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Late Pleistocene slip rate along the Owens Valley fault, eastern California

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[1] The Owens Valley fault zone (OVF) is one of the primary structures accommodating dextral shear across the Eastern California shear zone (ECSZ). Previous estimates of the Holocene slip rate along this structure rely on paleoseismic data and yield rates 2–3 times lower than those implied by geodetic velocities. Using displaced lava flows along the flank of Crater Mountain, we present the first estimate of slip rate along the OVF during the late Pleistocene. Subsurface characterization of the flow margin using a ground-penetrating radar (GPR) allows for relatively precise determination of dextral displacement, and terrestrial cosmogenic ^{36}Cl exposure ages of samples from the flow surface yield slip rates between ~2.8 – 4.5 mm/yr over the past 55–80 kyr. Our results suggest either that paleoseismic slip-rate estimates underestimate the long-term slip rate or that rates of strain release have not been steady during the latter part of the Quaternary.

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1. Introduction

[2] Space geodetic measurements across zone of active deformation over the past decades reveals that far-field velocities typically match relative plate motions [e.g., *d'Alessio et al.*, 2005], suggesting that the rates of plate boundary deformation are steady over timescales of 10^6 yr. Whether or not these far-field rates are matched by geologic slip rates across a deforming region, however, depends on the nature of how and where elastic strain is released. Seismic clustering [*Rockwell et al.*, 2000], transient post-seismic strain [*Dixon et al.*, 2003], switching between individual fault strands [*Bennett et al.*, 2004], and transient rates of loading [*Bellier and Zoback*, 1995; *Peltzer et al.*, 2001] all may influence the instantaneous distribution of deformation. In principle, comparison of geodetically-determined loading rates with geologic slip rates could yield insight into the relative contribution of these processes [e.g., *Meade and Hager*, 2005]. However, in practice, incomplete knowledge of the temporal and spatial distribution of fault slip often hinders such interpretations.

[3] A prominent example of a discrepancy between geologic slip rates and geodetic velocities occurs in eastern California. Here, ~10 to 14 mm/yr of right-lateral shear is accommodated across a shear zone (Eastern California Shear Zone – ECSZ) that extends from the Mojave Desert to the Walker Lane region [*Miller et al.*, 2001; *Savage et al.*, 1990]. This rate conflicts with budgets of geologic slip across active faults in the Mojave [*Dokka and Travis*, 1990a, 1990b; *Oskin and Iriondo*, 2004; *Oskin et al.*, 2007], and has been suggested to reflect transient strain accumulation within the shear zone [*Peltzer et al.*, 2001]. North of the Garlock fault, dextral shear is accomplished by oblique transtension on a network of strike-slip and normal faults east of the Sierra Nevada [e.g., *Unruh et al.*, 2003]. Although the discrepancy between geologic and geodetic data across this portion of the shear zone has been attributed to a post-seismic transient following the 1872 M_w ~7.5 rupture on the Owens Valley fault [*Dixon et al.*, 2003], recent slip-rate determinations on other faults in the system [e.g., *Frankel et al.*, 2007a] suggest that the discrepancy may simply reflect an incomplete understanding of geologic slip rates over appropriate timescales (10^4–10^5 yr).

[4] Central to this question is the rate of slip on the Owens Valley fault during the late Pleistocene (Figure 1). The fault is characterized by a sharp, linear array of scarps for ~100 km along strike in the central Owens Valley that record 6 ± 2 m of right-lateral slip during the 1872 event [*Beanland and Clark*, 1994]. Numerous studies have focused on the paleoseismic history of the fault [*Bacon and Pezzopane*, 2007; *Beanland and Clark*, 1994; *Lee et al.*, 2001; *Lubetkin and Clark*, 1988], determining that the recurrence interval ranges from 3–5 kyr to ~10 kyr. None of these studies, however, directly quantify the long-term slip rate across the fault. All are forced to rely on assumptions of uniform recurrence and characteristic slip per event to derive slip rates. Estimates thus derived range from 1.0 ± 0.5 mm/yr [*Bacon and Pezzopane*, 2007] to 3.6 ± 0.2 mm/yr [*Lee et al.*, 2001], with the majority of estimates falling near the lower end of this range.

[5] Direct dating of landscape features, enabled by cosmogenic isotopic methods [*Gosse and Phillips*, 2001], affords the opportunity to refine our understanding of the millennial-scale slip rate on fault systems, and to thus effect a more direct comparison to geodetic data [e.g., *Frankel et al.*, 2007a; *Kirby et al.*, 2006; *Oskin et al.*, 2007]. Here, we quantify right-lateral displacement rates across the Owens Valley fault using basaltic lava flows associated with the Big Pine volcanic center (Figure 1). We combine field surveys with ground-penetrating radar investigations to characterize the magnitude of displacement; cosmogenic ^{36}Cl samples from well-preserved remnants of the flow surface place bounds on the age of the flows. Our studies provide the first, direct measure of the long-term rate of slip along the Owens Valley fault zone and have important

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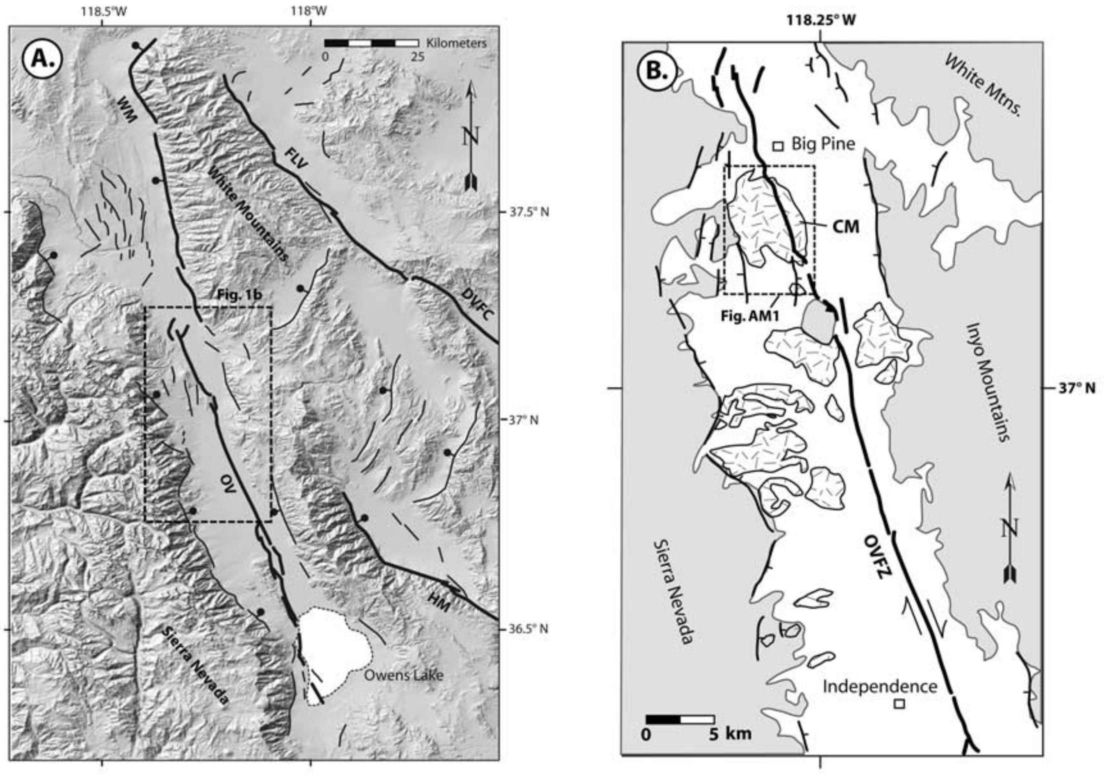

Figure 1. (a) Simplified map of major faults in the Eastern California shear zone. Abbreviations are DVFC, Death Valley/Furnace Creek fault zone; FLV, Fish Lake Valley fault zone; HM, Hunter Mountain fault zone; OV, Owens Valley fault zone; and WM, White Mountain fault zone. (b) Simplified map of the northern Owens Valley showing the distribution of Quaternary volcanic deposits of the Big Pine Volcanic Field (hachured pattern). CM, Crater Mountain. Modified following *Bacon and Pezzopane* [2007].

implications for the rates and patterns of strain release across eastern California.

2. Active Deformation in Owens Valley

[6] Dextral shear in the ECSZ between ∼36° and 38° north latitude is largely accomplished by dextral-oblique slip on a system of NNW-striking faults that include the Death Valley-Fish Lake Valley, Panamint Valley-Hunter Mountain, and Owens Valley fault zones (Figure 1a). Geologic data suggest that faults in Death Valley [*Frankel et al.*, 2007a] and Fish Lake Valley [*Frankel et al.*, 2007b; *Reheis and Sawyer*, 1997] account for the bulk of this shear, exhibiting Late Pleistocene slip rates in excess of ∼3 – 5 mm/yr. In contrast, geodetic data fit by elastic half-space models predict that at least half of the total shear is localized across the Owens Valley at rates of 5–7 mm/yr [*McClusky et al.*, 2001; *Miller et al.*, 2001]. Recent attempts to reconcile this with the relatively low slip rate inferred for the Owens Valley fault (1–3 mm/yr) call on transient post-seismic strain to explain the discrepancy [*Dixon et al.*, 2003].

[7] As noted above, long-term slip-rates along the Owens Valley fault (OVF) are highly uncertain, dependent on assumptions required to relate vertical displacement observed in fault trenches to horizontal slip. Most studies assume a uniform recurrence interval for seismic events along the fault; *Lubetkin and Clark* [1988] and *Beanland and Clark* [1994] both argued for three 1872-like events during past 12–24 ka [*Bierman et al.*, 1995] along the Lone Pine fault (a secondary strand of the OVF, Figure 1a), and *Lee et al.* [2001] made a similar argument along the primary fault trace. Assuming that the 6:1 ratio of horizontal to vertical slip observed following the 1872 event is characteristic of ruptures along the OVF, these studies estimated long-term dextral slip rates of 0.7 – 2.2 mm/yr, 1 – 3 mm/yr, and 1.2 – 1.8 mm/yr, respectively. *Lee et al.* [2001] further suggested that, if the assumption of uniform recurrence is relaxed, the maximum allowable rate could be as high as 3.6 mm/yr. In contrast, recent paleoseismic investigations along the central segment of the OVF reveal evidence for only two events during the Holocene [*Bacon and Pezzopane*, 2007] and suggest that the slip rate over this time may be as low as 1.0 ± 0.5 mm/yr.

3. Millennial Slip Rate of the Owens Valley Fault

3.1. Crater Mountain Site

[8] The key to surmounting uncertainties in slip-rates derived from paleoseismic data is to quantify finite offset of geologic or geomorphic markers along the fault zone. For much of its length, the fault runs along the floodplain of the Owens River, making this task challenging. However, the northern third of the fault transects the Big Pine Volcanic Field (Figure 1b), a collection of Late Quaternary bimodal volcanic centers. South of the town of Big Pine (Figure 2),

the fault displaces basaltic lava flows along the eastern flank of Crater Mountain [see *Beanland and Clark*, 1994, plate 4], although the similarity in composition among individual flows makes correlation difficult. At the northeast corner of the cone, however, the flow margin is displaced in a right-lateral sense across the main trace of the OVF. The fault geometry defines a small releasing step at this site (Figure 2), and it is possible that apparent lateral separation resulted from a component of east-side-down slip of the shallowly NE-dipping flow surface and subsequent burial by modern alluvium.

[9] To test the hypothesis that dextral separation observed at the surface is a reliable measure of the horizontal component of slip along the OVF, we conducted a ground-penetrating radar (GPR) survey of the site to characterize the subsurface geometry of the flow margin (Figure 2). Details of the instrument and methodology are available as auxiliary materials.[1] Surveys east of the fault reveal an abrupt transition between basalt and alluvium (Lines 9 and 11, Figures 2 and S1), suggesting that the flow margin is relatively steep and does not extend beneath the alluvium. West of the fault, "islands" of basalt surrounded by young alluvium (Figure 2a) indicate that the flow margin here is likely buried. Surveys in this region confirm this hypothesis, revealing reflectivity similar to the basalt (Lines 16 and 19, Figures 2 and S1) and a strong reflector at ~220 ns that may represent the base of the flow (Figure 2d). In contrast, transects crossing the fault (Lines 13 and 15, Figures 2 and S1) reveal only shallow, continuous reflectors characteristic of alluvium. These reflectors appear to truncate near the projected trace of the fault (Figure 2e). However, we observe no deeper reflectivity that would suggest the presence of a buried basalt flow east of the fault trace.

[10] We conclude that the apparent dextral separation of the flow margin is real and provides a measure of displacement integrated over the age of the flow. Surveys of the flow margin indicate ~235 ± 15 m of displacement; a similar value is achieved by measurements on USGS digital orthophotographs (Figure 2f).

3.2. Age of the Crater Mountain Basalt

[11] The chronology of eruptive volcanism in the Big Pine Volcanic Field is relatively well-known from K-Ar dating to range from ~1.2 Ma to <0.1 Ma [*Connor and Conway*, 2000; *Turrin and Gillespie*, 1986]. Although even higher precision ages are available from thermochronology of granitic xenoliths incorporated into magmas [*Blondes et al.*, 2007; *Gillespie et al.*, 1984], the age of flows emanating from the Crater Mountain vent is not well-known. A K/Ar age of 290 ± 40 ka was determined for flows west of the central vent [*Turrin and Gillespie*, 1986], whereas unpublished ^{3}He exposure ages from flows on the SE corner of the cone cluster between 105 – 115 ka (J. Stone, unpublished data, 2006, as referred to by A. Gillespie, personal communication, 2006).

[12] To determine the age of flows displaced across the OVF, we collected samples for exposure dating using ^{36}Cl (see auxiliary materials). The latter method has the advantage of relatively high production rates from a number of target elements, primarily K and Ca [*Gosse and Phillips*, 2001]. Three samples from the flow surface immediately west of the OVF yield exposure ages that range from 70 – 88 ka (Table S1), and an additional three samples from flows on the southwestern flank of the complex (Figure S1) yield ages ranging from 80 – 96 ka. These ages represent maximum estimates of the time of exposure; any mass loss during weathering of the flow surface implies younger ages (see auxiliary materials). To account for this effect, we model the age for samples subjected to steady surface erosion of 0.5 – 5 mm/kyr [cf. *Zehfuss et al.*, 2001], and we consider that the most probable erosion rates fall in the middle of this range (~1 to 3 mm/kyr). Using these criteria, our data indicate that the flows along the NE flank of Crater Mountain are likely between ~56 – 80 ka (Table S1). The flows on the SE flank of the vent may be slightly older, ranging from 63 – 84 ka (Table S1), although these ages ranges overlap within uncertainty. Notably, these ages (and the unpublished ^{3}He ages of J. Stone, unpublished data, 2006) differ significantly from the K/Ar age of 290 ± 40 ka [*Turrin and Gillespie*, 1986], and may point to the presence of excess Ar in this sample.

3.3. Slip-Rate of the Owens Valley Fault

[13] Our new age determinations (55 – 80 ka) and the offset of the flow margin across the OVF (235 ± 15 m) suggest that, at a minimum, slip rates along this structure have averaged ~2.8 mm/yr during the late Pleistocene. This value is consistent with, but at the high end of, previous estimates [*Beanland and Clark*, 1994; *Lee et al.*, 2001]. Moreover, it is 2 – 3 times greater than Holocene rates of *Bacon and Pezzopane* [2007]. Our data further permit the possibility that slip rates along the OVF have been as high as ~4.5 mm/yr since 55 ka.

4. Implications

4.1. Comparison With Paleoseismically-Determined Slip Rates

[14] One possible explanation for the difference between our results and previous slip rate estimates along the southern OVF [*Bacon and Pezzopane*, 2007] is that the paleoseismic rates underestimate the true slip along the fault. The limited spatial scope of trench coverage allows for the possibility that adjacent fault strands (not activated in 1872) were responsible for slip prior to the Holocene. A more intriguing explanation for the discrepancy, however, is the possibility that a significant amount of slip along the OVF was accomplished by episodes of temporally-clustered fault slip. Non-steady strain release associated with clusters of paleoseismicity appears to characterize fault systems in the southern ECSZ [*Rockwell et al.*, 2000]. Our data could be interpreted to indicate that the OVF experienced a period of rapid slip, sometime between ca. 80 ka and 20 ka. Confirmation of this, however, will require deep records of the paleoseismic behavior of the fault.

[15] Alternatively, the differences in slip rate between the southern and northern Owens Valley fault may reflect along-strike variations in fault slip that are maintained over geologic time. Slip gradients appear to be present along the Calico-Blackwater fault system in the Mojave [*Oskin and*

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2007GL031970.

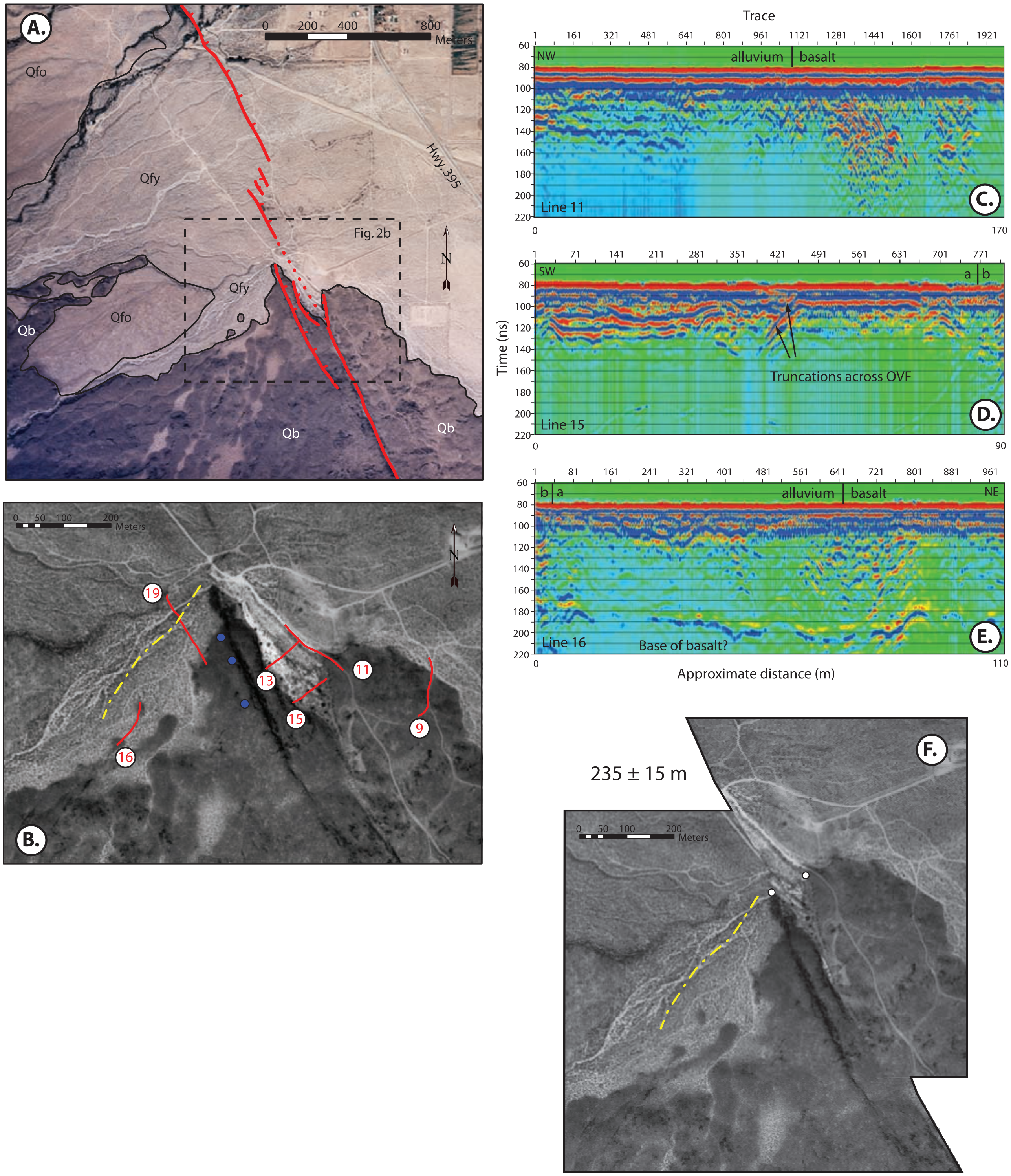

Figure 2. (a) Surficial geology of the northeastern flank of Crater Mountain overlain on a color air photo. Note that basalt flows (Qb) overlie older alluvial fans (Qfo) west of the study area, and appear to be buried by younger alluvium (Qfy) west of the trace of the Owens Valley fault (red). Hachures represent the facing direction of the fault scarps. (b) Close up of the offset flow margin. Background is a USGS digital orthophoto quadrangle (DOQ). Red lines represent GPR surveys conducted across the flow margin, and blue circles represent sampling localities for cosmogenic isotope exposure ages. Yellow dashed line represents the inferred position of the buried flow margin west of the Owens Valley fault. (c)–(e) GPR results from lines 11, 15, and 16, respectively. See text for discussion of results. (f) Reconstruction of slip along the Owens Valley fault restores inferred former positions of the flow margin. Dashed line represents inferred position of the buried flow margin. Note that the extensional component of slip is not well-constrained, but some degree of extension across the fault is geometrically required and appears to range from 30 – 50 m.

Iriondo, 2004; *Oskin et al.*, 2007] and are expected to be characteristic of youthful fault systems [*Cowie and Roberts*, 2001]. If such gradients are characteristic of long-term differences in strain accumulation, they may suggest a spatially-heterogeneous distribution of earthquakes over the past ca. 80 ka [*Bacon and Pezzopane*, 2007].

4.2. Strain Evolution Through Space and Time

[16] From a regional perspective, our results contribute to an emerging picture of spatial variations in slip rate along the ECSZ. New slip rate estimates for the Death Valley-Furnace Creek – Fish Lake Valley fault system suggest that late Pleistocene (ca. 80 ka) slip rates decrease northward from 4–5 mm/yr near the center of the Death Valley fault zone [*Frankel et al.*, 2007a] to 2–3 mm/yr along the Fish Lake Valley fault [*Frankel et al.*, 2007b]. Similarly, right-lateral slip rates in the Owens Valley appear to decrease northward, from 3 – 4 mm/yr along the OVF to ~0.5 mm/yr along the White Mountain fault zone [*Kirby et al.*, 2006]. These patterns suggest that simple approaches to reconciling geologic slip and geodetic strain by summing geologic slip along a two-dimensional transect are likely to be misleading. Although strain accumulation and release may reconcile across a given transect [e.g., *Frankel et al.*, 2007a], the spatial distribution of strain in a young, evolving fault system may be quite variable along strike.

[17] The ultimate cause of such spatial variations in fault slip within this portion of the ECSZ remains enigmatic. *Frankel et al.* [2007b] suggest that, if strain accumulation remains constant from south to north, then a significant proportion of slip may accommodated by faults to the east of Fish Lake Valley [*Oldow et al.*, 2001]. Alternatively, the northward decrease in slip rate along the Owens Valley and Fish Lake Valley fault systems may imply a greater role for strain release along distributed networks of faults [*Sheehan*, 2007] and/or block rotations [*Oldow et al.*, 2001].

[18] Both of these explanations call on steady rates of strain accumulation through time, an assumption that may not be entirely valid for this region. *Bellier and Zoback* [1995] first proposed that local stress fields may vary on timescales of 10^5 yr. Recent studies of the White Mountain fault zone [*Kirby et al.*, 2006] and of distributed extension in northern Owens Valley [*Sheehan*, 2007] appear to confirm variations in deformation rate during the middle and late Pleisotocene. Whether these variations reflect true transient variations in loading rate across the ECSZ, or whether they simply reflect the localization of strain during ongoing evolution and maturation of a fault system remains a first-order question. Regardless, our results provide the first constraints on Late Quaternary slip rates along the OVF and reveal rapid displacement across this portion of the Eastern California Shear Zone.

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