Fig. 1), record less-effective moisture between ~25,500

and 22,300 cal yr BP when intermediate to low levels are documented (Benson et al., 1990). Similar to both of these lakes, pluvial Owens Lake records a drop in lake level between ~25,000 and 24,000 cal yr BP (Fig. 3).

Pluvial Owens Lake subsequently transgressed, and last overflowed sometime before ~15,300 cal yr BP (Orme and Orme, 1993) (Fig. 3). Pollen records in cores indicate that climate became fairly warm and dry after this time compared to the earlier period when the lake was at moderate levels or overflowing (Mensing, 2001). The lake ceased to overflow because of a decrease in discharge from the Owens River caused by a decrease in effective moisture and increase in evaporation (Koehler and Anderson, 1994, 1995) (Fig. 1). Around this time, pluvial Searles Lake had low lake levels that were 180 m below its sill between ~16,800 and 14,400 cal yr BP that imply relatively little or no overflow from pluvial Owens Lake (Smith and Street-Perrott, 1983; Lin et al., 1998).

3.2. Post-Last Glacial Maximum Owens Lake and Sierra Nevada glacial records

The water-level record of pluvial Owens Lake appears to be in phase with the end of the Tioga glaciation (oxygen isotope stage 2) in the Sierra Nevada. Stratigraphic core data from Grass Lake Bog near Luther Pass in the central Sierra Nevada records the initial retreat of a Tioga glacier at 20,540–20,080 cal yr BP (Clark et al., 2003). Lake sediment cores from near Tioga Pass in the central Sierra Nevada indicate Tioga deglaciation was completed by ~15,500 cal yr BP (Clark et al., 2003) (Fig. 3). The same cores, from Greenstone Lake, preserve the entire section of outwash sediment related to the Recess Peak advance and retreat, which occurred between ~14,200 and 13,100 cal yr BP (Clark and Gillespie, 1997).

The timing of the deglaciation by ~15,500 cal yr BP roughly coincides with low lake levels prior to ~16,000 cal yr BP (Fig. 3). It appears that shoreline and core data record the Recess Peak advance dated between ~14,200 and 13,100 cal yr BP in the form of one significant oscillation centered at 13,420–13,200 cal yr BP that reached an altitude of ~1123 m (Fig. 3). Although it appears that pluvial Owens Lake likely overflowed for the last time around ~15,300 cal yr BP, the timing of the deglaciation roughly coincides with the end of overflow and the start of a major regression and low lake levels ending at ~11,000 cal yr BP. Based on TIC and $\delta^{18}\text{O}$ records from cores, the Pleistocene–Holocene transition (11,600–10,000 cal yr BP) was characterized by a drying trend that was interrupted by a brief (200 yr) wet oscillation centered at 10,300 cal yr BP (Benson et al., 2002). Furthermore, it is not clear if Holocene alpine glacier advances are synchronous with water-level changes since ~11,000 cal yr BP. The absence of till between Recess Peak moraines and the 200–300 year old Matthes (Little Ice Age) moraines, as well as the lack of evidence of outwash between 13,100 and 3400 cal yr BP, indicates that no significant glacial advances

occurred in the Sierra Nevada during that time, including the Younger Dryas interval (Clark and Gillespie, 1997). These new investigations have refined earlier studies of the Holocene glacial record that were based on soils, weathering characteristics, and limited ^{14}C dates (e.g., Burke and Birkeland, 1983).

3.3. Holocene lake-level record

Pluvial Owens Lake began a ~4000 yr long transgression at the Holocene–Pleistocene transition that culminated with a highstand at 7860–7650 cal yr BP, suggesting that the Sierra Nevada was relatively wet (Fig. 3). During this period, at ~8000 cal yr BP, the Owens River west of Bishop formed a fill-and-cut terrace above the flood plain of the river (Pinter et al., 1994). The age of this fill-and-cut terrace is similar to the age of alluvial fans that were deposited near Lone Pine Creek and along the Alabama Hills ~8000 yr ago (Bierman et al., 1995) (Figs. 1 and 2). These relations indicate that regional conditions were relatively wet between 11,000 and 7860–7650 cal yr BP compared to the earlier period when lake levels were lower than 1100 m between ~12,600 and 11,000 cal yr BP (Fig. 3). Core data (TIC and $\delta^{18}\text{O}$ records) lend further support to the interpretation of a wet early Holocene by showing that wet conditions prevailed from 10,000 to 7700 cal yr BP (Benson et al., 2002). We note that the well-documented 8200 cal yr BP cold event identified in climate proxy data sets throughout the circum-North Atlantic region and elsewhere occurs within this interval (e.g., Alley et al., 1997; Dean et al., 2002).

Based on Owens Lake cores and surface data, between 7860–7650 and 4300 cal yr BP drought conditions dominated in Owens Lake basin with the beginning of a major regression that coincides with the beginning of a widely recognized mid-Holocene “altithermal” event (Benson et al., 1997, 2002; Smith et al., 1997) (Fig. 3). An unusual ostracode assemblage in sediment cores existed in the lake from ~8300 to 6800 cal yr BP that was dominated by *Limnocythere sappaensis* with moderate occurrences of *Limnocythere ceriotuberosa* and rare occurrences of *Candona caudate* (Forester, 2000). This mixed assemblage indicates strong seasonal variability with low flow from the Owens River, but the occurrences of *C. caudate* and *L. ceriotuberosa* imply that there were wet decades and perhaps centuries during this period, when seasonal flow in the river was greater (Forester, 2000).

The early Holocene highstand at 7860–7650 cal yr BP is centered between times characterized by mixed ostracode assemblages. We infer that higher seasonal flows likely occurred at the beginning of the period coinciding with the 7860–7650 cal yr BP highstand. The last ostracode assemblage in the cores existed from ~4500 to 3800 cal yr BP and is represented by only abundant *L. sappaensis* (Forester, 2000). This ostracode, as described above, is indicative of a very saline lake, and after ~3500 cal yr BP brine and ephemeral lakes were common (Forester, 2000). Around

this time, Owens Lake apparently expanded between ~3800 and 3000 cal yr BP indicated by TIC and $\delta^{18}\text{O}$ records (Benson et al., 2002). The expansion of Owens Lake at this time is supported by the occurrence of 100 m lowering of tree line in the White Mountains between 4100 and 3500 cal yr BP, implying a 1 °C decrease in warm-season temperatures (LaMarche, 1973). Within this interval, cored lake sediments within the southern Sierra Nevada below rock glaciers (Konrad and Clark, 1998) and the Palisades Glacier (Bowerman and Clark, 2005) indicate the beginning of a Neoglacial advance at ~3500 cal yr BP. The late Holocene ostracode record apparently does not preserve a time of wetter or cooler conditions after ~4300 cal yr BP, whereas stratigraphic, geomorphic, geochemical, and dendrologic evidence apparently does (Fig. 3).

3.4. Latest Quaternary pluvial Owens Lake and regional climate records

The timing of significant oscillations of pluvial Owens Lake from ~15,000 cal yr BP to present is similar to the trend of pollen records in North America, which demonstrate wide evidence of 1500 yr climate variability during the past 14,000 yr (Viau et al., 2002). This terrestrial pollen record is supported by marine and ice-core records from the North Atlantic that contain evidence of millennial-scale climate oscillation that are independent of glacial–interglacial cycles (Viau et al., 2002). In addition, the abrupt, and high frequency lake-level oscillation between 12,900 and 11,600 cal yr BP, indicated in the Owens Lake core record, may correlate with the Younger Dryas interval (Benson et al., 1996, 1997; Mensing, 2001), which also appears apparent in the geomorphic record (Fig. 3). In southern Nevada, the formation of organic-rich layers (black mats) associated with spring discharge occurred from ~14,300 to 7200 cal yr BP (Quade et al., 1998), which is during a time of fluctuating lake levels and the early Holocene transgression of Owens Lake (Fig. 3). The formation of most black mats in southern Nevada date at ~11,600 cal yr BP, which suggests a link to Younger Dryas cooling at the end of the interval (Quade et al., 1998). An indication of relatively wetter conditions at Owens Lake around the end of the Younger Dryas interval is from an increase in lake level to an altitude of ~1100 m (Fig. 3).

Within the dating uncertainties, the six high frequency lake-level oscillations between ~18,000 and 11,000 cal yr BP shown in the lake-level record of pluvial Owens Lake appear to be roughly synchronous with variations in climatic conditions described in the North Atlantic region as Dansgaard–Oeschger oscillations, Heinrich Events, and Bond Cycles (Benson et al., 1996, 1997). Based on a comparison of climatic data sets from Owens Lake and Mono basins, dry events in western North America occur at approximately the same time as cold events in Greenland ice, with shifts between the climate regimes occurring within a few hundred years (e.g., Benson et al., 1996, 1997,

1998). Detailed lake records in the northwestern Great Basin substantiate the relation between high lake levels in western North America during warm North Atlantic climatic phases and low lake levels during cold ones (Zic et al., 2002).

4. Conclusions

Following a regression from its latest Pleistocene highstands at altitudes of ~1160 and 1145 m between ~27,000 and 15,300 cal yr BP, respectively, pluvial Owens Lake dropped ~45 m around ~11,400 cal yr BP (Lubetkin and Clark, 1988; Orme and Orme, 1993, 2000). The results from this work indicate that at least 10 significant latest Quaternary lake-level oscillations are distinguished from both near-surface stratigraphic and geomorphic data and sub-surface core data sets. Between 18,000 and 11,000 cal yr BP, the duration of six ~1000–2000 yr high frequency lake-level oscillations are consistent with the magnitude and duration of climatically driven events recognized in the North Atlantic region (e.g., Benson et al., 1996, 1997). At the last glacial termination, a lowstand at ~11,200 cal yr BP was followed by a fluctuating transgression that attained an early Holocene highstand near 1135 m, which was short lived before dropping to form shoreline features at 1120 m around 7860–7650 cal yr BP. The altitude and age of this early Holocene highstand was previously unrecognized and is chronologically well constrained. The occurrence of the early Holocene highstand from surface data is also present in the core record, where Benson et al. (2002) concluded that relatively wet conditions prevailed prior to and during the time of this highstand. Soon after the construction of the ~1120 m shoreline features, the lake lowered ~30 m to near desiccation lake levels between ~6500 and 4400 cal yr BP (Benson et al., 1997, 2002; Smith et al., 1997). Fluvial cut-and-fill relations at the ORMB north of Lone Pine and shoreline features that surround Owens Lake basin at ~1108 m indicate a minor lake-level oscillation after 4300 cal yr BP. This lake oscillation was followed by alkaline conditions with fluctuating and shallow lake-levels during the latest Holocene (Li et al., 2000).

The new latest Quaternary lake-level record of pluvial Owens Lake documents high frequency changes in the water balance of the Owens Lake system that have not yet been recognized in other pluvial lake basins in the western United States. The magnitude of these lake level oscillations can only be documented through field studies of deposits and landforms that actually constrain the altitude of lake levels, information that is unavailable through sediment core studies alone.

Acknowledgments

Journal reviews by Ken Adams and Doug Clark significantly improved the manuscript. We thank Jim Bischoff and Ken Adams for thoughtful and constructive reviews on an early version of the manuscript. We also

thank Andrei Sarna-Wojcicki for tephra identification and correlation, and Jack McGeehin for radiocarbon analysis. David Rhode graciously assisted with identification of plant remains in ^{14}C samples. We acknowledge Richard Forester for identification of ostracodes and William Miller III for identification of mollusks. We also thank Robert Negrini for sampling for paleomagnetism in fault trenches, which later proved to be sedimentologically unfavorable for laboratory analysis. We acknowledge the City of Los Angeles Department of Water and Power for permission to access their property and the California Department of Transportation for providing trench excavations at the Alabama Gates paleoseismic site. The University of California, White Mountain Research Station provided travel funding to S. Bacon (WMRS, Travel Mini-grants 1999–2001). Research was supported by the US Geological Survey's National Earthquake Hazards Reduction program under Awards #01-HQ-GR-0013 and #02-HQ-GR-0003. The views and conclusions contained in this report are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the US Government.

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