Holocene slip rates along the Owens Valley fault, California: Implications for the recent evolution of the Eastern California Shear Zone

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ABSTRACT

One of the largest historical earthquakes in California occurred in 1872 along the Owens Valley fault located along the western margin of the Eastern California Shear Zone. New paleoseismic and optically stimulated luminescence data are the first to bracket the timing of the pre-1872 rupture to between 3.3 ± 0.3 and 3.8 ± 0.3 ka. These data yield an earthquake recurrence interval between 4100 and 3000 yr, under the assumption of uniform return, and indicate a Holocene slip rate between 1.8 ± 0.3 and 3.6 ± 0.2 mm/yr. Our data are broadly consistent with a model proposed for the space-time evolution of the Eastern California Shear Zone. Our Holocene slip-rate estimates for the Owens Valley fault are slower than present-day slip rates determined from elastic half-space models of geodetic data. This discrepancy is reduced by using the recurrence interval estimated here and a viscoelastic model of geodetic data or by including geologic slip rates from adjacent faults.

Keywords: active tectonics, earthquakes, Owens Valley, paleoseismology, slip rates.

INTRODUCTION

One of the largest historical earthquakes in California, with an estimated M_w of $\sim$7.5, occurred in 1872 along the Owens Valley fault (Fig. 1), a spectacularly well exposed, right-lateral strike-slip fault (Beanland and Clark, 1994). Despite such a large earthquake, there are no specific age estimates for pre-1872 earthquakes. However, on the basis of cumulative offset of geomorphic features, Lubetkin and Clark (1988) and Beanland and Clark (1994) inferred that the Lone Pine and Owens Valley faults preserved evidence for three 1872-like earthquake events. By using sound inferential evidence and assuming uniform recurrence and characteristic slip, Lubetkin and Clark (1988) and Beanland and Clark (1994) argued for a late Quaternary slip rate of 0.7–2.2 mm/yr and 2 ± 1 mm/yr, respectively.

The Owens Valley fault is located in the northern part of the Eastern California Shear Zone, a zone of right-lateral shear characterized by three major subparallel strike-slip fault zones—the Death Valley–Furnace Creek–Fish Lake Valley, Hunter Mountain–Panamint Valley, and Owens Valley fault zones—and a series of connecting normal faults such as the Towne Pass–Emigrant and Deep Springs faults (Fig. 1). Geologic and geodetic data within this zone indicate that it is an important component of deformation within the Pacific–North American plate boundary zone (e.g., Dokka and Travis, 1990; Miller et al., 2001); results from recent GPS (global positioning system) measurements indicate a right-lateral shear rate of 10–13 mm/yr across this zone, accounting for $\sim$20%–25% of the total relative plate motion (e.g., Gan et al, 2000; Miller et al., 2001).

We completed new paleoseismic studies along the Owens Valley fault to determine the age of pre-1872 earthquakes, to better bracket Holocene slip rates, and to understand better the role of the Owens Valley fault in accommodating right-lateral shear within the Eastern California Shear Zone.

GEOLOGIC SETTING

Owens Valley is bounded by the Sierra Nevada to the west and by the White-Inyo Mountains to the east. The valley is dominated by Quaternary alluvial and lacustrine sediments and basaltic cinder cones and lava flows.

The Owens Valley fault, located along the western boundary of the Eastern California Shear Zone (Fig. 1), traverses the central part of the Owens Valley, extending $\sim$100 km from the northern shore of Owens Lake to just north of Big Pine. The fault exhibits impressive strike-slip geomorphic features, including pressure ridges, sag ponds, echelon scarps, vegetation lineaments, fault scarps, and groundwater barriers. The right-lateral component of slip during the 1872 earthquake averaged 6 ± 2 m; the ratio of horizontal to vertical slip is estimated at 6:1 (Beanland and Clark, 1994).

PALEOSEISMOLOGY

Trench Site

The key to understanding Holocene slip rates along the Owens Valley fault is bracketing the timing of pre-1872 earthquake events. Toward that goal, we completed trenching studies along the fault within an abandoned Owens River channel located in the middle of Owens Valley (Fig. 1). In this region, the approximately north-trending surface trace of the fault is characterized by vegetation lineaments, sag ponds, pressure ridges, left-stepping echelon fault scarps, grabens, and both

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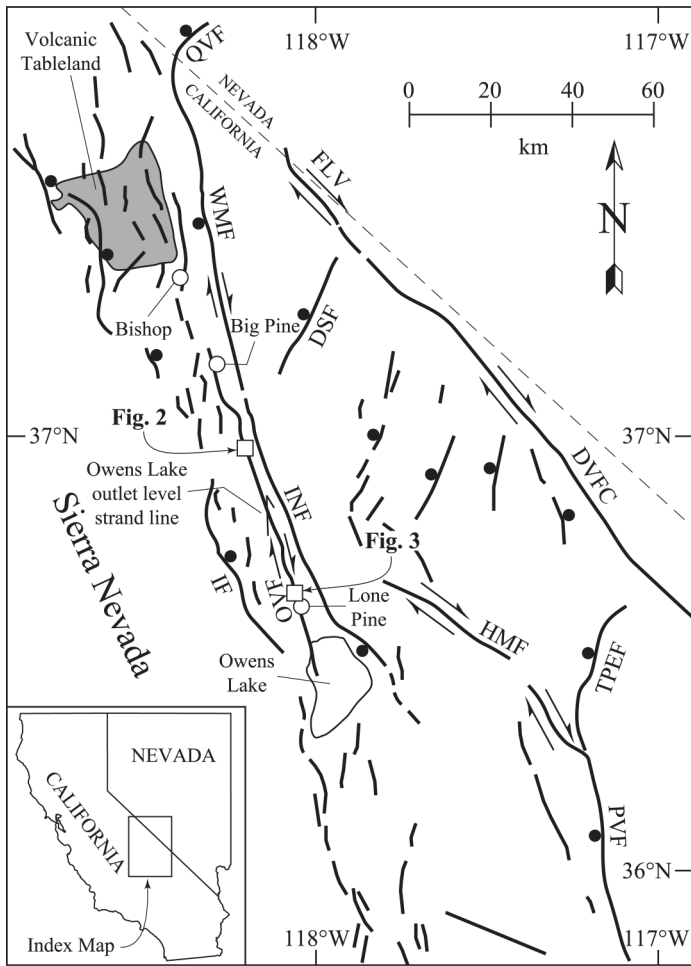
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Figure 1. Index map of major Quaternary faults in northern part of Eastern California Shear Zone. DSF—Deep Springs fault, DVFC—Death Valley–Furnace Creek fault zone, FLV—Fish Lake Valley fault zone, HMF—Hunter Mountain fault, IF—Independence fault, INF—Inyo Mountains fault zone, OVF—Owens Valley fault, PVF—Panamint Valley fault, QVF—Queen Valley fault, TPEF—Towne Pass–Emigrant fault system, WMF—White Mountains fault. Solid circle is on hanging wall of normal faults, and arrows indicate relative motion across strike-slip faults.

east- and west-facing fault scarps. The surface trace of the fault is well exposed along an east-facing fault scarp ~2 m high.

We opened an approximately east-trending, 10.5-m-long, 2.4–3.2-m-deep trench across the northern part of the fault scarp (Fig. 2). The trench cut through a sequence of playa and fluvial deposits. Both walls of the trench expose two steeply east-dipping fault strands, F1 and F2. The fault strands are defined by ≤15-cm-wide zones of massive, medium-grained sand with locally developed shear planes and pebbles aligned parallel to the fault plane. Fault F1 bifurcates to define a fault zone ~45 cm wide, cuts and offsets units 60–30 and the lower two-thirds of unit 28, and causes an apparent vertical separation in unit 30c of ~38 cm (Fig. 2). Fault F1 terminates just below a subtle color change within unit 28 that extends eastward from the contact between units 28 and 30a to the base of the discontinuous basalt cinder horizon (Fig. 2). Because this contact does not appear to be offset by fault F1, we interpret it as a post–F1 faulting stratigraphic contact. About 1.8 m of sand and silt (upper one-third of unit 28 and units 20 and 10) have been deposited across F1. Exposed ~2.1 m to the east is fault F2, which also bifurcates and is associated with a set of subparallel fractures defining a fault zone as much as ~1.6 m wide (Fig. 2). Fault F2

cuts and offsets all units except an ~20-cm-thick eolian sand (unit 10); the base of unit 25 shows an apparent vertical separation of ~15 cm across this fault.

This trench exposes evidence for the last two earthquake events. The 1872 rupture—fault F2—cuts and offsets all units except the eolian sand that has been deposited across the surface trace of the fault during the past ~130 yr. Fault F1 preserves evidence for a rupture that predates the 1872 event and is bracketed by deposition of unit 28. Units do not match across fault F1, except units 28 and 30c, implying that multiple rupture events affected this fault. However, individual events older than the penultimate event cannot be identified.

Optically Stimulated Luminescence (OSL) Dating

Five samples of fine- to coarse-grained sand from fluvial deposits were collected for OSL analysis to bracket the age of the penultimate rupture (Table A[1]; Fig. 2). Results from the hanging wall of F1 indicate ages of 4.0 ± 0.4 ka for unit 55 exposed at the base of the trench, 3.8 ± 0.3 ka and 3.3 ± 0.3 for the base and top of unit 28, respectively, and 2.5 ± 0.3 ka for the base of unit 20. In the footwall, unit 30d is bracketed between 3.0 and 14.0 ka; this wide age range is believed to be the result of incomplete bleaching of the sediment. These data are the first to bracket the timing of the pre-1872 rupture along the Owens Valley fault at between 3.3 ± 0.3 and 3.8 ± 0.3 ka. If we assume uniform return, these data indicate a recurrence interval of between 4100 and 3000 yr.

Pangborn Lane Site

At the Pangborn Lane site, ~2.3 km north of Lone Pine (Fig. 1), a repeatedly offset stream channel provides geomorphic evidence for the last three earthquake events along the Owens Valley fault (Fig. 3). Here, the west-northwest–striking, ~2.6-m-high, east-dipping fault scarp of the Owens Valley fault cuts through medium- to coarse-grained sand deposits that make up the distal part of an alluvial fan. Four channels have cut into the alluvial fan—the present-day channel, C4, and three older, beheaded channels, C1–C3. The present-day channel cuts nearly orthogonally across the Owens Valley fault and is more deeply incised in the footwall than in the hanging wall (Fig. 3). The cumulative right-lateral offsets of beheaded channels C3, C2, and C1 are 4.9 ± 0.4, 8.9 ± 0.8, and 12.9 ± 0.2 m, respectively (Fig. 3), suggest three 1872-like rupture events—4.9 m offset during the 1872 rupture and 4.0 m offset during each of the older events.

Holocene Slip Rates

We do not have absolute age limits on the older events preserved at the Pangborn Lane site, although the middle event (i.e., initial offset of channel 2) is probably the same age as the pre-1872 rupture described at our trench site. Nevertheless, limits can be placed upon the Holocene slip rate. The Pangborn Lane site is located below the most recent overflow-level strandline of Owens Lake at 1146 m, which is estimated at 10–12 ka (Beanland and Clark, 1994) (Fig. 1). The three rupture events must have occurred since then; otherwise, the right-lateral offset of these relatively shallow channels would not be preserved. Accordingly, these relations provide a minimum slip rate of 1.2 ± 0.1 mm/yr along the Owens Valley fault during the Holocene. The fact that channels C1–C3 appear to have been incised to a similar degree into the alluvial fan suggests that the time interval between initial incisement and final abandonment was approximately the same for each channel, thereby supporting our assumption of uniform re-

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[1]GSA Data Repository item 2001093, Optically stimulated luminescence dating results, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.
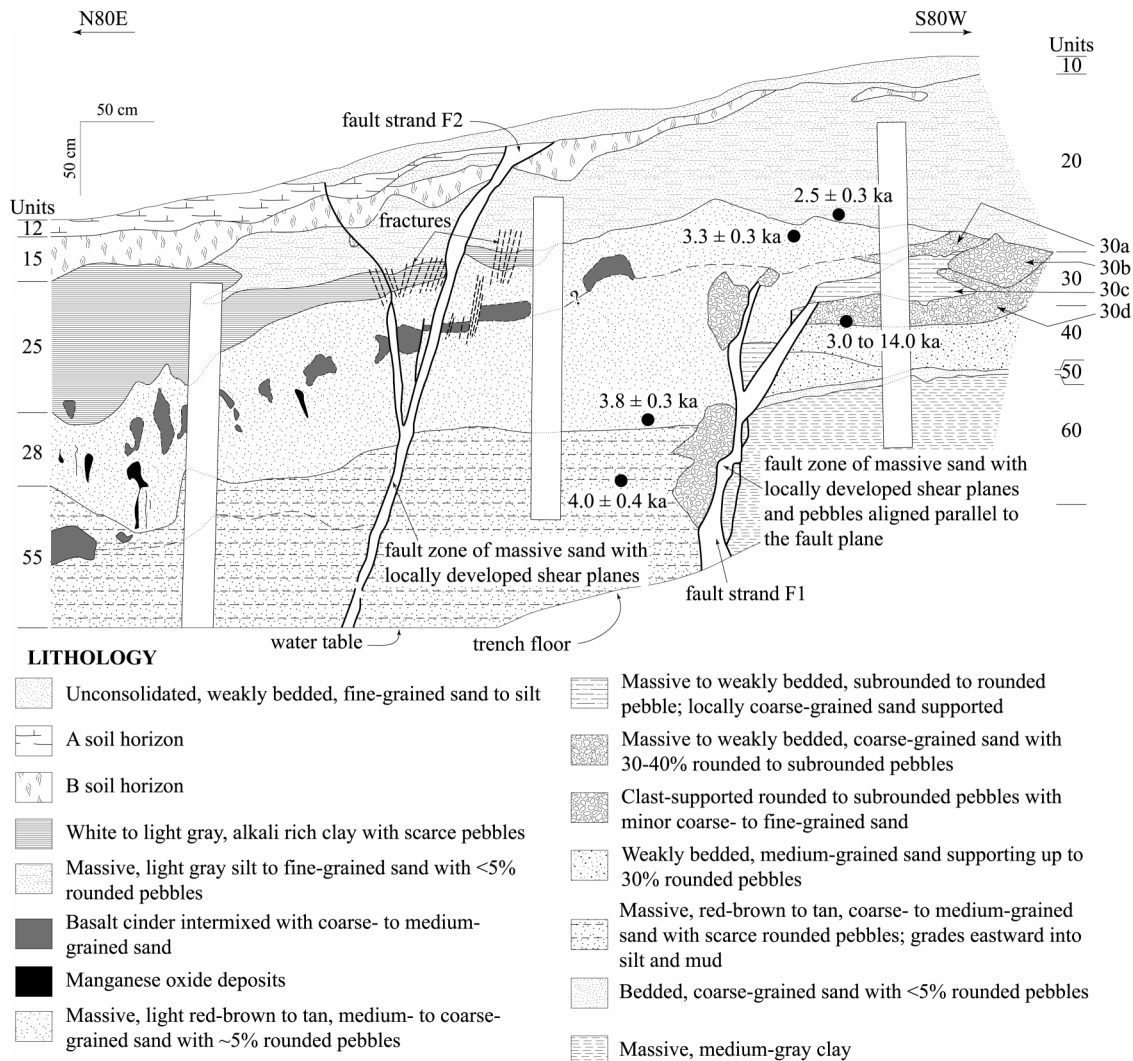
Figure 2. Synoptic log of trench excavated across Owens Valley fault. Trench records 1872 and penultimate ruptures. Location is shown in Figure 1.
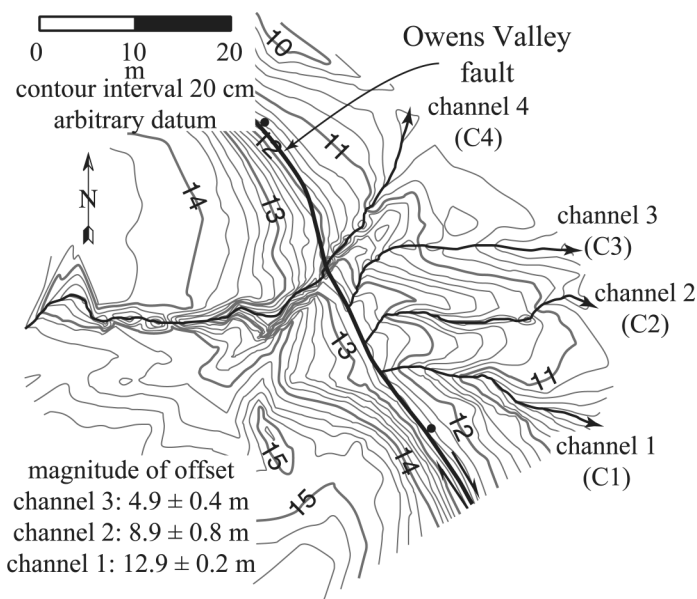

Figure 3. Contour map of repeatedly offset stream channel at Pangborn Lane site. Location is shown in Figure 1.

currence and providing a better estimate of minimum slip rate. The recurrence interval determined from our trenching studies implies that the oldest of the three rupture events preserved at Pangborn Lane occurred ca. 6.0–8.2 ka, indicating a minimum slip rate of 1.8 ± 0.3 mm/yr. Finally, if we forsake our assumption of uniform recurrence and assume that the older two events occurred within a few years of each other between 3.3 ± 0.3 and 3.8 ± 0.3 ka, this implies a maximum late Holocene slip rate of 3.6 ± 0.2 mm/yr.

DISCUSSION AND CONCLUSIONS

These new paleoseismic data bracket the timing of the pre-1872 rupture along the Owens Valley fault to between 3.3 ± 0.3 and 3.8 ± 0.3 ka and indicate a Holocene slip rate between 1.8 ± 0.3 and 3.6 ± 0.2 mm/yr, which is the same, within error, of Beanland and Clark's (1994) estimate of 2 ± 1 mm/yr. If we assume uniform return, the earthquake recurrence interval is between 4100 and 3000 yr. We cannot define the onset of faulting along the Owens Valley fault. However, the White Mountains fault contains geomorphic evidence for strike-slip faulting (dePolo, 1989) and was the site of a series of primarily strike-slip earthquakes in 1986 (Cockerham and Corbett, 1987), whereas faults along the eastern Sierra Range front (Berry, 1997) and Volcanic Table-land (e.g., Ferrill et al., 1999) exhibit geomorphic evidence for normal faulting. These relations suggest that slip along the Owens Valley fault

continues northward along the White Mountains fault. Because the Queen Valley fault (Fig. 1) forms the northern termination of the White Mountains fault, Stockli (1999) argued that the opening of the basin at 3.0 ± 0.5 Ma recorded the onset of slip along the White Mountains–Owens Valley fault system. Assuming that our calculated Holocene slip rate along the Owens Valley fault has remained constant since onset of slip at ca. 3 Ma implies that the total offset across the Owens Valley fault is ~3.8–13.3 km, in accord with estimates of total horizontal offset based on correlation of the Independence dike swarm and two Cretaceous plutons across the fault (Moore and Hobson, 1961; Ross, 1962).

Dixon et al. (1995) proposed a kinematic model for this part of the Eastern California Shear Zone that makes two predictions. The first states that since ca. 1.5 Ma, the locus of right-lateral shear has shifted or is in the process of shifting from the Death Valley–Furnace Creek fault zone to the Owens Valley fault. Because motion along the Owens Valley fault began at ca. 3 Ma, slip along the Death Valley–Furnace Creek, the Fish Lake Valley, and/or the Hunter Mountain–Panamint Valley fault zones must have decreased in order to accommodate motion along this new fault, consistent with this part of the model. Estimated late Pleistocene to Holocene slip rates along these faults (Klinger, 1999; Zhang et al., 1990; Oswald, 1998; Reheis and Sawyer, 1997; this work) are compatible with right-lateral shear concentrated along the Death Valley–Furnace Creek and Fish Lake Valley fault zones, with lesser slip along the Owens Valley and Hunter Mountain–Panamint Valley faults, or with slip equally distributed among these fault systems.

The second prediction of the Dixon et al. (1995) model states that northeast-striking, northwest-dipping normal faults, such as the Deep Springs and Towne Pass–Emigrant faults (Fig. 1), transfer slip from the Owens Valley and Hunter Mountain–Panamint Valley fault zones to the northern Death Valley–Furnace Creek and Fish Lake Valley fault zones. If we assume that our estimated Holocene slip rate for the Owens Valley fault is constant throughout its slip history, then initiation of slip along the Deep Springs fault ca. 1.7 Ma captured ~0.7 mm/yr (~15%–45%) (Lee et al., 2001) of Owens Valley fault slip. The remaining slip along the Owens Valley fault must continue northward along the White Mountains fault.

Elastic half-space modeling of geodetic data yields present-day slip rates of 4.0–8.5 mm/yr along the Owens Valley fault (e.g., Dixon et al., 2000; Gan et al., 2000), about twice our estimated geologic slip rate. Accounting for viscoelastic properties of the lower crust and seismic cycle effects may reduce this discrepancy. Using the recurrence interval estimated here, GPS data from Dixon et al. (2000), and the viscoelastic model of Savage and Lisowski (1998), Lee et al. (2000) estimated a present-day slip rate of 1.7 ± 1.0 mm/yr, in agreement with the geologic rate. Alternatively, geologic slip rates along the Lone Pine fault (Fig. 1) may contribute a significant proportion of right-lateral shear to the total slip across Owens Valley. Offset measurements (Lubetkin and Clark, 1988) and geochronologic data (Bierman et al., 1995) from the Lone Pine fault yield a Holocene right-lateral slip rate of 0.8 ± 0.4 mm/yr, suggesting a Holocene slip rate between 2.6 ± 0.5 and 4.4 ± 0.4 mm/yr across Owens Valley; this rate is the same, within error, as the geodetic rates.

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