A 25,000-year record of earthquakes on the Owens Valley fault near Lone Pine, California: Implications for recurrence intervals, slip rates, and segmentation models

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ABSTRACT

Seven trenches in eastern California across the Owens Valley fault near Lone Pine expose two episodes of faulting since early Holocene time in the form of ~1 m throw in lacustrine beds with liquefaction that were buried and then faulted again ~1 m by the M 7.5 to 7.75 A.D. 1872 Owens Valley earthquake. Geomorphic maps, applications of sequence stratigraphy, and analyses of radiocarbon from charcoal and tufa deposits indicate that the paleoearthquake, the penultimate event here, occurred between 10,200 ± 200 and 8800 ± 200 cal yr B.P. The cumulative vertical displacement from these last two earthquakes in three trenches averages 2.4 ± 0.3 m (2σ), and the penultimate event has slightly larger displacements. A synthesis of available data indicates that the antepenultimate event was probably as large and occurred between ca. 24,000 and 14,000 cal yr B.P. (2σ). Thus, the two interseismic intervals between the last three surface-faulting earthquakes on the southern Owens Valley fault are each ~10,000 yr. This ~25,000-year record indicates that the “two-event” normal-oblique slip rate on the Owens Valley fault near Lone Pine is 1.0 ± 0.5 m/k.y. This result is similar to that of several previous geological studies here, yet it is still slower than slip rates on the northern Owens Valley fault and several factors slower than contemporary geodetic measurements. This study attempts to account for different dating methods and interpretational uncertainties, to acknowledge how little is known about the slip history of the Owens Valley fault and adjacent faults, and to consider the role of segmentation, as well as splay and distributed faulting, in comparisons of displacement data among different sites along the entire ~100 ± 10 km length of the Owens Valley fault.

Keywords: Owens Valley fault, paleoseismology, recurrence interval, slip rate, segmentation.

INTRODUCTION

The largest historic earthquake in the Basin and Range Province occurred on the Owens Valley fault located east of the Sierra Nevada in east-central California (Fig. 1). The Owens Valley fault generated a M 7.5 to 7.75 earthquake on 26 March A.D. 1872 that is considered the third largest magnitude historic earthquake in the conterminous United States (Ellsworth, 1990; Beanland and Clark, 1994). This historic rupture had normal-oblique displacements, on average 6.0 ± 2.0 m of dextral offset with 1.0 ± 0.5 m of normal slip, mainly east-side-down, a minimum surface rupture length of 110 km (Beanland and Clark, 1994), and a maximum length of 120 km (Slemmons, 1995). One can trace the rupture relatively easily with aerial photographs; however, composite fault scarp and geomorphic evidence of recurrent offsets are neither common nor very impressive in comparison to other faults of similar length and setting.

Geologic slip rates for the Owens Valley fault vary from site to site with values from ~1 to 4 m/k.y. (Lubetkin and Clark, 1988; Beanland and Clark, 1994; Zehfuss et al., 2001; Lee et al., 2001a; Rogers, 2006). In contrast, contemporary ground- and space-based geodetic models across the region place ~2–8.5 mm/yr on the Owens Valley fault, ~2–3 times greater than geologic slip rates (Savage and Lisowski, 1995; Thatcher et al., 1999; Dixon et al., 1995, 2000, 2003; Gan et al., 2000; Miller et al., 2001). Some models have examined how strain is partitioned and distributed on the Owens Valley fault and nearby fault zones (Wesnousky and Jones, 1994), and others have attempted to reconcile the differences between geodetic measurements and geologic rates (Dixon et al., 2003). However, geologic slip rates are not well known for most faults in Owens Valley, especially for different sites along strike, and continued mapping and new fault studies are still adding to the sparse database.

This paper reports the results of detailed geomorphic and geologic slip studies on the southern Owens Valley fault and attempts to integrate this data with previous results into improved models for fault slip rate, recurrence, possible segmentation, and distributed ruptures. We map the latest Quaternary stratigraphy, geomorphology, and fault structure from surface and subsurface exposures in seven exploratory fault trenches and in four deep stratigraphic pits near Lone Pine, California. Detailed stratigraphic and geomorphic analyses of deformed deposits and landforms reveal key structural and stratigraphic relations, in addition to datable materials that allow us to establish the age of the most recent paleoearthquake and thus the length of the most recent interseismic interval on the Owens Valley fault near Lone Pine. We integrate our results with paleoseismological data from earlier investigations in an attempt to refine geologic slip rates, estimate better recurrence intervals, and speculate on segmentation and geodetic modeling for the Owens Valley fault zone and region.

Neotectonic Setting of Owens Valley

The Owens Valley fault is one of several north- to northwest-striking principal right-lateral faults that collectively accommodate 12 ± 2 mm/yr (~25%) of dextral shear inboard of the San Andreas plate boundary along the east side of the Sierra Nevada microplate, north of the Garlock fault (Argus and Gordon, 1991) and as such may be representative of the regional slip rate for this region of the western United States.
Figure 1. (A) Map of major Quaternary faults in the northern Eastern California shear zone and southern and central Walker Lane, as well as the locations of the Owens Valley fault. Faults are modified from Reheis and Dixon (1996) and Wesnousky (2005). Faults (F) and fault zones (FZ): AHF—Anchorite Hills; HVF—Hunton Valley; RF—Rattlesnake; EF—Excelsior; CF—Candelaria; CFS—Coadale; MLF—Mono Lake; SLF—Silver Lake; HSF—Hartley Springs; HCF—Hilton Creek; RVF—Round Valley; IF—Independence; SNFF—Sierra Nevada frontal—WMFZ—White Mountain; OVFZ—Owens Valley; IMF—Inyo Mountains; S IMF—southern Inyo Mountains; DSF—Deep Springs; EVF—Eureka Valley; SV-HMFZ—Saline Valley–Hunter Mountain; EMF—Emigrant; PVFZ—Panamint Valley; FLVFZ—Fish Lake Valley; NDVFZ—northern Death Valley; FCFZ—Furnace Creek; BMFZ—Black Mountain; LLFZ—Little Lake; AFZ; Argus; BWFZ—Black Water. (B) Generalized fault and geology map of south-central Owens Valley, showing the A.D. 1872 Owens Valley fault rupture and major fault zones in the valley (modified from Hollett et al. [1991] and Beanland and Clark [1994]). Abbreviations: OVFZ—Owens Valley fault zone from Vittori et al. (1993) and Beanland and Clark (1994); White Mountain fault zone (WMFZ), Sierra Nevada Frontal faults (SNFF), and northern and southern Inyo Mountains fault (N. and S. IMFZ) from Bacon et al. (2005), Centennial Flat fault (CCF) from A.S. Jayko (2006, personal commun.); Red Ridge fault (RRF) from Vittori et al. (1993); PH—Poverty Hills; CM—Crater Mountain.
(Fig. 1A). This broad, regional zone of overall dextral shear along the western edge of the Lassen Volcanic National Park and the extensional Basin and Range Province has been referred to as the northern Eastern California shear zone or southern Walker Lane (e.g., Dokka and Travis, 1990; Wesnousky, 2005). The Owens Valley fault strikes subparallel to principal regional faults to the east, including sections of the Panamint Valley, Death Valley, and Fish Lake Valley fault zones. The strikes of these normal-oblique faults are ~20° to 30° northward (clockwise) of the northwest extensional Basin and Range Province has been offset landforms along the trace of the A.D. 1872 earthquake rupture, which have an average ratio of horizontal to vertical slip of 6:1, east-side-down (Beanland and Clark, 1994).

The physiography of Owens Valley is made up of a well-developed graben formed by several discontinuous range-bounding fault zones, which include the Independence and Sierra Nevada frontal normal faults to the west and the oblique-dextral White and Inyo Mountains faults to the east, and the graben is split obliquely down the axis of the valley by the Owens Valley fault (Figs. 1 and 2A). The floor of Owens Valley slopes continuously from north to south, dropping the Owens River ~200 m in elevation over a distance of more than 100 km to ultimately

Figure 2. (A) Shaded relief map of southern Owens Valley showing fault zones and the ages of the most recent prominent highstands and recessionary shorelines of Owens Lake during the latest Quaternary (modified from Bacon et al., 2006). (B) Map of the field area and locations of paleoseismic study sites in relation to the A.D. 1872 Owens Valley earthquake fault trace near Lone Pine. Study sites are located on the Alabama Hills (AHS), Diaz Lake (DLS), and Manzanar (MZS) sections of the Owens Valley fault zone mapped by Bryant (1988) and Beanland and Clark (1994) from 1:12,000 aerial photographs.
drain into Owens Lake, which periodically overflowed its sill during times of high Owens River discharge in the latest Pleistocene or had high lake levels as recently as the early Holocene and low levels during the late Holocene (Bacon et al., 2006). Thus, the floor of Owens Valley has been buried with lacustrine, fluvial, alluvial, and eolian sediments, and the position of the Owens River is commonly controlled by the location of shorelines and fault scarps that have formed in the late Quaternary valley fill.

In map view, the entire ~100 ± 10 km length of the Owens Valley fault can be divided into three general segments on the basis of largerscale geometry and continuity (dePolo et al., 1991) (Fig. 1B). These three general segments can be further separated into seven sections based on continuity, strike, and splaying complexity (Beanland and Clark, 1994). Collectively, the segments correspond variously to the positions of pre-Cenozoic basement rocks, late Quaternary volcanic fields near Big Pine, and the Owens Lake basin (Fig. 1B). The Owens Valley fault strikes obliquely across the valley floor and has a relatively straight central segment that is roughly parallel to the strike of nearby range-bounding normal faults.

Models of stress conditions within Owens Valley have maximum and intermediate axes of nearly equal magnitudes that alternate during various seismic cycles or are partitioned between vertical and horizontal orientations, thus allowing, in theory, the coexistence of decoupled normal and lateral slip along parallel regional fault segments. The straight central segment of the Owens Valley fault at the latitude of Independence is locally less than 4 km west of the base of the Sierra Nevada range front (Figs. 1B and 2A). The paleoearthquake chronology for the central segment of the Owens Valley fault and for most of the Sierra Nevada frontal faults is poorly known. Jennings (1994) showed Holocene displacement for 12 km along the Independence fault at the latitude near Independence and discontinuous Holocene activity farther north near Big Pine, where recent mapping and cosmogenic

\(^{10}\)Be surface-exposure dating of boulders indicate surface ruptures younger than 4.1 ± 1.1 ka (Le et al., 2007). Late Pleistocene to Holocene normal-slip rates for the Sierra Nevada frontal faults vary from 0.1 to 0.3 m/kyr and appear to decrease in a northward progression from near Owens Lake basin to Bishop (Gillespie, 1982; Clark et al., 1984; Le et al., 2007).

Much of the valley floor and alluvial fans flank the east side of Owens Valley near the base of the Inyo Mountains range front. Devoid of Quaternary faults, but aeromagnetic and gravity surveys provide geophysical evidence for range-front faulting of Cenozoic deposits since ca. 5 Ma (Pakiser et al., 1964) and as recently as ca. 750 ka on mapping near Mazourka Canyon (Berman, 1999) (Figs. 1B and 2A). The lack of young scarps along the base of the Inyo Mountains may be because the fault is inactive, or the scarps are older than those on the Owens Valley fault and buried, or they are generally contemporary with the Owens Valley fault but have been eroded by fluctuating pluvial Owens Lake water levels in the latest Pleistocene and early Holocene, then followed by meandering and channeling from the Owens River until historical times (Bacon et al., 2005). The buried faults along the Inyo Mountains range front may have long recurrence intervals and might contribute to the overall late Quaternary slip budget within Owens Valley.

The southern segment of the Owens Valley fault in southern Owens Valley is the longest and most discontinuous of the three segments, and it had the largest vertical and lateral offsets during the A.D. 1872 earthquake near Lone Pine. Owens Lake is on the downthrown block east of the main Owens Valley fault trace, and it is located only a few kilometers east of the Sierra Nevada frontal fault (Figs. 1B and 2A). Recent mapping along the southern margin of Owens Lake basin has refined the trace of the A.D. 1872 surface rupture across Owens Lake playa and shorelines. Located on the north flank of the Coso Range, a previously unidentified fault named the Red Ridge fault also probably ruptured in A.D. 1872 (Whitney, 1872; Hobbs, 1910; Carver, 1970; Vittori et al., 1993) (Figs. 1B and 2A). Vittori et al. (1993) mapped scarps that they interpreted are ruptures from the A.D. 1872 earthquake, which lengthen the fault ruptures of Beanland and Clark (1994) by ~20 km to the south. However, no obvious through-going faults have yet to be identified that align with the Owens Valley fault near the Red Ridge fault or that are farther south within the northern Coso Range (Jayko, unpublished data, 2007).

A right-oblique fault zone along the northeast margin of Owens Lake basin near Keeler offsets well-developed drainages of a relict early Pliocene alluvial fan complex and forms shutter ridges and northeast-facing scarps that indicate long-term activity since ca. 4.3 Ma (Stone et al., 2004). This fault zone is referred to as the southern Inyo Mountains fault and exhibits latest Quaternary compound fault scarps that accommodate oblique-dextral displacement from two surface rupture events since ca. 13,000 cal yr B.P. and a single-event dextral offset of ~2.2 ± 0.8 m of a fan channel, which results in an oblique slip rate of 0.1–0.3 m/kyr (Bacon et al., 2005) (Figs. 1B and 2A). The mapped length of latest Quaternary faulting is at least 12 km, yet the zone is located rather high in the range front, nor are there many younger deposits that record subsequent faulting. Given the northwesterly strike, northeast dip, and location on the margin of Owens Lake basin, the southern Inyo Mountains fault is likely an independent seismogenic source that accommodates dextral shear in southeastern Owens Valley and is not a splay of the Owens Valley fault such as the Lone Pine fault near Lone Pine or Fish Springs fault near Big Pine. Another new late Quaternary fault mapped along the southeastern Owens Lake
basin is the Centennial Flat fault, which strikes northwest and parallel to the Owens Valley fault, is west-side-down, and projects northward into Owens Lake playa and southward into the Coso Range (A.S. Jayko, 2006, personal commun.) (Figs. 1B and 2A).

South of the A.D. 1872 fault rupture and Red Ridge fault, strongly folded Pliocene lacustrine sediments are exposed along zones of poorly developed faults that project southeastward from the southern Owens Lake basin into the Coso Range (Vittori et al., 1993). Regional fault maps and kinematic models indicate a structural connection across the Coso volcanic field between the southern Owens Valley fault and the Little Lake fault zone (Unruh et al., 2002; Monastero et al., 2005). Shear within the Coso Range and volcanic area appears to be distributed along a series of poorly integrated dextral and normal faults that form a releasing step-over in the area of the Coso geothermal field (Unruh et al., 2002; Monastero et al., 2005) (Fig. 1A). Further south, geodetic data indicate a locus of dextral shear along a narrow zone that can be traced from faults in the Mojave Desert, across the Garlock fault, and northward into the Little Lake fault zone (Savage et al., 1990; Sauber et al., 1994). Peltzer et al. (2001) used interferometric maps to show a dextral shear rate of $7 \pm 3$ mm/yr in a relatively narrow zone between the northern end of the A.D. 1992 Landers surface rupture and the southern end of the A.D. 1872 Owens Valley surface trace. This deformation is a strain transient from the Landers event (Peltzer et al., 2001) in part because the zone is not marked by a fault and the shear rate is much faster than the sum of geologic slip rates across all of the mapped Quaternary faults in the area.

Geologic versus Geodetic Slip Rates and Interseismic Intervals

Geodetic and kinematic models of faulting indicate that the Owens Valley region accommodates a significant amount of regional dextral slip, yet geologic slip rates on the Owens Valley fault are much less than geodetic measurements across this region of numerous active faults (e.g., Dokka and Travis, 1990; Savage et al., 1990; Dixon et al., 1995, 2000, 2003; Miller et al., 2001; Reheis and Dixon, 1996). Remarkably accurate information is known about the overall motions across many fault zones from continental-scale geodetic measurements, but on any given fault, detailed paleoseismic studies to determine accurate slip rates are rare, especially considering how many local faults could contribute to the motions that geodetic methods measure in some areas. Many active faults in remote areas are obscured or buried and thus are not mapped well. For example, the ground-based trilateration networks of Savage and Lisowski (1995) spanned the southern Owens Valley fault from the 1970s to 1990s and measured dextral shear across Owens Valley into Owens Lake basin to a station as far southeast as Cerro Gordo Peak (Fig. 1B). Savage and Lisowski (1995) found that the strain field in the southern Owens Valley was broadly distributed, complicated, and between certain stations, more strain was accumulating than could be accounted for by slip rates on known active faults. Since then, additional active faults have been mapped in the network area in southern Owens Valley (Stone et al., 2004; Bacon et al., 2005).

For perspective, we note that in this region, the most modern geodetic data are from global positioning satellite (GPS), the results of which are only about a decade old (e.g., Dixon et al., 1995, 2003). Some of the earliest geodetic networks in Owens Valley were land-based trilateration installed only ~30 yr ago, or ~100 yr after the A.D. 1872 earthquake. Most of the geologic slip rates in the analysis presented here are based on the amount of cumulative fault offset of a landform or deposit of a certain age, which commonly includes the historic offset of the A.D. 1872 earthquake, now 135 yr old. The cumulative offset also commonly includes the surface displacements from one or more previous paleoearthquakes that are a few thousand years old to several tens to hundreds of thousands of years old. At any one site, the number of events and the extent to which they may have ruptured different fault segments along strike are usually unknown.

The seismic effects from recent earthquakes can often overprint the average strain accumulation of an interseismic cycle, thereby producing contemporary (30+ yr) deformation rates that significantly differ from both short- and long-term geologic strain rates (e.g., Wernicke et al., 2000). The discrepancy between geologic and geodetic slip rates may be explained by the release of coseismic strain during large earthquakes, when the average strain accumulation of a fault’s interseismic cycle becomes perturbed by postseismic strain relaxation (Wernicke et al., 2000; Malservisi et al., 2001; Dixon et al., 2003; Hammond and Thatcher, 2004). This may be the case for contemporary slip rates measured in Owens Valley as observed in the wake of the A.D. 1872 Owens Valley earthquake.

From the available data and our interpretations and analysis presented here, the youngest paleoearthquake on the Owens Valley fault occurred ~3000–4000 yr ago (Lee et al., 2001a), was limited to the northern segment near Big Pine, and likely was a distributed rupture concurrent with a late Holocene paleoearthquake on the White Mountains fault (dePolito et al., 1993). The next paleoearthquake back in time occurred ~9000–10,000 yr ago, and it likely ruptured the entire fault on the basis of similar amounts of vertical offset as the A.D. 1872 earthquake at several sites along strike near Lone Pine, based on the results of this study and of Lubetkin and Clark (1988) and Bierman et al. (1995). In this study, as well as previous paleoseismic studies, the Owens Valley fault slip rate at a given site is commonly based on the cumulative displacements from the A.D. 1872 earthquake and subsequent paleoearthquakes, and the number of earthquake displacements must equal the number of interseismic intervals or seismic cycles (Lubetkin and Clark, 1988; Beanland and Clark, 1994). Thus, we pay careful attention to the ages and amounts of displacement of paleoearthquakes from site to site, which are the basis for calculating earthquake recurrence and slip rates for the overall Owens Valley fault zone.

METHODS

To understand the stratigraphic and chronostratigraphic context of trench deposits, Bacon et al. (2006) mapped and dated the latest Pleistocene and Holocene fluvial-deltaic and lacustrine stratigraphy in the study area, and in particular, along ~1.5 km of the Owens River bluffs near Lone Pine. Bacon et al. (2006) developed a lake-level curve of pluvial Owens Lake that spans the interval of time from ca. 27,000 cal yr B.P. to the present, which temporally places the stratigraphy identified at paleoseismic sites in a regional context. This lake-level curve is based on the compilation of 45 radiocarbon ($^{14}$C) dates and one tephra correlation from an investigation of the lacustrine stratigraphy in Owens Lake basin, information from prior geomorphic and sediment core studies, as well as the chronological data presented in this study.

The stratigraphy along the cliffs and in fault trenches and pits was described using standard sedimentological techniques (e.g., Adams, 2007; Baucom and Riggsby, 1999; Einsele, 2000), and the interpretations and correlations of the fluvial-deltaic and lacustrine deposits are based on the fundamentals of sequence stratigraphy. Each sequence has specific lithofacies and facies associations that are classified according to grain size, sedimentary structure, biological components, and lateral and vertical stratigraphic position (Einsele, 2000). In the study area, the sequence stratigraphy is characterized by one or more transgressive and regressive lake cycles of pluvial Owens Lake and subsequent erosion and deposition from a meandering stream system.

In general, the sequence stratigraphy includes three facies associations that include the
following depositional environments: (1) the delta front, which represents areas of progradation or retrogradation into a lake where sediment is transported by distributary channels and deposited subaqueously at shallow depth, forming distal and distributary mouth bars within a fluvial-dominated deltaic system; (2) the delta plain, which represents terrestrial low-gradient sedimentation in playas and floodplains, consisting of distributary channels, marshes, and ponds, as well as the deposition of alluvial and eolian sediment; and (3) lacustrine sediment, which represents offshore, nearshore, and shore sedimentation within a lake system. Sequence boundaries (SB) are interpreted to separate specific facies associations or lithofacies boundaries that are defined and used in all exposures to determine the number of transgressive or regressive sequences or lake cycles. A given lake-level oscillation is recorded by a recognizable sedimentary sequence and, in places, an unconformity, both of which can be correlated in certain sections throughout the study area.

Twelve ¹⁴C dates by Beta Analytical Inc., Miami, Florida, and three tephra correlations analyzed by A.M. Sarna-Wojcicki, U.S. Geological Survey, Menlo Park, California (Table 1 and GSA Data Repository) were used to establish a lake age control of fault trench stratigraphy. Following depositional environments: (1) the delta front, which represents areas of progradation or retrogradation into a lake where sediment is transported by distributary channels and deposited subaqueously at shallow depth, forming distal and distributary mouth bars within a fluvial-dominated deltaic system; (2) the delta plain, which represents terrestrial low-gradient sedimentation in playas and floodplains, consisting of distributary channels, marshes, and ponds, as well as the deposition of alluvial and eolian sediment; and (3) lacustrine sediment, which represents offshore, nearshore, and shore sedimentation within a lake system. Sequence boundaries (SB) are interpreted to separate specific facies associations or lithofacies boundaries that are defined and used in all exposures to determine the number of transgressive or regressive sequences or lake cycles. A given lake-level oscillation is recorded by a recognizable sedimentary sequence and, in places, an unconformity, both of which can be correlated in certain sections throughout the study area.

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**Table 1: Radiometric and Accelerator Mass Spectrometry Radiocarbon Analytical Data for Paleoseismic Sites Near Lone Pine**

<table>
<thead>
<tr>
<th>Sample number and material dated</th>
<th>Sample location and stratigraphic unit</th>
<th>Radiocarbon date* (yr B.P. ± 1σ)</th>
<th>δC/σ</th>
<th>Calibrated age (cal yr B.P. ± 2σ)</th>
<th>Mean age ± 2σ</th>
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<tr>
<td>Beta-163554 (AMS-charcoal)</td>
<td>T2 (AMS-charcoal) lithofacies 4b</td>
<td>9060 ± 40 (22.9)</td>
<td>–10.260 –10.180</td>
<td>Mean age ± 2σ = 10,200 ± 200</td>
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<td>Beta-163555 (AMS-organic sediment)</td>
<td>T2 (AMS-organic sediment) lithofacies 4b</td>
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<td>–10.370 –9.920</td>
<td>Mean age ± 2σ = 10,200 ± 200</td>
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<td>Beta-163556 (AMS-organic sediment)</td>
<td>T4 (AMS-organic sediment) lithofacies 4b</td>
<td>9160 ± 50 (25.2)</td>
<td>–10.490 –10.230</td>
<td>Mean age ± 2σ = 10,200 ± 200</td>
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<tr>
<td>Beta-163557 (Radiometric-organic sediment)</td>
<td>T4 (Radiometric-organic sediment) lithofacies 4b</td>
<td>9680 ± 50 (25.1)</td>
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<td>Mean age ± 2σ = 10,200 ± 200</td>
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<td>Beta-163558 (AMS-charcoal)</td>
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<td>Beta-165600 (AMS-charcoal)</td>
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<td>–10.660 –10.280</td>
<td>Mean age ± 2σ = 10,200 ± 200</td>
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<td>Beta-163560 (Radiometric-tufa)</td>
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<td>12.790 –12.400</td>
<td>Mean age ± 2σ = 14,900 ± 400</td>
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<td>8980–8600</td>
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<td>7920–7620</td>
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<td>15.120 –14.400</td>
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<td>15.270 –14.750</td>
<td>Mean age ± 2σ = 14,900 ± 400</td>
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*Note: Radiometric and accelerator mass spectrometry (AMS) ages were provided by Beta Analytical Inc., Miami, Florida. friedly sea levels between ca. 6850 and 4300 cal yr B.P. The overall lake history is recessional, with the INTCAL04 data set (Reimer et al., 1993) using the CALIB v. 5.0.1 program (Stuiver and Reimer, 1993) to correct and/or modify the dates by Beta Analytical Inc., Miami, Florida.

**GEOLOGIC SETTING OF PALEOSEISMIC SITES**

**Latest Pleistocene and Holocene History of Pluvial Owens Lake**

The landscape and fault scarps in central and southern Owens Valley have been buried, eroded, or modified periodically during their evolution in the latest Pleistocene and Holocene by oscillations in elevation of the Owens Lake level. Bacon et al. (2005) noted that a transgression and consequent highstand in the early Holocene that reached an elevation near 1135 m, followed by ~15 m of downcutting at the sill (saddle separating basins), and the freshly exposed lake and delta plain deposits experienced fluvial-deltaic reworking and sedimentation. During the Pleistocene-Holocene transition at ca. 11,600 cal yr B.P., lake level lowered to ~1100 m, which is an elevation similar to the modern edge of Owens Lake playa. Based on sediment core data of Benison et al. (2002), pluvial Owens Lake expanded in the early Holocene, corresponding to wetter climatic conditions in the region. Bacon et al. (2006) showed a transgression and consequent highstand in the early Holocene that reached an elevation near 1135 m before dropping again to 1120 m at 7800 cal yr B.P. (Fig. 2A). The lake lowered another ~30 m to shallow and near desiccation levels between ca. 6850 and 4300 cal yr B.P. Fluvial cut-and-fills within the Owens River meander belt and well-preserved shoreline features at ~1108 m in Owens Lake basin were formed during a minor lake-level rise after ca. 4300 cal yr B.P., which was followed by recession to alkaline and shallow conditions.
during the latest Holocene (Bacon et al., 2006).

The upper sections of sediment exposed in almost all of the fault trenches and pits in the study area were deposited during this early Holocene transgression, and both paleoseismic sites have remained relatively free from Owens River erosion since ca. 6850 cal yr B.P.

Given that the lake level was moderately high during much of the latest Pleistocene and early Holocene, any paleoearthquake rup- tures during this period near Lone Pine were likely under water. Portions of the scarp may have formed under water and remained so for a considerable amount of time, a possible reason why recurrent offsets and composite scarps are difficult to find, especially as one goes lower in elevation and more southward into Owens Lake basin (Beanland and Clark, 1994). Similarly, the A.D. 1872 fault scarps that continue south beneath historical Owens Lake have recently been reworked and eroded by water (Carver, 1970). Also, as far north as Big Pine, the A.D. 1872 fault scarps have been enhanced, altered, or destroyed by river erosion, road construction, and agricultural activities. These factors highlight the usefulness of deep and numerous fault trenches accompanied by detailed stratigraphic and geomorphologic mapping.

Paleoseismic Study Sites near Lone Pine

Seven fault trenches and four stratigraphic pits were excavated across and adjacent to the Owens Valley fault at the Quaker and Alabama Gates paleoseismic sites (Fig. 2B). The Alabama Gates site is ~7 km north of Lone Pine, along the road cut of U.S. Highway 395, and it is equivalent to site 15 of Beanland and Clark (1994) within the Alabama Hills section of the Owens Valley fault of Bryant (1988). The Quaker paleoseismic site is located ~4 km north of Lone Pine and ~200 m west of U.S. Highway 395, and is also site 12 of Beanland and Clark (1994), along the Díaz Lake section of the Owens Valley fault of Bryant (1988). For reference, site 14 of Bryant (1988) and Beanland and Clark (1994) is located nearby halfway between the Alabama Gates and Quaker sites (Fig. 2B).

The Lone Pine paleoseismic site of Lubetkin and Clark (1988), Beanland and Clark (1994; their site 9), and Bierman et al. (1995) is located on the Lone Pine alluvial fan, ~1.2 km west of Lone Pine and ~3 km south of the Quaker site (Fig. 2B). These study sites collectively span ~7% of the total A.D. 1872 rupture length and share common fault sections.

Several relatively long topographic profiles were sampled across the scarp and trench sites and onto nearby shoreline features to establish elevation control, as well as to aid in accurate interpretations of the geomorphology and sequence stratigraphy at each of the paleoseismic sites of this study (GSA Data Repository, see footnote 1). For reference, the elevation that latest Pleistocene Owens Lake last overflowed its sill is at ~1145 m, south of Olancha (Smith and Street-Perrott, 1983) (Fig. 2A). The Lone Pine paleoseismic site is located at an elevation of ~1160 m, or ~15 m above the sill. From highest to lowest, site 14 (Bryant, 1988; Beanland and Clark, 1994) is located near 1140 m, only ~5 m below the sill. Our trenches at the Alabama Gates site are ~15–25 m below the sill, whereas the Quaker site is between 1114 and 1122 m, ~20–30 m below the sill. In A.D. 1872, the water level of Owens Lake was at an elevation of 1097 m (Gale, 1914), ~48 m below the sill, but only ~17–30 m below the trench sites. The lacustrine stratigraphy in the study area is relatively planar, flat-lying, continuous, and recognizable in exposures throughout the study area and from trench to trench; therefore, we have a high degree of confidence in most of our correlations between these sites. Thus, fault scarps at our sites, as well as others below the sill elevation, were exposed to more pluvial and fluvioglacial modification during the Holocene in contrast to those at the Lone Pine site, which is located ~15 m above the overflow sill level (Fig. 2A).

THE ALABAMA GATES PALEOSEISMIC SITE

Geomorphology at the Alabama Gates Site

Four long topographic profiles were surveyed across the scarp near the Alabama Gates site at the northeastern flank of the Alabama Hills (Figs. 2B, 3, and GSA Data Repository). The inset figure shows an example profile B–B’, which, like the other three, shows two to three changes in slope that are associated with shoreline features mapped in the area. We interpret the highest shoreline feature to be a wave-formed platform ranging from 1132 to 1134 m in elevation; a few meters higher, there is an associated wave-formed notch at 1135–1136 m that was reoccupied and modified by a ca. 7800 cal yr B.P. lake level (Bacon et al., 2006). A lower, more discontinuous, wave-formed notch is at an elevation of 1128 m, and the western meanders of the Owens River have created risers set against and into the base of the scarp at elevations near 1116 m (Fig. 3).

The composite scarp ranges from 4 to 10 m in height and commonly slopes 18° to 35° east (Beanland and Clark, 1994). In places, the scarps have been enhanced by erosion. Runoff originating from the Alabama Hills and ephemeral springs related to the fault zone have produced numerous sinuous channels that have incised into and across the scarp and shoreline features and even across the A.D. 1872 fault scarp, which is ~1 m in height and not obvious everywhere along strike (Fig. 3). Several sets of relatively deep sinuous channels north of the trench site appear as the expression of repeated fault offsets in combination with as much as 7 m of incision related to at least one, and likely multiple, base-level changes of Owens River and pluvial lake (Fig. 3). Some channels were likely deepened by humans for irrigation or drainage, whereas some channels were enhanced by floods and outbursts related to the dynamiting of the Los Angeles Aqueduct spillway at Alabama Gates (AGS, Fig. 3) by angry citizens of Owens Valley on 23 November A.D. 1924 and again in the spring of A.D. 1927 (Schumacher, 1962). Thus, fault scarps in the southern Owens Valley have a complicated geomorphic history inherited from fluvial incision and reworking, most importantly between 7800 and <4300 cal yr B.P. (Bacon et al., 2006).

Stratigraphy at the Alabama Gates Site

Three fault trenches (T1–T3) and one 2-m-deep stratigraphic pit (P1) were excavated within ~10–20 m of each another along the north-striking fault trace near Alabama Gates (Fig. 4 and GSA Data Repository). The trenches range from 5 to 7 m in length and from 2 to 2.5 m in depth and are oriented slightly oblique to the trend of the fault scarp in a road cut on the west side of northbound U.S. Highway 395 (Fig. 3). The upper portions of the scarp in T2 and T3 had been beveled to bury a highway drainpipe and to construct a road-cut bench. Exposures of the faulted stratigraphy as deep as ~5–7 m beneath the original surface could be observed using trenches only a few meters deep beneath the altered surface and only ~5–10 m from the shoulder of U.S. Highway 395.

Most of the sediments exposed in the Alabama Gates trenches are lacustrine. The oldest sediment is a stiff, green clayey silt that is only exposed in T2 and is mapped as lithofacies la or 1b (Fig. 4). Lithofacies la or 1b has a sharp upper erosional boundary, interpreted as an abrasion platform representing sequence boundary SB1. Lithofacies 1a or 1b is massive and fine grained and is interpreted to have been deposited in an offshore lacustrine environment. The abrasion platform exposed in T2 is overlain by lithofacies 7b, a massive, moderately sorted, well-rounded, and fine to coarse sand with minor amounts of fine pebbles of scoria, basalt, tuff, and pumice, which are lithologies commonly found from up-valley source areas.

Lithofacies 7b is exposed at the bottom of all three trenches (T1–T3; Fig. 4) and was
likely deposited in a shore (beach) depositional environment based on its sedimentologic characteristics and stratigraphic position above the abrasion platform in T2. Overlying lithofacies 7b with a conformable contact, there is a 10–40-cm-thick silty sand to sandy silt deposit that defines a fining-upward sequence placed in lithofacies 3b. The facies association is characteristic of a nearshore lacustrine depositional environment.

Overlying lithofacies 1a or 1b, 3b, and 7b are sediments deposited in a terrestrial and flat environment, including thinly interbedded (0.25–0.4 m) diatomaceous silts with a reworked tephra, organic-rich silts with detrital charcoal, and nonorganic silts and fine sands that are collectively mapped into lithofacies 4b in T3. Lithofacies 4b in T1 and T2 is relatively thicker and composed primarily of a fining-upward sequence of ~0.3 m of charcoaled plant fibers to 0.25–1.75-m-thick organic silts and fine sands (Fig. 4). In T2, the charcoaled plant debris was concentrated in a 30-cm-thick, silty organic peat layer, which was sampled for 

14C dating (Fig. 4). Sediment of lithofacies 4b was deposited in a marsh and/or spring terrestrial environment within the delta plain. A massive, 0.25–0.70-m-thick poorly sorted silty sand with trace fine pebbles unconformably overlies lithofacies 4b in T3; it possesses characteristics of alluvium and, specifically, a colluvial apron across a bluff, and it is mapped as lithofacies 9a (Fig. 4). Collectively, the contact between lithofacies 3b and 4b defines sequence boundary SB2. Sediments exposed along the road cut mapped as lithofacies 3b, 4b, and 9a in this study were also described by Beanland and Clark (1994) to represent a shore (beach) and back-bar depositional environment.

Overlying lithofacies 4b and 9a is a 0.1–0.5-m-thick sandy silt deposit that is similar in sedimentology to lithofacies 3b. This deposit is mapped as lithofacies 3c, and it exhibits a sharp lower contact with lithofacies 4b in T1 and T3 (Fig. 4). In addition, lithofacies 3c contains a relatively thin (0.1–0.2 m) sandy silt bed in the western portions of T1 and T3, which is truncated by faults and pinches out to the east in T1 (Fig. 4). Lithofacies 3c in T1 and T3 is overlain by another massive sandy silt deposit but differs because it contains 10%–15% angular fine to medium pebbles. The lower boundary of this deposit with lithofacies 3c is sharp, and it is interpreted to be an erosional contact, defining the sequence boundary SB3 (Fig. 4). This same deposit is also underlain by lithofacies 4b in T2 with an erosional contact that also defines sequence boundary SB3 (Fig. 4). Because this massive silt deposit contains angular pebbles with lithologies of the Alabama Hills, it is mapped as lithofacies 11. The depositional environment of lithofacies 11 is interpreted to have been nearshore and likely related to a regressive lake level, based on the occurrence of angular pebbles that are poorly sorted within a silty matrix and the erosional lower contact of sequence boundary SB3 with the underlying lithofacies 3c and 4b. The upper boundary of lithofacies 11 in all three trenches is sharp and related to excavation into the scarp to construct a road-cut bench; fill and disturbed sediment lie above this boundary.

Stratigraphy east of U.S. Highway 395 is significantly different from stratigraphy exposed in natural and trench exposures west of the highway. Exploratory pit P1 is located ~10 m east of T2 at an elevation of 1122.5 m (Fig. 3). Stratigraphy exposed in the pit includes 1.5 m of alternating fine sand and silt that is moderately sorted, moderately rounded, and soft to slightly

Figure 3. Annotated black-and-white low-sun-angle aerial photograph of the Alabama Gates paleoseismic site. Fault trenches (T1–T3), exploratory pit (P1), site 14 of Bryant (1988), and the Alabama Gates Spillway (AGS) are shown in relation to the A.D. 1872 Owens Valley fault rupture. Also shown is the Alabama Hills (Mz), middle to late Holocene alluvium derived from the Alabama Hills (Hal), early Holocene lacustrine shore and nearshore sediment (Hls), and middle to late Holocene sediment of the Owens River meander belt (Hf), as well as the location of the ~1120 m shoreline of pluvial Owens Lake (photo from Slemmons, 1968). Inset geomorphic profile along transect B-B’ shows the log of T1 in relation to U.S. Highway 395 and the projection of the Owens Valley fault at depth. Two wave-cut notches are evident on the profile at elevations ~1119 and 1134 m and a fluvial riser is evident at an elevation of ~1116 m. Reconstructed scarp profile is based on the unmodified portion of the scarp along transect A-A’ (see GSA Data Repository for transect locations [see text footnote 1]).
hard (GSA Data Repository, see footnote 1). This deposit is mapped as lithofacies 12 and has sedimentologic characteristics of a meandering stream similar to floodplain silts and fine sands of the delta plain. Lithofacies 12 is underlain by poorly to moderately sorted and subangular to well-rounded fine to coarse sand and fine gravel at the bottom ~40 cm of the pit. This deposit contains lithologically heterogeneous sediment derived from up-valley source areas, which consists of scoria, basalt, tuff, and pumice. The contact between this deposit with lithofacies 12 is wavy, with sandy discontinuous lenses over ~20 cm long. The contact is conformable and indicates that the sandy deposit is likely the facies of a distributary channel in a meandering stream system of the delta plain mapped as lithofacies 5c. These relations indicate that the meandering stream deposits are situated in a buttress unconformity and that cut-and-fill processes have occurred into the base of the older lacustrine and delta-plain section as distinguished by fault trenches.

Geochronology at the Alabama Gates Site

Two AMS 14C samples from lithofacies 4b in T2 are of charcoalized plant fibers that formed a peat and bulk organic sediment from the base of a fining-upward sequence of silty peat to organic-rich silt and clay to peat, diatomaceous silt containing a reworked tephra, abundant charcoalized woody detritus containing rhizome fragments of bulrush (Scirpus sp.) and pondweed (Potamogeton cf. gramineus) and 14C dates between ca. 12,200 and 9920 cal yr B.P. (Fig. 4). The peat sample contained numerous seeds and rhizome fragments of bulrush (Scirpus sp.) and pondweed (Potamogeton cf. gramineus), which are indicative of freshwater springs, ponds, and marshes. The AMS analyses provide dates of 10,370–9920 cal yr B.P. and 10,260–10,180 cal yr B.P., with a median age of 10,200 ± 200 cal yr B.P. (2σ) (Table 1).

A radiometric date from T3 is incorporated from the results of Beanland and Clark (1994), because we could find and recognize the unit...
they sampled in the road cut along U.S. Highway 395 and could correlate that unit with the same deposit in the T3 section to be equivalent to the lower section of lithofacies 4b, which consists of interbedded diatomaceous silt, a reworked tephra, and nonorganicsilts and finesands. Beanland and Clark (1994) derived a date of 10,200 + 70 yr B.P., which was calibrated to 12,230–11,410 cal yr B.P. (Fig. 4). Stratigraphy of T3 consists of reworked pieces of tephra scattered within a diatomaceous-rich bed of lithofacies 4b (Fig. 4). Samples of the tephra were identified by A. Sarna-Wojcicki (written comm. to S. Bacon, 2002) to be a heterogeneous mixture of glass shards primarily from two sources: the 0.76 Ma Bishop, Glass Mountain ash bed (Long Valley Caldera) and the younger Wilson Creek ash beds (Mono Craters) (see GSA Data Repository for the tephra analyses). Glass shards in our samples that were obviously from the Wilson Creek beds had a chemistry that correlates best with those beds numbered 8–15, which have a correlative age of from 33,200 to 30,000 cal yr B.P. However, the ash-rich units appear poorly sorted, were likely reworked in a fluvial-deltaic setting, and are underlain by beds with 14C dates between ca. 12,000 and 10,000 cal yr B.P. in T3 (Fig. 4). Thus, the ash-rich units appear to have been reworked and then deposited sometime after ca. 12,000 cal yr B.P.

Paleoearthquakes at the Alabama Gates Site

The A.D. 1872 earthquake is recorded in all three trenches in the form of near-vertical fault strands and fissure fills composed of soft eolian-derived silt that likely continued to the modern ground surface if the scarp had not been beveled during highway construction (Fig. 4). Trenches T1 and T2 expose deformation interpreted to be the result of two earthquakes, the A.D. 1872 earthquake and one earlier large paleoearthquake, the penultimate event at the site. Trench T1 exhibits an erosional contact characterized as sequence boundary SB3 that abruptly terminates fault strands in the western portion of the trench (Fig. 4). The principal fault zone exposed in T2 separates lithofacies 3b, 4b, 7b, and 11, and displays a similar amount of apparent vertical separation as T1, but throw is mostly across a narrow fault zone attributed to the A.D. 1872 earthquake (Fig. 4). Trench T3 exhibits no footwall and therefore only records mainly hanging-wall deformation related to the A.D. 1872 earthquake (Fig. 4). The total apparent vertical separation across all faults within the zones exposed in T1 and T2, based on the lower and horizontal boundary of lithofacies 4b, is 2.2–2.6 m, which was measured at the end of the trench and is consistent across a distance of ~15 m between both trenches (Fig. 4). Based on these paleoseismic relations, evidence of at least two large rupturing events with an apparent vertical separation of 2.2–2.6 m since 10,200 ± 200 cal yr B.P. is indicated at the trench site. Figure 5 is a composite stratigraphic column that shows lithofacies, sequence boundaries, and the position of 14C dates and tephra correlation, as well as event chronologies.

THE QUAKER PALEOSEISMIC SITE

Geomorphology at the Quaker Site

Five profiles surveyed across the scarp and shoreline features near the Quaker paleoseismic site show a composite scarp that has tread surfaces and platforms, wave-formed notches, meander risers, and a beach ridge that were all deformed by the A.D. 1872 earthquake (Figs. 2B, 6, and GSA Data Repository). The highest shoreline feature is a platform between 1122 and 1123 m in elevation and inset fluvial meander bends defined by arcuate-shaped risers that have different tread-surface morphologies (Fig. 6). A lower fluvial trelod is located near an elevation of 1121 m, as well as an even lower wave-formed notch that ranges in elevation from 1118 to 1119.5 m. The shoreline that formed the wave-formed notch also constructed a remnant beach ridge near T4, which has a ridge crest elevation between 1118.5 and 1119 m that is deformed only by the A.D. 1872 earthquake (Fig. 6). Fluvial risers below an elevation of 1116.5 m are from meanders that eroded most of this beach ridge north and south of profiles 2 and 3 (Fig. 6). Bryant (1988) recognized the eroded fault scarps at the Quaker site, and Beanland and Clark (1994) described how scarps to the north show more throw and thus are likely composite at slightly higher elevations.

The trace of the A.D. 1872 earthquake is evident as an ~1 m scarp along the top and near the base of a composite scarp that ranges from 1 to
4 m in height and slopes 13° to 25° east (Bea-
land and Clark, 1994). Runoff, mostly from
the Alabama Hills, has produced many small
ephemeral channels that are incised into and
across the scarp. Offset reconstructions show
stream channels cannot be matched confidently
across the scarp, and trenching reveals a history
of faulting that the scarp morphology does not
mimic well.

**Stratigraphy at the Quaker Site**

Four fault trenches (T4–T7) at the Quaker
site were excavated within ~20–50 m of one
another along an ~100-m-length of the Owens
Valley fault at elevations from 1113.5 to 1124 m
(Fig. 6). Each trench was 13–33 m in length and
from 2 to 4 m in depth. Three stratigraphic pits
P2–P4, each 3–4 m in depth, were excavated on
nearby geomorphic surfaces in order to map the
unfaulted stratigraphy (Fig. 6). Trenches T4, T5,
and pit P4 are the best examples of the stratig-
raphy and structure at the Quaker site (Fig. 7).
Trenches T6 and T7, as well as pits P2 and P3
are presented in the GSA Data Repository. The
sequence stratigraphy exposed at the Quaker
site contains lithofacies that are laterally con-
tinuous and that can be correlated between the
trenches and pits. In addition, the lithofacies and
facies associations used to describe the units in
the trenches are also common to the Alabama
Gates paleoseismic site. Because of the large
horizontal component of displacement on the
Owens Valley fault, only five lithofacies units
are exposed in the trenches that correlate across
the fault zone, but most of the lithofacies are
time-stratigraphic equivalent. As a result, the
lithofacies descriptions are grouped into foot-
wall and hanging-wall stratigraphic sections.

**Footwall Stratigraphy**

The oldest sediment observed in the footwall
and exposed at the base of the trenches is a firm,
plastic, green clayey silt that is exposed in T5
and grouped into lithofacies 1b (Fig. 7). The
depositional environment of lithofacies 1b is
offshore lacustrine related to sedimentation in a
relatively deep water column. Lithofacies 1b has
a clear to gradual upper contact with an organic-
rich brown and firm clayey silt that contains
5% disseminated and detrital charcoal, which
range from 1 to 3 mm in length. The organic-
rich deposit is exposed in all trenches and pits
and forms sequence boundary SB1, where it is
0.25–1.25 m thick and mapped into lithofa-
cies 4b (Fig. 7). Lithofacies 4b is interpreted to
represent a soil that developed within a marsh
and/or mud flat of the delta plain. Lithofacies 4b
is overlain by a massive, silty, fine sand that is
well rounded, well sorted, and slightly hard. The

**Figure 6.** Annotated black-and-white low-sun-angle aerial photograph of the Quaker paleo-
seismic site. Fault trenches (T4–T7) and pits (P2, P3, and P4) are shown in relation to the A.D. 1872 Owens Valley fault rupture, the Alabama Hills (PMz), Holocene alluvium (Hal),
fluvial sediment (Hf), lacustrine sediment (Hls), and a beach ridge and prominent tread
and risers (hachures) formed by shoreline and fluvial processes. The ~1-m-high A.D. 1872
Owens Valley fault scarp is located along a 1- to 4-m-high composite scarp that contains
shoreline and fluvial erosional and constructional features at elevations of 1116–1125 m
shown on inset profiles 2 and 3 (photo from Slemmons, 1968).
lower contact of the massive deposit with lithofacies 4b is abrupt and mapped as lithofacies 13a. This deposit is interpreted to represent a transition between nearshore and shore lacustrine depositional environments (Fig. 7). Lithofacies 13a has sedimentologic characteristics that are similar to massive eolian deposits. It is plausible that lithofacies 13a was originally accumulated as an eolian sand sheet or dune above lithofacies 4b within the delta plain and then subsequently reworked by nearshore to shore lacustrine processes during a transgression in lake level.

Lithofacies 13a has a clear upper boundary with a 5–20-cm-thick very hard sand tufa sheet that defines sequence boundary SB2 between the two deposits in T5 (Fig. 7). The sand tufa sheet is also exposed in natural channels as discontinuous broken plates along the A.D. 1872 fault scarp between T4 and T7. The sand tufa sheet is overlain by poorly sorted, well-rounded to subangular pebble– and fine gravel–sized tufa fragments that are supported by a slightly hard to hard, massive, well-sorted silty fine sand. This tufa-rich deposit is mapped into lithofacies 14a and is interpreted to be the result of subaerial precipitation of CaCO₃ in the form of a tufa sheet on a sandy substrate in a nearshore to shore depositional environment (Fig. 7). The tufa precipitated at a time of a relatively stable water column that was deep enough to form and preserve the tufa sheet prior to sedimentation during fluctuating lake levels. Fluctuating lake levels are indicated by the presence of well-rounded to subangular, pebble– and fine gravel–sized tufa fragments that came from the tufa sheet. Changes in wave base related to fluctuating lake levels would have likely eroded and reworked the existing tufa sheet into angular to subangular clasts. These relations are similar to isolated patches of tufa that formed on flat-lying unconsolidated lake sediments in the Pyramid Lake basin (Benson, 1994).

Other tufa deposits exposed in T4 and P4 consist of well-rounded, well-sorted, medium sand to fine gravel cemented by CaCO₃. These deposits are very hard and contain primary cross-bedding and foreset (lakeward dipping) sedimentary structures that are common in beach ridges (Adams and Wensoulsky, 1998). The tufa-rich deposits are mapped into lithofacies 7e, and they represent beach deposits of a shoreline that was adjacent to older sediment and that eroded into older sediment (Fig. 7). Lithofacies 7e contains lithologically heterogeneous sediment derived from up-valley source areas, which consists of scoria, basalt, tuff, and pumice. Lithofacies 7e has an erosional lower contact with lithofacies 2b, 4b, and 13a that defines sequence boundary SB5 and has an upper surface that reflects the original surface morphology near T4 (Fig. 7). The strata exposed in the upper sections of T4 and P4 are within the beach ridge mapped in Figure 6 that is truncated to the west by the composite scarp (profiles 3 and 4; Fig. 6). Trench T4 exhibits an erosional contact and interfinger ing relation between the beach ridge and older sediments that comprise the scarp in the western portion of the trench (Fig. 7). The erosional contact consists of many discontinuous lenses and rotated blocks of older sediment that are composed of fine sand, faintly bedded silty sand, fine sand with tufa fragments, and organic clayey silt, which we group into lithofacies 13b. Lithofacies 13b interfingers with lithofacies 7e, and, therefore, they are time-stratigraphic equivalents.

Overlying the strata of the footwall block is a 0.3–0.5-m-thick massive, well-sorted coarse silt and fine sand. This deposit is exposed in all trenches and is mapped as lithofacies 16, and we interpret it as a loess sheet. In addition, a poorly sorted and slightly hard, pebbly, silty, sand deposit that contains lithologies derived from only the Alabama Hills locally overlies nearly flat slopes at the site. This deposit is mapped into lithofacies 9b in P3 and is interpreted to be alluvial deposition from the Alabama Hills, whereas lithofacies 9c in T4 is from a colluvial apron derived locally from the scarp and sand dunes (Fig. 7).

**Hanging-Wall Stratigraphy**

Sediment exposed in the hanging wall at the Quaker paleoseismic site is generally coarser grained, well stratified, and has more sequence boundaries compared to stratigraphy exposed in the footwall. The oldest sediment at the site is exposed in P4 (Fig. 7). At the base of P4 is a 0.25–0.4-m-thick clayey silt that contains well-preserved charcoaled woody stems that are 1–8 cm in length and 0.5–2.0 cm in diameter. This organic-rich deposit defines sequence boundary SB0 and is mapped as lithofacies 4a, which represents deposition in a marsh or mud flat of the delta plain. Lithofacies 4a is overlain by interbedded clayey silts, mapped as lithofacies 1b, and alternating sequences of sands and silts, mapped as lithofacies 2a, that reflect the depositional of both lacustrine and deltaic facies associations during fluctuating lake levels. Lithofacies 1b and 2b are also exposed in T4 and T5 (Fig. 7). Lithofacies 2b has an erosional upper contact with lithofacies 7e in T4, which defines sequence boundary SB5, and an erosional contact with lithofacies 7d in T5, which defines sequence boundary SB1 (Fig. 7). Lithofacies 4b has been completely or partially eroded in...
the areas of T5 and the western half of T4, as defined by sequence boundary SB1 (Fig. 7). Lithofacies 2b is exposed in T5 and preserved within the fault graben in T4 and represents an upward-finishing sequence of soft, moderately sorted, medium to coarse sand with faint and discontinuous wavy and planar laminations that grade into interbedded to structureless, loose, well-sorted fine sand and silt to a slightly hard, massive silt. The interbedded fine sand and silt exhibit prominent soft-sediment deformation structures and thin, 0.2–0.4-cm-thick sand dikes in T5, and the entire deposit is interpreted as fluvial-deltaic sedimentation in the delta front at a distributary mouth bar. Lithofacies 2b has lower and upper contacts that are abrupt, in addition to the upper contact of sequence boundary SB2, which truncates zones of soft-sediment deformation and sand dikes (Fig. 7).

Sequence boundary SB2 in T5 is overlain by alternating 10–30-cm-thick, fine to coarse sand with climbing ripples, planar laminations, and cross-bedding that is mapped as lithofacies 7d in T5 (Fig. 7). Lithofacies 7d is interpreted to represent deposition in a shore depositional environment. The relation of sequence boundary SB2 with lithofacies 7d defines an abrasion surface. Along the surface of this abrasion platform and at the base of lithofacies 7d, there are 0.5–1.5-cm-thick and 2–4-cm-long, hard to very hard, subangular cemented fine sand fragments of platy tufa exposed only in T5 (Fig. 7). Overlying lithofacies 7d is a 0.4-cm-thick massive sandy silt mapped as lithofacies 3d that conforms overly lies lithofacies 7d in T5 and is interpreted to represent sedimentation in a nearshore depositional environment. Exposed in T5, lithofacies 3d and 7d form an angular unconformity that is overlain by lithofacies 10b above this contact (Fig. 7). Lithofacies 10b is 0.4–1.5 m thick and consists of well-rounded and well-sorted fine to medium sand that displays prominent forest sedimentary structures. The upper half of the deposit contains ~30% well-rounded pebble-sized reworked pumice clasts that can be correlated to the 0.76 Ma Bishop and/or Glass Mountain ash (A. Sarna-Wojcicki, written commun. to S. Bacon, 2002), in addition to 1.0–3.0-cm-thick and up to 10.0-cm-wide, discontinuous in situ tufa cemented sand fragments and pumice along foreset bedding planes. Lithofacies 10b has sedimentary characteristics similar to eolian dune sands. The angular unconformable contact of lithofacies 10b with lithofacies 3d and 7d defines sequence boundary SB3 (Fig. 7).

The upper boundary of lithofacies 10b is an unconformable contact with a 0.4–2.2-m-thick massive sandy silt deposit that has sedimentologic characteristics similar to the nearshore deposit of lithofacies 3d mentioned earlier. This massive sandy silt is mapped into lithofacies 3e and is exposed in T5–T7 (Fig. 7). The relatively thick sandy silt deposit of lithofacies 3d is overlain by lithofacies 14b. The contact between lithofacies 3e and 14b is conformable, indicating a depositional boundary that is only observed in T5 (Fig. 7). The sequence of lithofacies 3e overlain by lithofacies 14b suggests that lithofacies 14b was deposited during an overall regressive but fluctuating lake level, where the stratigraphic position between the two lithofacies defines sequence boundary SB4 (Fig. 7). The entire package of strata in the hanging wall is overlain by sediment deposited in the delta plain. Lithofacies 16 is a massive coarse silt and fine sand that resembles a loess sheet deposit and correlates across the fault only in T5 (Fig. 7). In addition, colluvial deposits, mapped as lithofacies 9c, and eolian sand dunes, mapped as lithofacies 10c, are exposed in T4 (Fig. 7).

**Geochronology at the Quaker Site**

The ages of sediment exposed in trenches and pits at the Quaker paleoseismic site are from six AMS 14C analyses on charcoal and bulk organic material and one radiometric analysis on bulk organic sediment from T4 and P4 (Table 1). Three radiometric dates of tufa are from T4, T5, and P4 (Fig. 7). The oldest sediment at the Quaker site is mapped as lithofacies 4a in P4 and is from three AMS 14C samples of well-preserved charcoaled fragments of willow/cottonwood (*Salix* sp.) that resulted in a range of dates from 14,900 ± 400 cal yr B.P. at 2σ (Table 1; Fig. 7). Additionally, three AMS 14C samples and one radiometric sample from lithofacies 4b in the eastern part of T4 are from an organic-rich clayey silt that contains 5% disseminated and detrital charcoal (Fig. 7). The AMS 14C date on the bulk organic sediment is 10,490–10,230 cal yr B.P., and the radiometric date on the bulk organic sediment is 11,220–10,790 cal yr B.P., whereas the AMS 14C date on the charcoal is 11,600–11,230 cal yr B.P. The median value of all three calibrated dates is 10,800 ± 600 cal yr B.P. (2σ). In addition, the age of an AMS sample of detrital charcoal from lithofacies 13b in T4 is 10,660–10,280 cal yr B.P. (Table 1; Fig. 7).

The tufa sample in T5 is from a very hard, fine to medium sand tufa sheet (beach rock) located at the base of lithofacies 14a (Fig. 7). The radiometric date on the tufa from T5 is 8980–8600 cal yr B.P. (Table 1). The age of one tufa sample from the beach ridge in the central portion of T4 (lithofacies 7e) is 12,790–12,400 cal yr B.P. (Table 1; Fig. 7). An additional analysis of one tufa sample of lithofacies 7e in P4 resulted in a date of 7920–7620 cal yr B.P., and this sample is notably similar in grain size, lithology, and indentation of the tufa sampled in T5, indicating deposition in similar environments (Table 1; Fig. 7).

The 14C date from the beach ridge in T4 is 11,600–11,230 cal yr B.P., which is stratigraphically below it; thus, it is not in stratigraphic agreement with the other dates. The ca. 7800 cal yr B.P. tufa date from P4 represents the age of lithofacies 7e. Evidence to support the dates of the tufa samples from P4 and T5 of ca. 7800 and 8800 cal yr B.P., respectively, comes from the proxy indicator of total inorganic carbon from the Owens Lake sediment cores. Benson et al. (1997) showed that the amplitude of total inorganic carbon variability in the cores increased between 8800 and 6700 cal yr B.P. and proposed that the maxima in total inorganic carbon were caused by carbonate precipitation in shallow lakes. The lake-core data support our 14C dates of ca. 7800 and 8800 cal yr B.P. from P4 and T5 and indicate the onset of basinwide precipitation of tufa. We acknowledge the uncertainties in dating tufa carbonates (e.g., Bischoff et al., 1993), yet they seem to offer reliable age control where used with additional stratigraphic and geochronologic analyses.

**Retrodeformation Analysis of the Quaker Paleoseismic Site**

Sequence stratigraphy and geomorphic relations at the Quaker paleoseismic site suggest that the composite scarp was constructed and the trace of the Owens Valley fault has been eroded and/or modified by at least four transgressive and regressive lake cycles of pluvial Owens Lake between ca. 15,000 and 6900 cal yr B.P. (Bacon et al., 2006). These lake cycles were punctuated with episodes of cut-and-fill from fluvial-deltaic erosional and depositional systems. To illustrate the sequence stratigraphy and structural relations at the Quaker site one event at a time, we retrodeformed T5 because it contained a more complete stratigraphic sequence compared to the other fault trenches. Our retrodeformation analysis of T5 took into consideration a large horizontal component of displacement not directly measured and incorporated other stratigraphic and paleoseismic relations exposed in adjacent fault trenches and stratigraphic pits. Eight schematic depictions were developed to represent the history of deposition and faulting since the time of the antepenultimate event (Fig. 8).

15,000–10,000 cal yr B.P.

Sometime after the antepenultimate event, the oldest deposits in P4 indicate a mud flat terrestrial environment dated at ca. 15,000 cal yr B.P., which was followed by a deeper-water
A lacustrine environment that deposited clayey silts and deltaic silty sands. During a regressive lake cycle between ca. 11,000 and 10,000 cal yr B.P., a terrestrial delta-plain depositional environment existed, a marsh soil developed, and sand dunes subsequently accumulated (Fig. 8, depiction A). Shortly after, erosion and incision by a fluvial-deltaic system occurred during lower lake levels, and these processes were followed by a relative rise in lake level after ca. 10,000 cal yr B.P., which produced cut-and-fill structures in the delta-plain deposits (Fig. 8, depiction B). The location of the cut-and-fill line is interpreted to be a buttress unconformity, where the location of the unconformity was likely influenced by earlier deformation along the fault zone in the form of subtle near-field warping and/or faulting at depth.

**10,000–8800 cal yr B.P.**

In Figure 8, depiction C illustrates deformation related to the penultimate event between 10,200 ± 200 and 8800 ± 200 cal yr B.P., which had an apparent ~1.4 m of vertical displacement. This depiction shows an upward-fining sequence of medium to coarse sand that grades into interbedded fine sand and silt that is in turn overlain by a massive silt cap with prominent liquefaction dikes and sand intrusions generated by the paleoearthquake (Fig. 8, depiction C). At the time of the penultimate event, pluvial Owens Lake had already begun its early Holocene transgression, and at an elevation of ~1120 m, the Quaker site was likely submerged under shallow water and periodically exposed to shoreline erosion and delta-plain cut-and-fill processes (Bacon et al., 2006); therefore, the loose sands were saturated and easily liquefiable.

**8800–7800 cal yr B.P.**

The top of the unit that shows liquefaction, sand dikes, and fault strands is truncated by sequence boundary SB2, which represents a transgression prior to ca. 8800 cal yr B.P. Sequence boundary SB2 represents an abrasion platform from...
shoreline erosion into the penultimate event fault scarp. Deposition of interbedded lacustrine and eolian strata followed the shoreline erosion (Fig. 8, depiction D). Two different lake cycles are represented by two packages of lacustrine sediment between SB2 and SB3 and between SB3 and SB4. Sequence boundary SB2 is the lower contact of a fining-upward sequence of shore to nearshore lacustrine deposits. Sequence boundary SB3 is an angular unconformity between the two lacustrine packages, and SB4 marks the end of relatively deep water and return to a shallow-water depositional setting.

The angular contact defined by SB3 resembles a buried thalweg of a channel, likely a cut-and-fill structure into older lacustrine sediments, probably related to incision of a paleochannel of the Owens River or one draining the Alabama Hills associated with a lowering lake level. The eolian sand deposit that overlies sequence boundary SB3 is additional evidence to suggest a return to terrestrial conditions. Incision that generated the thalweg eroded into older lacustrine sediments and across the trace of the fault, in similar relation to an earlier episode of cut-and-fill shown in depiction B (Fig. 8). Soon after channel abandonment, sand dunes accumulated atop a ravinement surface, within the thalweg, and against channel walls. The deposition of the sand dune was followed by a rise in lake level, which submerged the sand dune, precipitated tufa, deposited nearshore sediments, and reworked and deposited shallow-water sediments during a period of fluctuating lake levels. The last sequence of lacustrine sedimentation in the area near T5 is indicated by sequence boundary SB4, which marks a conformable contact between nearshore sediments and shore sediments that contain reworked tufa fragments. The stratigraphic relation of coarsening-upward, shallow-water facies underlain by relatively deeper-water and fine-grained facies is indicative of a regressive sequence caused by lowering of lake level.

7800–4300 cal yr B.P.

A paleochannel of Owens River cut into the area of T5 after the lake lowered below an elevation of 1120 m, similar to what occurred during the two prior regressive lake cycles. The fluvial system generated prominent fluvial terraces and risers in the footwall (Fig. 6) and laterally eroded lacustrine strata to form an ~3 m riser or bluff along the western margin of the meander belt. Subsequent erosion into the base of the bluff occurred during a relative rise and stabilization in lake level that reached a maximum elevation of 1118.5–1119 m, where it created wave-formed notches along the base of the bluff near T5 and constructed the beach ridge in the area of T4 and P4 at ca. 7800 cal yr B.P. (Fig. 8, depiction E).

The last phase of deposition and bluff modification occurred after the latest lake level lowered below the trenches at an elevation of 1116 m after 7800 cal yr B.P. Between ca. 7800 and 4300 cal yr B.P., the Owens River was entrenched below the trench site within the area of the active meander belt east of U.S. Highway 395 in response to falling lake levels between the elevations of 1085 and 1116 m (Bacon et al., 2006). During this time, sand dunes collected against the bluff and a mantle of windblown silt formed a loess sheet at the site (Fig. 8, depiction F).

4300 cal yr B.P. to Present

Since 4300 cal yr B.P., the Owens River has been deeply entrenched into the lake plain and has not reached an elevation as high as the Quaker trench site (Bacon et al., 2006). Between 4300 cal yr B.P. and A.D. 1872, the landscape here experienced loess deposition, sand dune stabilization, and minor ephemeral alluviation at the base of the bluff, as well as mass-wasting processes (Fig. 8, depiction G). In depiction H, the entire package of bedded strata that is above SB2, and thus is younger than ca. 8800 cal yr B.P., shows only one episode of faulting, with ~1 m of apparent vertical separation of the bluff as the result of the A.D. 1872 Owens Valley earthquake (Fig. 8).

Paleoearthquakes at the Quaker Site

All four trenches (T4–T7) at the Quaker paleoseismic site exhibit faulting from the A.D. 1872 earthquake in the form of near-vertical fault strands and fissure fills composed of soft eolian-derived silt that both continue vertically to the modern ground surface (Fig. 7 and GSA Data Repository [see footnote 1]). Trench T5 records reliable evidence for deformation of at least one large paleoearthquake (Fig. 7). Throw in T4 is attributed to the A.D. 1872 earthquake, which separates all units that overlie the abrasion platform defined by sequence boundary SB5, which formed as a result of basal erosion from a transgression of Owens Lake just prior to 7920–7620 cal yr B.P. (Fig. 7). Furthermore, faulting attributed to the A.D. 1872 earthquake in T5 displaces lithofacies 3d, 3e, 7d, 7e, 10b, and 14b above the abrasion platform defined by sequence boundary SB2 in the hanging wall, which is related to basal erosion from a transgression just prior to 8980–8600 cal yr B.P. (Fig. 7). The unconformity coincident with sequence boundary SB2 truncates near-vertical fault strands, as well as upward-terminating sand dikes, sand-filled veins and fissures, and earthquake-induced liquefaction features similar to those described by Obermeier (1996). Both sequence boundaries SB2 and SB5 are coincident with paleoearthquake event horizons. The age of sequence boundary SB2 provides a minimum age and the age of sequence boundary SB1 provides a maximum age for the penultimate event (Figs. 5 and 7).

The total apparent separation attributed to the A.D. 1872 earthquake in T5 is 0.6–0.8 m, measured using six piercing points across all the faults above the horizontal abrasion platform (sequence boundary SB2), which is considered a minimum estimate. The lower contacts of lithofacies 7d in the hanging wall and lithofacies 14a in the footwall are interpreted to be time-stratigraphic equivalent, based on the position of SB2 and nearby stratigraphy (Fig. 7). The elevation difference between these horizontal contacts in T5 is 2.1–2.5 m, which records the total cumulative apparent vertical separation from the A.D. 1872 earthquake and paleoearthquake. Subtraction of the apparent vertical separation related to the A.D. 1872 earthquake in T5 from the corresponding total apparent vertical separation provides a maximum apparent vertical separation of 1.3–1.6 m for the paleoearthquake, which is the penultimate event at the site.

PALEOSEISMIC TRENCH RESULTS

Timing of Paleoearthquakes near Lone Pine

All paleoseismic sites near Lone Pine record faulting from the A.D. 1872 earthquake. The Alabama Gates and Quaker trench sites show two episodes of faulting from the penultimate event and the A.D. 1872 earthquake. Previous studies of offsets of older fan deposits located above the elevations of the latest pluvial lake levels have provided evidence for three surface-faulting earthquakes including the A.D. 1872 earthquake.

The oldest sediment in the deepest trench exposures is at P4 of the Quaker site, and it was 14C dated between 15,270 and 14,400 cal yr B.P. This basal unit is correlative with trench units that record faulting related to at least two earthquakes and no evidence of the third event back or antepenultimate event. We infer that the age of the oldest units (ca. 15,000 cal yr B.P.) not faulted by more than two earthquakes can be used to provide a minimum age for the antepenultimate event. The maximum age of an alluvial fan offset by the antepenultimate event at the Lone Pine site is 26,200–23,200 cal yr B.P. (Lubetkin and Clark, 1988). Using these broad timing constraints, we estimate that the antepenultimate event near Lone Pine occurred in the interval from ca. 25,000 to 15,000 cal yr. B.P. (Table 2), which was a time of high water levels and deep-water lacustrine deposition at the paleoseismic sites (Bacon et al., 2006). The latest Pleistocene lacustrine section appears to be
thick, and the amount of slip for the antepenultimate event was not observed from the deepest exposures in the trenches.

Displacement and deformation from the penultimate event is exposed in T1 and T2 at the Alabama Gates site and in T5 at the Quaker site (Figs. 4 and 7). The event horizon exposed in T5 is coincident with sequence boundary SB2, an erosional unconformity into units deformed by the penultimate event. The event horizon and SB2 contain plates and sheets of tufa that are overlain by lithofacies 14a, which can be correlated across the fault zone (Figs. 5 and 7). Therefore, lithofacies 14a provides a minimum age of 8980–8600 cal yr B.P. for the penultimate event. Lithofacies 4b in T2 provides a maximum age constraint for the penultimate event as distinguished by sequence boundary SB3, which is dated at younger than 10,200 ± 200 cal yr B.P. (Figs. 4–5). Thus, the penultimate event near Lone Pine is constrained between 10,200 ± 200 and 8800 ± 200 cal yr B.P., with a median age of 9500 ± 900 cal yr B.P. (2σ) (Table 2).

**Interseismic Intervals near Lone Pine**

The trenches on the main trace of the Owens Valley fault near Lone Pine record two episodes of faulting, one from the A.D. 1872 earthquake and one from the penultimate event. From our trenching data alone, we have established the timing of the penultimate event and thus can calculate the length of the most recent interseismic interval on the Owens Valley fault near Lone Pine. Accounting for an elapsed time of ~80 yr between A.D. 1872 and 1950, the interseismic interval between the penultimate event and A.D. 1872 earthquake is 8500–10,300 yr (9400 ± 900 yr) (Table 2).

Based on available data, the interseismic interval between the antepenultimate event and penultimate event is within the broad range from 6100 to 15,900 (11,000 ± 4900 yr) (Table 2). Although the uncertainty in the timing of the antepenultimate event is much greater than that for the penultimate event, the median values for the two latest interseismic intervals are within 2000 yr. The two median values of the interseismic intervals between the last three large-magnitude earthquakes near Lone Pine are ~10,000 ± 1000 yr.

**Earthquake Displacements near Lone Pine**

Trench exposures reveal faulting that is distributed across a 5–6-m-wide zone along the more northerly trending fault trace at the Alabama Gates site and a 5–23-m-wide zone along the more northerly trending fault trace at the Quaker site (Fig. 2B). Faulting at both sites
consists of numerous near-vertical to west-dipping antithetic fault strands and near-vertical to east-dipping principal faults. Collectively, the faults form a half graben that is structurally similar to a negative flower structure as described by Sylvester (1988). Evidence of two earthquakes in T1, T2, and T5 is based on upward-terminated fault strands and a systematic increase in displacement down section. T1 and T2 at the Alabama Gates site are separated by ~15 m from each other and show the same amount of total vertical separation, based on the lower boundary of lithofacies 4b as a marker bed that crosses all faults in the exposure and is horizontal at both ends of the trenches. The fault strands terminated by sequence boundary SB3 in T1 indicate that they formed prior to erosion and deposition of lithofacies 11 and the A.D. 1872 earthquake. This same sequence boundary SB3 can be correlated from T1 and T2, where it is faulted by the A.D. 1872 earthquake in both trenches. Although there are not clear terminated fault strands in T2, sequence boundary SB3 is deformed less if you compare the apparent separation of this boundary with the base of lithofacies 4b, which is situated below it. These relations are evidence for progressive deformation in T2 and indicate faulting from at least two earthquakes at the site (Fig. 4). Similar relations are also shown in T5 at the Quaker site, where sequence boundary SB2 is vertically separated less within the half graben of the trench by the A.D. 1872 earthquake when compared to the total vertical separation of the same boundary at both ends of the trench. Thus, all evidence exposed in three trenches at two different sites indicates ~2.0 m of vertical separation since ca. 10,000 cal yr B.P., which we interpret to be the result of two earthquakes.

The preferred values and measurement uncertainties ($\pm 3$) of the total vertical separations in T1, T2, and T5 were combined into a cumulative distribution function from which the median and $\sigma$ (95% confidence level) values were derived. The average dip of faults measured in the trenches is 75°E (±15°), similar to the average dip determined by Lubetkin and Clark (1988) and Beanland and Clark (1994). Therefore, the total vertical displacement from the two earthquakes measured in T1, T2, and T5 is 2.4 ± 0.3 m (2σ). The minimum vertical displacement of the A.D. 1872 earthquake is 0.6–0.8 m measured in T5; by difference, the maximum vertical displacement for the penultimate event measured in T5 is 1.3–1.6 m. Given the mostly flat-lying lacustrine bed, large lateral component of displacement, and lack of piercing points, lateral offset measurements in fault-parallel trenches at the Quaker site were equivocal. In contrast, the fault-perpendicular trenches at both sites exposed the best evidence to assess earthquake timing and to measure the vertical separations, which are the subordinate slip components for this regional lateral-slip faults.

**Vertical and Oblique Fault Slip Rates near Lone Pine**

The trenches at both sites cut perpendicular across the Owens Valley fault rupture and thus resolve the timing much better than lateral displacements. There is no obvious surface evidence at the Alabama Gates and Quaker paleoseismic sites for lateral offsets associated with paleoearthquakes. Our geomorphic interpretations for topographic reconstructions of lateral offsets related to the A.D. 1872 earthquake are equivocal at both sites. We suspect the lack of obvious recurrent fault scarps is the result of fluctuating early Holocene lake levels that beveled the landscape prior to and around ca. 7800 cal yr B.P. Thus, to establish the oblique fault slip rate, we rely, as did Beanland and Clark (1994) and Zeltfuss et al. (2001), on a method to scale the horizontal offset to the vertical displacement, based on the averages of numerous scarp height and offset measurements from the entire A.D. 1872 fault rupture. The vertical displacements from earthquakes at the paleoearthquake sites are multiplied by the average (6:1) and maximum (10:1) horizontal to vertical displacement ratios determined by Beanland and Clark (1994).

In this study, the cumulative displacement from the penultimate event and A.D. 1872 earthquake of 2.4 ± 0.3 m (2σ) and the interval of time between the antepenultimate event and A.D. 1872 earthquake of 20,400 ± 5800 cal yr B.P. (2σ) results in a vertical slip rate of 0.12 ± 0.03 m/k.y. Scaling the vertical measurement with the displacement ratios in oblique slip rates of 0.7 ± 0.3 m/k.y. and 1.2 ± 0.5 m/k.y., respectively (Table 3). Our preferred value for the oblique slip rate for the Owens Valley fault near Lone Pine is 1.0 ± 0.5 m/k.y.

South of the trench sites of this study, the vertical component of slip on the Owens Valley fault appears to step west to the Lone Pine fan site. The average and maximum oblique slip rates of this study are similar to estimates calculated by Lubetkin and Clark (1988) for the Lone Pine fault splay, as well as the slip rates based on the recalculated $^{10}$Be model ages of Bierman et al. (1995) (Table 3). We do not add the slip rate of the Lone Pine splay to the slip rate of this study to calculate total slip.

**TABLE 3. SUMMARY OF GEOLOGIC SLIP RATES FROM THIS STUDY AND PREVIOUS INVESTIGATIONS ON THE SOUTHERN AND NORTHERN OWENS VALLEY FAULT**

<table>
<thead>
<tr>
<th>Location: Southern Owens Valley fault</th>
<th>Location: Lone Pine fault splay, southern Owens Valley fault</th>
<th>Entire Owens Valley fault</th>
<th>Fish Springs fault splay, northern Owens Valley fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investigation: This study</td>
<td>Investigation: Lubetkin and Clark (1988)</td>
<td>Beanland and Clark (1994)*</td>
<td>Martel et al. (2001)*</td>
</tr>
<tr>
<td>Displacement</td>
<td>Slip rate (m/k.y.)</td>
<td>Slip rate (m/k.y.)</td>
<td>Slip rate (m/k.y.)</td>
</tr>
<tr>
<td>Vertical</td>
<td>0.12 ± 0.04</td>
<td>0.12 ± 0.05 (0.12 ± 0.04)</td>
<td>0.25 ± 0.03</td>
</tr>
<tr>
<td>6:1 (oblique)</td>
<td>0.7 ± 0.2</td>
<td>Min. (0.5 ± 0.2)</td>
<td>1.0</td>
</tr>
<tr>
<td>10:1 (max. oblique)</td>
<td>1.2 ± 0.4</td>
<td>Max. (0.9 ± 0.4)</td>
<td>3.0</td>
</tr>
</tbody>
</table>

*Average Holocene slip rate based on indirect age control and inferred number of events.

†Holocene slip rate based on indirect age control and inferred number of events near Lone Pine combined with recurrence model based on trench data of two earthquakes near Big Pine.

§Slip rate based on the recalculated $^{10}$Be model ages (Table 2) from Bierman et al. (1995) on the Lone Pine fan and two-event offsets.

††Given their spatially unrelated data, recalculated slip rate using Lee et al. (2001a) data and the methods described by Lubetkin and Clark (1988) and Beanland and Clark (1994) to calculate slip rate.

Displacement ratios (horizontal to vertical) represent the average (6:1) and maximum (10:1) net oblique slip from the A.D. 1872 and prehistoric earthquakes estimated by Beanland and Clark (1994).
across the fault zone because it is not directly perpendicular across strike (Fig. 2B).

**DISCUSSION OF PALEOEARTHQUAKE TIMING AND FAULT SLIP RATES ON THE OVENS VALLEY FAULT**

To accurately compare the paleoearthquake timing and slip rates of this study with previous investigations, we calibrated conventional 14C dates to cal yr B.P. and used these values to recalculate paleoevent timing and slip rates from available data. Also, we recalcualted the cosmogenic radionuclide 10Be model ages of Bierman et al. (1995) from the Lone Pine site using the CRONUS 10Be and 26Al exposure age and erosion rate calculator version 1.1 (http://hess.ess.washington.edu/math), which is based on methods discussed in Gosse and Phillips (2001) and the scaling factors in Lal (1991) as modified by Stone (2000). Bierman et al. (1995) discussed how their reported 10Be and 26Al model ages likely had propagated uncertainties in isotopic abundance and as much as 20% uncertainty in production rates at that time. Since then, workers have refined the production rates, and, on average, the recalculated 10Be model ages are ~20% older than previously reported.

The methods used to calculate slip rates in this study are the same as those used in Lubetkin and Clark (1988) and Beanland and Clark (1994), wherein the number of earthquake displacements must equal the number of interseismic intervals in order to sum across equivalent "ali-quot" of the seismic cycle. Beanland and Clark (1994) estimated a Holocene slip rate of 2 ± 1 m/k.y., based on a 14C date of ca. 11,800 cal yr B.P. from an elevation ~20 m below the 1145 m overflow level, and inferred the occurrence of two paleoearthquakes (three earthquakes including A.D. 1872) within this time interval. The ca. 11,800 cal yr B.P. age was inferred, based on direct age control, to represent the maximum age of the oldest Owens Valley sediments deformed by the fault at or below an elevation near 1125 m. Beanland and Clark (1994) inferred two to three events and estimated an average recurrence interval for the entire Owens Valley fault of 3800–6100 yr (Tables 2 and 3).

**Lone Pine Fan Site, Southern Segment**

Evidence for three earthquakes, including the A.D. 1872 earthquake, can be found at the Lone Pine alluvial fan, based on geomorphology, fault trenches, and numerical dates (Lubetkin and Clark, 1988; Beanland and Clark, 1994; Bierman et al., 1995). Latest Quaternary slip rates are from a composite fault scarp on the Lone Pine fault splay that is 6–6.5 m in height and has channel and levee features that are dextrally displaced 10–18 m by three A.D. 1872–style rupturing events, each of which have an average net displacement of 4.3–6.3 m (Lubetkin and Clark, 1988; Beanland and Clark, 1994) (Fig. 2A).

The Lone Pine fan has been constrained by 14C dates to between 24,700 ± 1500 and 11,500 cal yr B.P., which results in an average recurrence interval estimate of 5800–13,200 yr and limits the age of the antepenultimate event to 18,900 ± 7400 cal yr B.P. (26Be (Lubetkin and Clark, 1988) (Table 2; Fig. 9). This same fan, which is faulted by three earthquakes, has a maximum 10Be model age of 23.3 ± 2.4 ka from near the oldest abandoned channel and a mean 10Be model age from three boulders of 13.7 ± 3.3 ka for the rest of the fan to the north; this reflects geomorphic relations observed by Bierman et al. (1995, p. 448), who stated "the faulted fan is composed of debris flows emplaced over a period of time and therefore has no single age" (Table 2; Fig. 9).

The youngest 10Be model age of 10.4 ± 1.2 ka is "...located at the margin of the youngest abandoned channel, which was probably active after the first faulting event...," and it provides a maximum age for the penultimate event at the site (Bierman et al., 1995, p. 448). Benn et al. (2006) treated the oldest 10Be model age of ca. 23.3 ka as an outlier, which differs from the geomorphic interpretations of Bierman et al. (1995). Based on the crosscutting relations between abandoned channels, the morphostratigraphic position of alluvial fan surfaces, and boulder weathering characteristics, which collectively are consistent with the 10Be model ages, we favor the interpretations of Bierman et al. (1995) at the Lone Pine site. Therefore, the age of the antepenultimate event is 17.9 ± 7.5 ka (26Be) (Table 2), which is the interval between the maximum age of a boulder situated on the oldest part of the fan and the mean age of three boulders deposited on the younger northern margin of the fan.

Slip rates for the Lone Pine fault splay are based on the two-event vertical separation of 2.3 ± 0.1 m and dextral offset of 10 ± 2 m of an inset alluvial fan deformed by the penultimate event and A.D. 1872 earthquake (Lubetkin and Clark, 1988; Beanland and Clark, 1994). The displacement data can be combined with the 14C and 10Be ages of the Lone Pine alluvial fan. The 14C ages provide vertical and average oblique slip rates of 0.12 ± 0.05 m/k.y. and 0.5 ± 0.2 m/k.y., respectively. The 10Be ages applied to the same displacement data provide vertical and average oblique slip rates of 0.12 ± 0.04 m/k.y. and 0.5 ± 0.2 m/k.y., respectively (Table 3). A maximum horizontal slip rate across the entire Owens Valley fault combines the horizontal offsets of 2.7–4.9 m attributed to the A.D. 1872 earthquake from Lone Pine (Diaz Lake) section with the Lone Pine fault (Alabama Hills section) two-event offsets (Lubetkin and Clark, 1988), and the result is a slip rate of 1.0 ± 0.4 m/k.y., and the recalculated 10Be age slip rate is 0.9 ± 0.4 m/k.y. (Table 3). The vertical slip rate we calculate for the Lone Pine fault splay is significantly slower than the vertical slip rate of 0.5 ± 0.2 m/k.y. from Le et al. (2007), who used the uncorrected cosmogenic ages of Bierman et al. (1995) and the three-event vertical separation of the Lone Pine alluvial fan.

The inset alluvial fan faulted by both the penultimate event and A.D. 1872 earthquake has a recalculated 10Be model maximum age of 10.4 ± 1.2 ka, whereas adjacent to and south of the Lone Pine fan site and creek, a much younger inset alluvial fan has a 14C date of 4810–4300 cal yr B.P. (Bierman et al., 1995) (Table 2; Fig. 9). Based on mapping by Beanland and Clark (1994), the surface of the late Holocene inset fan appears faulted only by the A.D. 1872 earthquake (Fig. 2B). Therefore, we interpret these relations to bracket the age of the penultimate event between 10,400 ± 1200 yr ago and 4810–4300 cal yr B.P. (7900 ± 3700 yr ago [2σ]), where the minimum age limit is considered to be a poor estimate of the lower bound of the penultimate event age (Table 2).

**Pangborn Lane Site, Southern Segment**

A study by Lee et al. (2001a) interpreted three laterally offset stream channels at their Pangborn Lane site near Lone Pine to represent faulting from three earthquakes that had nearly equal lateral displacements and were inferred to have occurred since ca. 8 ka (Fig. 6). Based on a model using the offsets measured at Pangborn Lane and timing data from a trench near Big Pine, they derived minimum and maximum oblique slip rates of 1.8 ± 0.3 and 3.6 ± 0.2 m/k.y., respectively. Given their spatially unrelated data set, and using the methods of Lubetkin and Clark (1988) and Beanland and Clark (1994) to calculate a slip rate, we derive slower rates of 1.3 ± 0.2 and 2.5 ± 0.5 m/k.y. (Table 3). However, we do not agree with the interpretation by Lee et al. (2001a) that the stream channels at Pangborn have been offset by three events. The trench sites of our study are ~1–5 km north of the Pangborn Lane site and at a similar elevation (Fig. 6), and they reveal evidence for the A.D. 1872 earthquake and only one paleoearthquake in early Holocene time. The A.D. 1872 displacements are expressed in the surface topography, but a scarp related to the penultimate event is absent at the surface and is expressed as increasingly larger displacements, twice that of the
Figure 9. Fault segmentation and section map of central and southern Owens Valley showing overlap and possible distributive faulting and linkage between the northern segment of the Owens Valley fault (OVF) and southern White Mountains fault (WMF) near Big Pine. The trace of the A.D. Owens Valley fault rupture and section boundaries of Beanland and Clark (1994) and segment boundaries of dePolo et al. (1991) are shown in relation to the central and southern White Mountains fault and the location of the Black Mountain rupture of dePolo (1989). RRF—Red Ridge fault; LP—Lone Pine; I—Independence; BP—Big Pine; OSL—optically stimulated luminescence; PE—Penultimate event; APE—antepenultimate event; MRE—most recent event.
A.D. 1872 earthquake, at depths of 1–3 m in the trenches, and evidence for the antepenultimate event is buried much deeper.

Deformed Beach Ridges near Owens Lake, Southern Segment

At the northwest edge of Owens Lake playa, ~2 km north-northwest of Bartlett Point, at an elevation of ~1100 m, a beach ridge complex shows deformation from two events, including the A.D. 1872 earthquake (Carver, 1970; Bryant, 1988; Beanland and Clark, 1994) (Fig. 2, site 3). The youngest and most basinward beach ridge was constructed in historical times and is faulted only by the A.D. 1872 earthquake, which generated a 0.3–0.5 m vertical scarp across the crest (Carver, 1970; Beanland and Clark, 1994). The crest of a higher and relatively older beach ridge is warped ~2.2 m vertically across a distance of ~30 m of the crest (Carver, 1970). Carver (1970) and Beanland and Clark (1994) inferred that this older beach ridge was constructed in late Holocene time, thereby indicating at least one late Holocene paleoearthquake at this site. If so, this paleoearthquake had a vertical throw of ~1.3–1.7 m at this site, similar to the 1.3–1.6 m measured for the penultimate event in trench T5. Furthermore, the 2.2 m height of the warp is similar to the size of the two-event 2.3 ± 0.1 m oblique-normal fault scarp on the Lone Pine fan, as well as the average two-event vertical displacement of 2.4 ± 0.3 m (2σ) measured from trenches in this study.

Since the Carver (1970) and Beanland and Clark (1994) investigations, Orme and Orme (1993) dated shells in sediments at 1100 m elevation from the north-northeast portion of the same beach ridge complex, which is the lowest of several dated recessional shorelines associated with the latest Pleistocene regression of pluvial Owens Lake (Orme and Orme, 1993; Bacon et al., 2006). The 14C age of shells from the beach ridge is 11,900–12,200 cal yr B.P., which we interpret to provide a maximum age constraint for the paleoearthquake timing. We posit that the beach ridge was warped and not faulted, because it was constructed prior to the early Holocene highstand described by Bacon et al. (2006) and was subsequently deformed by the penultimate event near Lone Pine, possibly beneath as much as ~20 m of lake water. The warp is interpreted to be the expression of a scarp formed under water.

Alabama Hills Borrow Pit, Site 14, Southern Segment

Additional evidence for the penultimate event and A.D. 1872 earthquake occurs near the base of the Alabama Hills in a borrow pit at site 14 north of Lone Pine (Figs. 2B and 3). Two distinct traces of the Owens Valley fault are separated by ~4.6 m across a compound scarp in coarse alluvium derived from the range front at an elevation of ~1140 m (Bryant, 1988). The pit extends across the western trace but does not reach the eastern trace. The western trace may not have ruptured in A.D. 1872, based on a gentle scarp (slope angle of 26°), ~1.5 m of scarp retreat, and colluvial wedge stratigraphy (Bryant, 1988). Although the trench did not extend across the eastern trace, it probably ruptured in A.D. 1872, given its steeper scarp angle and pristine morphology, which are characteristics of A.D. 1872 fault scarp (Bryant, 1988). The alluvial fan faulted by two events at site 14 appears to be geomorphically similar to the nearby inset alluvial fan dated at less than ca. 10.4 ka, which is also faulted by two events. Thus, there is additional evidence for only two faulting events on the southern segment of the Owens Valley fault since the early Holocene.

Owens Valley Fault Trenches near Independence, Site 18, Central Segment

Near the southern end point of the central segment of the Owens Valley fault near Independence, two fault trench revealed displacement and liquefaction related to the A.D. 1872 earthquake and no evidence of earlier faulting within fluvial deposits of the Owens River (Beanland and Clark, 1994; Site 18, Figs. 2A and 9). The trenches were located between meander channels within the Owens River meander belt that have been offset only by the A.D. 1872 earthquake. This trench site and the Lee et al. (2001a) trench site on the northern segment near Big Pine are situated within similar geomorphic and depositional settings.

Owens Valley Fault Trenches near Big Pine, Northern Segment

The A.D. 1872 fault rupture terminated north of Big Pine along the northern segment of the Owens Valley fault, which shows the shortest and most distributed ruptures, as well as the most complicated map geometry compared to the rest of the fault zone (Fig. 1B). A single trench excavated by Lee et al. (2001a) crossed the trace of the Owens Valley fault near Big Pine and revealed faulting from the A.D. 1872 earthquake and a paleoearthquake (Fig. 9). The trench was situated in an abandoned channel of the Owens River meander belt, and it revealed two steeply east-dipping fault strands that faulted a sequence of playa and fluvial deposits. The fault strand that extended to near the surface was attributed to the A.D. 1872 earthquake, whereas the other fault strand terminated ~1.25 m below the surface and was attributed to a paleoearthquake. Optically stimulated luminescence (OSL) data bracket the timing of the paleoearthquake or penultimate event to between 3.8 ± 0.3 and 3.3 ± 0.3 ka, thereby indicating a recurrence interval between 3000 and 4100 yr at this site near Big Pine (Lee et al., 2001a) (Table 2).

Owens Valley Fault and Fish Springs Fault Splay, Northern Segment

Immediately south of Big Pine, the Owens Valley fault splays out and steps west around the Poverty Hills (Taylor, 2002) and northwest across the Fish Springs fan cinder cone, mostly as normal fault displacements, especially along the Fish Springs fault splay (Martel et al., 1987; Beanland and Clark, 1994; Zehfuss et al., 2001), and as apparent dextral offsets along the northern flank of Crater Mountain (Rogers, 2006) (Fig. 1B). Late Quaternary vertical slip rates on the Fish Springs fault splay range from 0.24 ± 0.04 m/k.y. to 0.25 ± 0.03 m/k.y. since ca. 300 ka (Martel et al., 1987; Zehfuss et al., 2001), whereas on northern Crater Mountain, the lateral slip rates range from ~1.4 to 3.5 m/k.y. since ca. 115 ka (Rogers, 2006) (Table 3). The Fish Springs fault has an ~1.0 m scarp that was probably created by the A.D. 1872 earthquake based on consistent amounts of offset and scarp morphology (Martel et al., 1987; Beanland and Clark, 1994). The scarp crosses an alluvial fan that has a 10Be model age of ca. 8 ka (Zehfuss et al., 2001). If the scarp is only from the A.D. 1872 earthquake, the age of the fan can be regarded as a minimum value for the last interseismic interval. So, like on the southern segment near Lone Pine, the penultimate event on the Fish Springs fault is older than 8 ka, or the scarp in the early Holocene fans would have recorded two events.

Southern White Mountains Fault East of Big Pine

The most pronounced fault segment discontinuity along the entire Owens Valley fault occurs at the Poverty Hills, where the northern Owens Valley fault and southern White Mountains fault are nearly parallel dextral-oblique faults, separated in map view by ~5 km, overlap along strike for ~20 km, and dip steeply toward each other to form a transtensional graben in a right-step east of Big Pine (Bryant, 1984; dePolo, 1989) (Figs. 1B and 9). dePolo (1989) mapped evidence that faults along the southern White Mountains fault experienced distributed slip during the A.D. 1872 earthquake in the form of fresh ~0.5-m-high scarps (Fig. 9). The most
recent paleoearthquake along the White Mountains fault occurred on the southern ~16 km of the fault, which is named the “Black Mountain rupture” (dePolo, 1989; dePolo et al., 1993). This paleoearthquake produced scarp as tall as 3 m and is estimated to have occurred ~3000 ± 2000 yr ago based on scarp morphology, relative dating of alluvial fans, and diffusion equation models (dePolo, 1989) (Table 2; Fig. 9). Little is known about the latest Quaternary history of faulting on the White Mountains fault.

**Possible Distributed Faulting, Northern Segment**

We speculate on the basis of the timing coincidence, close proximity, and rupture setting that the late Holocene (3.0–4.1 ka) paleoearthquake on the northern segment near Big Pine (Lee et al., 2001a) was associated with distributive faulting or was within a possible step-over associated with the Black Mountain rupture on the southern White Mountains fault. The southern White Mountains fault is only a few kilometers east and is within a releasing step-over in a right-lateral rupture along these zones. It seems likely that the southern White Mountains fault ruptured and triggered slip along the north-central segment of the Owens Valley fault near Big Pine, either concurrent with the Black Mountain rupture, or some time afterward. Given the data, the timing of these two paleoearthquakes overlaps within hundreds to a few thousand years. The late Holocene paleoearthquake on the northern segment of the Owens Valley fault (Lee et al., 2001a) is not expressed and has yet to be documented on the central Owens Valley fault, the southern Owens Valley fault, or the Fish Springs fault splay. If the northern Owens Valley fault experienced or produced a late Holocene earthquake, it did not rupture farther south than to site 18 near Independence, which is ~25 km south of the Lee et al. (2001a) trench site and of the southern end of the White Mountains fault and Poverty Hills step-over (Fig. 9). More trenches might resolve this issue. Unfortunately, the latest Quaternary paleoseismic record is not well established for the central and northern segments of the Owens Valley fault, as well as for nearby faults; therefore, the rupture patterns and structural connections between the Owens Valley fault and White Mountains fault have yet to be resolved.

**Possible Secondary Evidence of Paleoeartuquakes in Owens Valley**

During the A.D. 1872 earthquake, strong seismic shaking generated secondary effects in the form of lateral spreading around historical Owens Lake (Carver, 1970; Bryant, 1988) and liquefaction features at the valley floor consisting of sunken ground, craters filled with water, and sand blows or boils composed of conical accumulations of sand (Whitney, 1872; Beanland and Clark, 1994). During this earthquake, numerous rockfalls were observed in the central and southern Sierra Nevada Range (Schumacher, 1962; Ellsworth, 1990; Bull, 1996). Moreover, several sediment cores from Owens Lake reveal liquefaction features that are truncated by tsunami sand deposits associated with the A.D. 1872 earthquake (Smoot et al., 2000). The documented secondary evidence associated with the A.D. 1872 earthquake demonstrates how susceptible Owens Valley sediments are to earthquake-induced secondary effects under the historical climatic regime. During pluvial climatic regimes, when lake levels and groundwater tables would be higher than they were in A.D. 1872, the degree of susceptibility and the magnitude of seismically induced secondary effects would almost certainly be much greater.

**Possible Earthquake-Induced Liquefaction in Owens Valley**

In a sediment core from Owens Lake playa, within a continuous section of deep-water lacustrine silt and clay, there is a 3-m-thick section of similar sediments that Smith (1997) interpreted as “(bioturbated?).” This thick section of disturbed sediment is bounded by bedded stratigraphy that has 14C dates of 19,100 ± 180 cal yr B.P. near the base and 16,060 ± 420 cal yr B.P. near the top of the 3 m section (Smith, 1997). During this interval of time, pluvial Owens Lake had mostly low and fluctuating water levels, but between 18,470 and 17,690 cal yr B.P., the lake had a water depth of ~40 m (Bacon et al., 2006). Given the available data, we interpret the ~3-m-thick section of disturbed bedding as possible evidence of seismically induced liquefaction associated with a paleoearthquake in Owens Valley, rather than a thick section of bioturbated sediment within an otherwise deep-water depositional setting. We accept the age limits of 17,500 ± 1800 cal yr B.P. (2σ) for the bedded sediments that bound the disturbed zone to be the age limits for the paleoevent. The age range are within error of the age limits of Lubetkin and Clark (1988), Bierman et al. (1995), and this study for the antepenultimate event on the Owens Valley fault near Lone Pine (Table 2; Fig. 9).

**Paeleoeartuquake Chronologies on the Owens Valley Fault**

Based on the A.D. 1872 Owens Valley fault rupture map and slip distribution, previous workers have separated the fault zone into different segments or sections in order to identify and characterize discontinuities along strike that may influence the extent and style of earthquake ruptures (dePolo et al., 1991; Beanland and Clark, 1994) (Fig. 9). The spatial arrangement of earthquake recurrence data from this study and other paleoseismic studies on the southern and northern Owens Valley fault and the southern White Mountains fault is shown in the top diagram in Figure 9. The paleoevent timing data from this study and previous investigations, as well as what we interpret as secondary evidence of a paleoearthquake, were characterized with a mean and 2σ value in order to derive a timing distribution function (probability density function) that has a normal distribution (Gaussian function) (Table 2). Two slightly different results are shown: the timing of a paleoearthquake determined from dating stratigraphic offsets in trench exposures, as well as the numerical or inferred ages of landforms interpreted to be offset by one or more paleoearthquakes. Also, the figure combines results from four different dating methods, including calibrated 14C ages, 10Be, OSL, and diffusion equation model ages (Table 2; Fig. 9).

The timing data for each paleoevent on the Owens Valley fault are described by a normal
The event is of a given age within the entire 3σ distribution. For example, if one knows the age of a paleoearthquake to within one year, the relative probability is one, which would plot as a horizontal line like that for the A.D. 1872 earthquake (Fig. 9). Unlike historical records, paleoearthquake data commonly combine geological information from many sources and have much greater errors. For example, for the same paleoevent, the errors in the individual timing data vary by as much as a factor of four (Table 2; Fig. 9). Also, the antepenultimate event includes timing data from five paleoevents, whereas the penultimate event has only two paleoevents, hardly a statistically robust number of measurements.

The normal density functions are calculated for 1 year intervals, and these are summed and averaged by the number of events that overlap in time. Thus, the resultant odd-shaped (non-Gaussian) probability density functions represent the composite distributions for the timing of the various paleoearthquakes, as shown in the top left of Figure 9. Each timing input is treated with equal weight because the geological uncertainties possess quite different precisions, including the various age dating methods of the various materials, stratigraphic controls (or lack thereof), and various interpretations from the various investigators. The significance of the uncertainties in timing data input is evident from the height of the peak and the overall width of the density function, which demonstrate that the older the paleoearthquake, the more uncertainty (less precision) in the age.

Figure 9 shows the graphical results for the composite timing distributions of the penultimate event and antepenultimate event on the basis of the various input data sets. Basically, the youngest paleoevent occurred on the northern segment between 2000 and 4000 yr ago, and the most likely age is ca. 3500 yr ago. The penultimate event on the southern segment occurred between 6000 and 11,000 cal yr B.P.; the most likely age is ca. 9500 cal yr B.P. The southern penultimate event is probably an A.D. 1872–type earthquake because of the relatively larger displacement and associated effects, whereas the youngest event on the northern segment seems more likely to be associated with distributed rupture from the White Mountains fault or another nearby zone. The penultimate events on the northern and southern segments are based on only two timing inputs, and the composite results are skewed towards younger ages, whereas the timing of the antepenultimate event is skewed toward an older age on the basis of five timing inputs. The antepenultimate event occurred in the range between ca. 24,000 and 14,000 cal yr B.P., and the most likely age is ca. 18,700 cal yr B.P.

Most investigators have interpreted at least two, but others have inferred as many as three or four paleoearthquakes from offset latest Pleistocene deposits as old as ca. 25,000 cal yr B.P. However, we did not find any basis or evidence to infer more than two paleoearthquakes near Lone Pine during this time period. Chronologic data from the northern segment of the Owens Valley fault indicate that the penultimate event may be younger than what is observed on the southern segment, yet the latest Quaternary paleoearthquake record for the northern segment is incomplete (Fig. 9). Our most confident data are for only two paleoearthquakes on the southern segment near Lone Pine, and we can preclude the occurrence of a late Holocene event.

All available subsurface evidence from trench investigations indicates that the latest significant paleoearthquake near Lone Pine and Independence occurred in early Holocene time, contrary to the geomorphic results of Lee et al. (2001a) (Table 2). There is no subsurface or geomorphic evidence of a late Holocene paleoearthquake at the two trench sites of this study or at the Lone Pine paleoseismic site. Because of the elevations within the valley and confinement of the Owens River relative to both paleoseismic sites of this study, the Lone Pine paleoseismic site of Lubetkin and Clark (1988), as well as site 14 of Bryant (1988), the stratigraphic, geomorphic, and thus paleoseismic records are intact and relatively complete since the occurrence of the latest highstand of pluvial Owens Lake and subsequent meandering of the Owens River. The pristine preservation of the beach ridge that abuts the stratigraphic section at the Quaker paleoseismic site and the history of fluvial entrenchment below the site after ca. 7800 cal yr B.P. imply that no significant erosion has affected the site since that time, but only eolian deposition of loess and localized alluviation.

CONCLUSIONS

We have described the age and history of some of the neotectonic geomorphic features and lacustrine sequence stratigraphy in southern Owens Valley through the detailed mapping and analysis of landforms and stratigraphy in exploratory fault trenches across the Owens Valley fault and in deep pits and natural exposures nearby. The sequence stratigraphy records fluctuating latest Pleistocene to early Holocene lacustrine and fluvial-deltaic systems and middle to late Holocene fluvial systems that collectively have influenced the morphology of the landscape and removed surface evidence of pre–A.D. 1872 fault scarps below an elevation of ~1120–1135 m near Lone Pine. Because of oscillating lake levels between ca. 15,000 and 7800 cal yr B.P. and subsequent fluvial modification, evidence of recurrent lateral fault offsets below an elevation of 1135 m is equivocal to nonexistent. This is similar to the observations of Beanland and Clark (1994), who documented recurrent lateral offsets in the Owens Valley almost exclusively above an elevation of ~1140 m, which is above the latest pluvial highstand lake levels. The most critical uncertainty of this study is that we did not measure the lateral component of displacement, but relied on horizontal to vertical displacement ratios to determine oblique slip rates.

Results of this study serve to refine the results of the most extensive neotectonic investigation on the Owens Valley fault by Beanland and Clark (1994), and they essentially corroborate previous estimates of stratigraphic and paleoseismic parameters determined by Beanland and Clark and previous workers near Lone Pine. The age of the most recent paleoearthquake, considered to be the penultimate event on the Owens Valley fault near Lone Pine, is constrained between 10,200 ± 200 and 8800 ± 200 cal yr B.P., whereas the age of the antepenultimate event is poorly constrained between ca. 25,000 and 15,000 cal yr B.P. The age of the antepenultimate event is corroborated by other studies at the Lone Pine paleoseismic site and by the ages of liquefaction and rockslides that we interpret to be likely secondary evidence related to strong shaking from this event. Thus, the length of the last interseismic interval is ~9500 yr, and, on average, the last two interseismic intervals are ~10,000 ± 1000 yr each. In three of the seven trenches, the average of the total vertical displacement from the last two earthquakes is 2.4 ± 0.3 m (2σ), and our preferred estimate for the two-event oblique slip rate on the Owens Valley fault near Lone Pine is 1.0 ± 0.5 m/k.y.

The paleoseismogenic behavior of the Owens Valley fault is not understood well because the data are temporally and spatially incomplete. Large-magnitude earthquakes distribute slip broadly across many different fault segments and splays, as well as adjacent primary fault zones such as the White Mountains fault or southern Inyo Mountains fault, which likely distribute slip onto the Owens Valley fault and nearby regional faults in complicated ways. Because different earthquakes appear to have ruptured different fault segments with different amounts, the evaluation of fault slip rate for the overall fault zone is complicated and fundamentally incomplete. Not all slip is measured on any one particular fault,
and the slip measured at the surface is commonly attenuated or accentuated by the shape and strength of near-surface deposits.

Geologic, geodeitic, and seismic measurements tend to sample complementary, but significantly different temporal and spatial aspects of the earthquake deformation field. We have presented an ~25,000-year record of earthquakes on the Owens Valley fault near Lone Pine, which shows relatively long interseismic intervals of ~10,000 yr between large surface-faulting earthquakes like the A.D. 1872 earthquake. Relatively accurate and confident geologic data for these three events are used to derive a slip rate that is much slower by factors of 2–3 than geodetic measurements imply. We submit that geodetic rates are faster possibly because of relaxation processes from the A.D. 1872 earthquake, or transient strain from other Holocene and historical earthquakes in the valley or region, or possibly because the geodetic measurements span across nearby regions, which contain many faults for which little information is known. Consequently, the simplistic single-fault model for Owens Valley is a poor representation for the distributed deformation within the valley and along the Sierra Nevada, White Mountains, and Inyo Mountains fault systems. According to Savage and Lisowski (1995, p. 151) “the observed deformation across Owens Valley apparently implies processes more complicated than those represented by the conventional models of strain accumulation along a throughgoing fault”.

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