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Pliocene sinistral slip across the Adobe Hills, eastern California–western Nevada: Kinematics of fault slip transfer across the Mina deflection

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ABSTRACT

The Adobe Hills region (California and Nevada, USA) is a faulted volcanic field located within the western Mina deflection, a right-stepping zone of faults that connects the northern Eastern California shear zone (ECSZ) to the south with the Walker Lane belt (WLB) to the north. New detailed geologic mapping, structural studies, and 40Ar/39Ar geochronology in the Adobe Hills allow us to calculate fault slip rates and test predictions for the kinematics of fault slip transfer into the Mina deflection. The Adobe Hills are dominated by Pliocene tuffaceous sandstone, basaltic lavas that yield 40Ar/39Ar geochronology of 11.17 ± 0.04 Ma, and Quaternary tuffaceous sands, alluvium, and lacustrine deposits cap the sequence. Northwest-striking normal faults, west-northwest–striking dextral faults, and northeast-striking sinistral faults cut all units; the northeast-striking sinistral faults are the youngest and most welldescribed fault set. We calculate ~0.1 mm/yr of approximately east-west horizontal extension and northwest dextral shear since the Pliocene. The prominent northeast-striking sinistral faults offset basalt ridgelines, normal fault–hanging-wall intersections, a channelized basalt flow, a basalt flow edge, and a basalt flow contact a net minimum of 921 ± 184 to 1318 ± 264 m across the Adobe Hills. These measured sinistral offsets yield a minimum Pliocene sinistral fault slip rate of 0.2–0.5 mm/yr; our preferred minimum slip rate is 0.4–0.5 mm/yr. The geometry and orientation of the prominent sinistral faults are consistent with simple shear/couple clockwise block rotation within a broad dextral shear zone. Vertical axis block rotation data are needed to test this interpretation.

We propose that a set of faults subparallel to Sierra Nevada–North America motion and associated releasing steps, located west of the White Mountains fault zone and east of the Long Valley Caldera, transfer a portion of dextral Owens Valley fault slip northward onto the sinistral faults in the Adobe Hills. Dextral slip distributed across faults between the White Mountains fault zone and the Sierra Nevada and east of the Fish Lake Valley fault zone may account for the apparent discrepancy between summed long-term geologic slip rates and present-day geodetic rates across the northern ECSZ. Fault slip in the Adobe Hills is part of a regional pattern of initiation and renewal of dextral, sinistral, and normal fault slip during the Pliocene that extends from lat ~40°N to ~36°N within the ECSZ-WLB and along the western margin of the Basin and Range Province. This regional deformation episode may be related to changes in gravitational potential energy.

INTRODUCTION

Geologic and geodetic studies indicate that the San Andreas fault accommodates ~75%–80% of relative dextral motion between the Pacific–North American plates, and the Eastern California shear zone (ECSZ)–Walker Lane belt (WLB) accommodates the remaining 20%–25% (Fig. 1A) (e.g., Dokka and Travis, 1990; Dixon et al., 1995, 2000; Bennett et al., 2003; Frankel et al., 2007; Lee et al., 2009a). In the northern ECSZ, dextral shear is primarily accommodated along four major northwest-striking dextral faults (Fig. 1B). These faults transfer slip northward onto several smaller primarily east-northeast–striking faults within the Mina deflection, an ~125-km-long, ~45-km-wide deformation zone. The Mina deflection transfers slip northward onto northwest-striking dextral faults of the central WLB (Figs. 1B and 2). Thus, the Mina deflection defines an east-northeast–trending right-stepping relay zone within a dominantly northwest-trending dextral shear zone.

Three mechanisms have been proposed to explain the fault kinematics that accommodate displacement transfer across the Mina deflection: (1) the displacement-transfer model (Fig. 3A) (Oldow, 1992; Oldow et al., 1994), in which connecting faults transfer slip via normal slip; (2) the transtensional model (Oldow, 2003) (Fig. 3B), in which oblique (sinistral) normal slip occurs along the connecting faults; and (3) the simple shear couple/fault block rotation model (Wesnousky, 2005) (Fig. 3C), in which sinistral slip occurs along the connecting faults. Geologic map relations, structural data, and seismicity in the northern ECSZ, Mina deflection, WLB, and Basin and Range Province led Oldow (1992) and Oldow et al. (1994) to propose the displacement-transfer model for the Mina deflection, whereby extension across northeast-striking normal faults proportionally accommodates the magnitude of Middle Miocene to Pliocene dextral fault slip transferred between the northern ECSZ and central WLB (Fig. 3A).

Using a combination of global positioning system velocities, earthquake focal mechanisms, and fault-slip inversions, Oldow (2003) postulated that instantaneous deformation across the Mina deflection region is currently accommodated by transtension (Fig. 3B). In this model, deformation in the western Mina deflection is characterized by extension-dominated transtension, whereas the eastern part is characterized by wrench-dominated transtension. Fault geometries, sinistral offset, and paired basins at the ends of active east-northeast–striking faults in the Mina deflection led Wesnousky (2005) to hypothesize that during the Holocene, fault blocks bounded by northeast-striking sinistral
faults rotated clockwise in response to north-west-dextral shear across the Mina deflection (Fig. 3C). Paleomagnetic studies in the eastern Mina deflection imply clockwise rotation of ~74° and ~14° since the Miocene and Pliocene, respectively (Rood et al., 2011). These data suggest that the Wesnousky (2005) model is also applicable to older deformation within the Mina deflection. In contrast, geologic studies centered on Quaternary faults in the Queen Valley area did not yield evidence for recent clockwise block rotation (Lee et al., 2009b), suggesting that clockwise rotation is temporal and/or occurs in discrete zones within the Mina deflection.

The results from new detailed geologic mapping, kinematic, and ⁴⁰Ar/³⁹Ar geochronology studies completed in the Adobe Hills, western Mina deflection, are reported in this paper. These data allow us to test models for fault
slip transfer across the Mina deflection. From these data, we infer that a portion of dextral slip along the Owens Valley fault is transferred to the sinistral faults in the Adobe Hills and that Pliocene deformation in the Adobe Hills is part of a regional Pliocene event the length of the ECSZ-WLB.

TECTONIC SETTING AND GEOLOGY OF THE ADOBE HILLS

The Adobe Hills, an ~110 km² faulted volcanic field located east of the Sierra Nevada, are located along the eastern edge of the Mono Basin within the western Mina deflection (Figs. 1B, 2, and 4). The Mina deflection is underlain by Paleozoic miogeoclinal sedimentary rocks and Mesozoic volcanic rocks and granitic plutons, Neogene ignimbrite, andesite, and basalt flows, tuffaceous sediments, and volcanic breccias, and Quaternary lacustrine and eolian sediments (e.g., Gilbert et al., 1968; Krauskopf and Bateman, 1977; Oldow, 1992; Reheis et al., 2002; Bradley, 2005; Tincher and Stockli, 2009; Petronis et al., 2009; Oldow et al., 2009; this study). Structural, paleomagnetic, and strontium isotopic studies suggest that east-northeast– to northeast-striking active sinistral faults within the Mina deflection followed mid-Paleozoic to Mesozoic contractional structures, which followed the morphology of an embayment in the early Paleozoic rifted continental margin of the western U.S. (Oldow et al., 1989, 2009; Tosdal et al., 2000).

Pliocene basaltic lavas and cinder cones form the Adobe Hills, interfinger with lesser early Pliocene lacustrine sediments, and overlie tilted Miocene andesite flows (Gilbert et al., 1968, this study). Two episodes of deformation in the Adobe Hills were noted by Gilbert et al. (1968) and our study: (1) pre-Pliocene deformation marked by tilted and offset Miocene ignimbrite flows where the stratigraphic throw is larger than the throw of basalt flows, and (2) Pliocene to present deformation evidenced by normal, dextral, and sinistral faulting of Pliocene basalt flows. Extension and strike-slip faulting across the area has formed a complex ridge and valley morphology.

As part of a larger mapping project, Krauskopf and Bateman (1977) mapped the southern Adobe Hills at a 1:62,500 scale and documented welded latite tuff, basaltic flows, and basalt scoria cut by northwest-, north-south-, and northeast-trending normal faults. Reheis et al. (2002) completed a more detailed geologic map of the western Adobe Hills that focused on Quaternary units, faults, and the Adobe Hills Spillway bedrock channel. Formation of the Adobe Hills Spillway suggests that Pleistocene faulting lowered topography and allowed southward drainage of Pleistocene Lake Russell (Reheis et al., 2002).

GEOLoGIC ROCK UNITS AND AGES

The oldest unit exposed in the Adobe Hills comprises tilted Late Miocene welded and unwelded porphyritic plagioclase + biotite ± augite-bearing latite ignimbrite (Figs. 4 and 5). Welded ignimbrite is exposed in the northern Adobe Hills at the foothills of the Excelsior Mountains, while a single outcrop of unwelded ignimbrite is exposed in the footwall of a normal fault in the southern Adobe Hills (Fig. 4). Nearly horizontal Late Miocene aphyric to phyric olivine + pyroxene– and plagioclase-bearing basalt flow cover ~80% of the Adobe Hills region and unconformably overlie tilted latite ignimbrite. The relatively high standing exposure of Mlt in the northeastern part of the field area (locality...
of the $^{40}$Ar/$^{39}$Ar sample that yields a $11.17 \pm 0.04$ Ma age; see following) and the curved Mlt-Pbo contact (Fig. 4) along both cross-sections suggest that Mlt had paleorelief prior to eruption of the Pliocene basalt lavas (Fig. 4). Four different basalt flow units, mapped based on mineralogy and flow character, interfinger across the Adobe Hills. The source areas for these flows were not observed. Basalt flows thin to the north and northeast, where they mantle older ignimbrite units (Fig. 4A) (Gilbert et al., 1968). A unique channel of subrounded cobble- to boulder-sized clasts of basalt lava (a channelized rubble basalt flow) containing sector-zoned pyroxene is exposed in the south-central part of the map area (Figs. 4A and 5). Lacustrine deposits and tuffaceous sandstones are locally interbedded with lower basalt flows; 13 Pliocene red-weathering cinder cones overlie basalt flows. Quaternary sediments in the Adobe Hills include undifferentiated tuffaceous sands, playa deposits, basalt alluvium, landslides, and eolian deposits. Quaternary lacustrine deposits and beach gravels are concentrated in the western Adobe Hills (Reheis et al., 2002).

$^{40}$Ar/$^{39}$Ar Geochronology

To constrain the age of basalt flows and faulting, and to calculate fault slip rates in the Adobe Hills, one ignimbrite sample and five basalt samples were dated using $^{40}$Ar/$^{39}$Ar incremental heating techniques (Figs. 4A and 6; Table 1; Supplemental File 1'). Analytical and data interpretation techniques are described in the Supplemental File (see footnote 1). Plagioclase separated from a welded latite ignimbrite from the northeastern Adobe Hills (unit Mlt; sample AH09–41) yields an $^{40}$Ar/$^{39}$Ar plateau age of $11.17 \pm 0.04$ Ma. Groundmass concentrates from samples of dense basalt flow interiors yield either plateau ages or decreasing age spectra due to $^{39}$Ar recoil (Turner and Cadogan, 1974; Onstott et al., 1995). Recoil model ages for these recoil-affected samples are calculated by incorporating age dispersion into the weighted mean age error, and are interpreted as the most reliable ages. The oldest dated basalt flow, unit Pbc (sample AH09–42), collected on the same ridge as the dated welded ignimbrite, yields a plateau age of $3.43 \pm 0.01$ Ma. Two unit Pbo basalt flows were dated; one from the top of a normal fault–bounded ridge (sample AH08–35) yields a plateau age of $3.28 \pm 0.03$ Ma, and the other from the base of the same ridge (sample AH09–201) yields a recoil model age of $3.39 \pm 0.03$ Ma. The channelized, rubble basalt flow, unit Pbr (sample AH08–19b), offset along a sinistral fault in the south-central Adobe Hills, yields an $^{40}$Ar/$^{39}$Ar plateau age of $3.20 \pm 0.03$ Ma. The youngest dated basalt flow, collected from unit Pbc at the top of a sinistral fault scarp in the northeastern Adobe Hills (sample AH08–33), yields a recoil model age of $3.13 \pm 0.02$ Ma. Our geochronologic data suggest that the basalt flows exposed across the Adobe Hills were emplaced over a short time period, <400 k.y.

Figure 3. Block diagrams illustrating models proposed to explain fault slip transfer across the Mina deflection. (A) Displacement transfer model in which normal slip along connecting faults transfers fault slip (modified from Oldow, 1992; Oldow et al., 1994). (B) Transtensional model showing a combination of sinistral and normal slip along connecting faults. (C) Clockwise block rotation model in which sinistral slip along connecting faults, combined with vertical axis rotation of intervening fault blocks, transfers fault slip (modified from McKenzie and Jackson, 1983, 1986). Single-barbed arrows show dextral fault motion across faults of the Eastern California shear zone (ECSZ) and Walker Lane belt (WLB) and sinistral motion along faults in the Mina deflection; half-circle double-barbed arrows indicate clockwise rotating fault blocks; solid ball is located on the hanging wall of normal slip faults; thin short lines indicate slip direction on fault surfaces.

Supplemental File 1. PDF file of $^{40}$Ar/$^{39}$Ar analytical techniques. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00825.S1 or the full-text article on www.gsapubs.org to view Supplemental File 1.
Figure 4 (on this and following page). (A) Geologic map of the Adobe Hills region (1:24,000 scale). See Figure 2 for location. Figure 4A is intended to be viewed at a width of 38.3 in. To view the full-sized figure, please visit http://dx.doi.org/10.1130/GES00825.S2.
North-northwest–striking normal faults, west-northwest–striking dextral faults, and northeast-striking sinistral faults cut and offset Miocene ignimbrite flows, Pliocene sediments and basalt flows, and some Pliocene cinder cones (Figs. 4 and 7). Fault scarps are primarily characterized by nearly vertical faces that expose flow features within basalt, and slickenlines are rare. Seismicity in the area indicates that faults are still active (Ryall and Priestly, 1975; Rogers et al., 1991; dePolo et al., 1993); however, ash fallout and wind-blown volcanic glass, ash, and small lithics from Mono and Inyo Craters obscure latest Pleistocene and Holocene fault scarps, if developed. Reheis et al. (2002) noted that some fresh fault scarps are exposed in the western Adobe Hills.

Fault Geometry and Geomorphology

Although a small data set, tilted bedding and flow foliation measurements within Mlt along with paleorelief on Mlt suggest an episode of deformation prior to eruption of the Pliocene basalt lavas. Map, structural, paleomagnetic, and geochronologic data reveal Late Miocene east-west extension, dextral slip, and vertical axis rotations within the central WLB and northern ECSZ (e.g., Dilles and Gans, 1995; Stockli et al., 2003; Tincher and Stockli, 2009; Rood et al., 2011), indicating that the region underwent deformation at that time. This deformation episode combined with erosion likely resulted in the paleorelief along the unconformity between Mlt and the overlying Pliocene lavas (Fig. 4). However, because of the limited exposure of Mlt, the nature of this Late Miocene deformation in the Adobe Hills area is not known.

The oldest set of faults are north-south- to northwest-striking curvilinear to straight normal faults that are ~0.2–2 km in length and 10–130 m in fault scarp height (Figs. 4 and 7). Evidence for normal faulting includes linear to moderately curved valleys in conjunction with vertically offset basalt flows and exposed Miocene ignimbrite flows and Pliocene sandstone in the footwall of faults. In the southern Adobe Hills, normal faults strike northwest near the trace of fault 3 and strike north with increasing distance away from this fault (Figs. 4A and 7). Some normal faults in the Adobe Hills are sinistrally or dextrally offset, while others define left steps along sinistral faults (Figs. 4A, 7, and 8). All normal faults displace late Pliocene basalt flows and older units; therefore, all normal faulting postdates Pliocene basalt volcanism, and mostly predates sinistral faulting.
A few northwest-striking, right-lateral faults, exposed near the southern boundary of the Adobe Hills (Figs. 4A and 7), are the least abundant fault type. These faults offset normal faults, but not sinistral faults; therefore, dextral faulting occurred after normal faulting and before sinistral faulting. The youngest and most prominent faults in the Adobe Hills are five major and numerous minor northeast-striking near-vertical sinistral faults, ranging from 6 to 12 km in fault trace length and tens of centimeters to ~100 m in scarp height (Figs. 4 and 7). Sinistral faults traverse nearly the entire field area, are well defined in the central, northern, and eastern areas, and become more diffuse toward the south and southwest, where they are represented by several en echelon short fault strands. Sinistral faults are characterized by linear valleys, alternating scarp facing directions along fault strike, left-stepping extensional (Fig. 8) and right-stepping compressional stepovers, and sinistrally offset normal fault–hanging-wall surface intersections, ridgelines, contacts, and channelized flows (Figs. 4A, 7, and 9). Linear valleys in conjunction with fault scarps tens of centimeters to 100 m in height along the sinistral fault traces may indicate that these faults also accommodated a small

Figure 5. Stratigraphic column of Miocene and Pliocene volcanic and sedimentary rocks exposed in the Adobe Hills. Relative thicknesses are shown.
component of extension in addition to the dominant sinistral offset. However, two field observations imply that the magnitude of extension is likely negligible: (1) fault traces are linear and crosscut topography, suggesting nearly vertical fault dips (80°–90°), and (2) the fault scarps change facing direction along strike, suggesting that this geometry is the result of sinistral fault slip along a nearly vertical fault that juxtaposed topographic lows against topographic highs.

Magnitude of Fault Slip and Fault Slip Rates

The north-south- to northwest-striking normal faults in the south-southwestern Adobe Hills suggest this area underwent approximately east-west–directed extension over a relatively short period of geologic time, after late Pliocene basalt emplacement, but before Pliocene sinistral faulting began. In the absence of vertically displaced marker beds, we estimate a minimum approximately east-west horizontal extension magnitude along transect A (Fig. 7), using the height of exposed fault scarps and assuming a fault dip of 60°. The transect records a minimum vertical offset of 495 m, which, along with the range of basalt ages of 3.13 ± 0.02 to 3.43 ± 0.01 Ma, yields a minimum horizontal extension rate of ~0.1 mm/yr.

| Sample   | Unit | Coordinates | Plateau | Isochron |
|----------|------|-------------|---------|----------|
| AH09-41  | Mit  | 38°3.6400, 118°37.6116 | 11.17 ± 0.04 | 11.17 ± 0.03 | 300.4 ± 11.8 | 1.89 | 81.4 |
| AH09-42  | Pbc  | 38°3.6816, 118°37.5750 | 3.43 ± 0.01 | 3.41 ± 0.01 | 299.7 ± 3.2 | 1.06 | 96.3 |
| AH09-201 | Pbo  | 38°0.1812, 118°41.0100 | 3.39* ± 0.03 | 3.38 ± 0.09 | 291.3 ± 6.9 | 10.54 | 100.0 |
| AH08-35  | Pbo  | 38°0.1140, 118°41.2350 | 3.28 ± 0.03 | 3.38 ± 0.09 | 294.1 ± 2.5 | 0.59 | 64.7 |
| AH08-19b | Pbr  | 38°0.7464, 118°41.6280 | 3.20 ± 0.03 | 3.33 ± 0.09 | 294.1 ± 1.9 | 0.64 | 83.3 |
| AH08-33  | Pbc  | 38°3.6906, 118°36.1794 | 3.19* ± 0.02 | 3.14 ± 0.02 | 295.4 ± 2.5 | 10.70 | 100.0 |

Note: See Figures 4 and 5 for unit descriptions. MSWD—mean square of weighted deviates.

*Recoil model age. Supplemental data and detailed methodology are in Supplemental File 1 (see text footnote 1).
could be an order of magnitude higher if this extensional episode, bracketed between basalt emplacement and onset of sinistral faulting, were a few hundred thousand years.

Dextral faults are limited to the southern Adobe Hills and offset normal faults, but do not offset sinistral faults. One northwest-striking dextral fault in the southern Adobe Hills offsets a normal fault–hanging-wall surface intersection lineation and Pbo basalt ridgeline by 281 ± 42 m. This offset measurement, combined with an 40Ar/39Ar basalt age range of 3.28 ± 0.03–3.39 ± 0.03 Ma for unit Pbo, yields a minimum dextral slip rate of ~0.1 mm/yr. Like the east-west extension rate, the rate of dextral shear could be an order of magnitude higher if this deformation episode, bracketed between basalt emplacement and onset of sinistral faulting, were a few hundred thousand years.

The youngest, longest, and most prominent sets of faults exposed across the field area are five major northeast-southwest–striking sinistral fault zones. Measurable sinistral offset magnitudes along individual fault strands range from 151 to 527 m and calculated minimum slip rates along individual fault zones range from 0.1 to 0.2 mm/yr (Figs. 4A, 7, and 9; Table 2).

Fault 1, located in the southeastern Adobe Hills, offsets a Pbc basalt flow edge and a contact between a scoria deposit (Pbs) and underlying Pbo basalt flow 225 ± 33 m and 268 ± 54 m, respectively. The latter may be an apparent offset because the contact between Pbs and Pbo is shallow. Fault offset magnitude, combined with an 40Ar/39Ar basalt age range of 3.28 ± 0.03–3.39 ± 0.03 Ma, yields a minimum sinistral slip rate of ~0.1 mm/yr for this fault (Table 2). This slip rate is similar or less than rates along the other sinistral faults within the Adobe Hills (see following), which suggests to us that the measured apparent 268 m sinistral offset of the Pbs–Pbo contact is reasonably accurate.

Evidence for the magnitude of sinistral offset along fault 2 is exposed along its northeastern trace and a set of splays along its southwestern trace. In the northeast, the fault consists of two splays that sinistrally offset units Pbc and Pbo and the intersection line defined by a northeast-dipping normal fault and the subhorizontal surface of its hanging-wall basin a total of 695 ± 139 m (Figs. 4A, 7, and 9A). This offset measure-
Combining these measurements with the age range of basalts of $3.13 \pm 0.02$ to $3.43 \pm 0.01$ Ma yields a minimum net sinistral slip rate of between 0.2 and 0.5 mm/yr. If our assessment of sinistral offsets 4 and 5 is similar to fault 1, but less so than faults 2 and 3, are valid and each records fault slip rates of $-0.1$ mm/yr, we suggest that 0.4–0.5 mm/yr is a reasonable estimate for a minimum Pliocene sinistral slip rate across the Adobe Hills.

**DISCUSSION**

**Mechanisms of Fault Slip Transfer across the Mina Deflection**

The Adobe Hills area, located in the southwestern part of the Mina deflection, accommodated late Pliocene to Holocene fault slip. Five geomorphically prominent northeast-striking sinistral fault zones dominate the region. Fault slip to a lesser extent also occurred along older north-south–to-northwest–striking normal faults and northwest-striking dextral faults. All faults cut Pliocene basalts and older units, and likely Quaternary deposits (Fig. 4A). We calculate a minimum Pliocene sinistral fault slip rate of 0.2–0.5 mm/yr across the Adobe Hills; our preferred minimum sinistral slip rate is 0.4–0.5 mm/yr. Calculated minimum Pliocene west-northwest–east-southeast extension rates across older normal faults and northwest dextral fault slip rates are both ~0.1 mm/yr.

The Mina deflection defines a right step between the northwest-striking dextral faults in the northern ECSZ and the northwest-striking dextral faults exposed in the central WLB (Figs. 1B and 2). The prominent northeast-striking sinistral faults in the Adobe Hills are exposed in the southwestern part of this right step. A similar geometric configuration exists in the Carson domain of the central WLB (see grey shaded area southeast of Reno; Fig. 1B), an ~2420 km$^2$ zone of northeast-striking sinistral faults that transfers dextral slip between northwest-striking Pyramid Lake, Warm Springs Valley, and Honey Lake dextral faults exposed to the north and northwest-striking Gumdrop Hill, Benton Springs, and Petrifield dextral faults exposed to the south (Cashman and Fontaine, 2000) (Fig. 1B). Paleomagnetic data from the Carson domain indicate that dextral fault slip transfer has occurred via ~55° to ~11° of Miocene to Pliocene clockwise block rotation (Cashman and Fontaine, 2000).

Clockwise rotation of blocks has been also documented in the eastern, southeastern, and northwestern parts of the Mina deflection. Petronis et al. (2009, 2007) documented block rotations of 20°–30° and 20°–25° since the Late Miocene to early Pliocene in the Candelaria Hills (eastern Mina deflection) and the Silver Peak area (south of the Mina deflection; Fig. 1B). Similarly, in the Bodie Hills region northwest of Mono Lake Basin and northwest of the Mina deflection (Fig. 1B), paleomagnetic studies indicate clockwise rotations of ~74° and ~14° since the Miocene and Pliocene, respectively (Rood et al., 2011).

Northeast-striking right steps between dextral systems are documented elsewhere in the northern ECSZ, and include the Queen Valley, Deep Springs, Towne Pass, and numerous other normal faults that transfer dextral slip from the Owens Valley and Hunter Mountain–Panamint Valley fault zones to the Death Valley–Fish Lake Valley fault zone (Figs. 1B and 2) (e.g., Lee et al., 2009b, 2001; Reheis and Dixon, 1996; Sternlof, 1988). These faults are unlike those in the Adobe Hills area and Carson domain in that they act as right-stepping releasing bends and
Pliocene fault slip across the Adobe Hills

transfer dextral fault slip via normal faulting. None of these faults shows geologic evidence (e.g., oblique slip) for vertical axis rotation.

Three fault kinematic models have been proposed to explain the mechanisms by which dextral fault slip is transferred from the northern ECSZ through the Mina deflection and into the central WLB. Each model was developed for a particular time period and taken together imply that the mechanism of fault slip transfer has changed through time. In the displacement-transfer model, curved northeast-striking normal faults in the Mina deflection accommodated the magnitude of dextral fault slip transfer from the northern ECSZ to the central WLB during the Middle Miocene to Pliocene (Fig. 3A) (Oldow, 1992; Oldow et al., 1994). In the Adobe Hills region, the north-to-northwest strikes of normal faults and hanging-wall basins, and a basalt ridgeline (narrow dashed line). The net offset across these sinistral faults is ~523 m. (C) The edge of the basalt rubble flow, unit Pbr (see Figs. 4A and 5 for description), is sinistrally offset ~527 m by fault 3. Paired arrows, solid ball, and hachures are defined in Figure 4A, and locations are shown in Figure 4A.

Figure 9. Detailed fault maps superimposed on digital orthophotographs and digital elevation map–generated contours showing left-lateral offset of geologic features along sinistral faults 2 and 3 (see Fig. 7). (A) The intersection line of a normal fault and the surface of its hanging-wall basin are sinistrally offset twice for a total of ~695 m along the northeastern segment of fault 2. (B) The southwestern segment of fault 2 is characterized by several subparallel sinistral fault strands that offset the intersection of line of normal faults and hanging-wall basins, and a basalt ridgeline (narrow dashed line). The net offset across these sinistral faults is ~523 m. (C) The edge of the basalt rubble flow, unit Pbr (see Figs. 4A and 5 for description), is sinistrally offset ~527 m by fault 3. Paired arrows, solid ball, and hachures are defined in Figure 4A, and locations are shown in Figure 4A.
normal slip. Therefore, this model is not applicable to this part of the Mina deflection.

In the transtensional model, instantaneous fault slip today across the western Mina deflection is characterized by extension-dominated transtension, and across the eastern part is characterized by wrench-dominated transtension (Oldow, 2003) (Fig. 3B). In the Adobe Hills, north-northwest–striking normal faults are exposed in the southwestern part of the Adobe Hills and accommodate a minimum of ~0.1 mm/yr of horizontal extension, a rate smaller than the minimum sinistral fault slip rate (although see discussion in Magnitude of Fault Slip and Fault Slip Rates section regarding the possibility of an order of magnitude higher extension rate), and are older than the sinistral faults. Thus, in the Adobe Hills extensional and transcurrent deformation episodes were partitioned in space and time, and transcurrent fault slip was the dominant deformation style. We conclude that the extension-dominated transtension model proposed for instantaneous fault slip transfer today across the western Mina deflection was not the style of deformation that resulted in the types and geometries of faults exposed across the Adobe Hills region.

In the simple shear couple/fault block rotation model (Wesnousky, 2005) (Fig. 3C), east-northeast–striking sinistral faults spaced 10 km apart in the Mina deflection rotated ~20°–30° clockwise during the Holocene from an original vertical axis fault block rotation data from paleomagnetic studies, to test the mechanisms of fault slip transfer across the western Mina deflection.

### Kinematics of Fault Slip Transfer into the Western Mina Deflection

Field-based studies of faults in Queen Valley, located in the southwestern part of the Mina deflection (Figs. 1A and 2), led to a proposal (Lee et al., 2009b) of a kinematic fault slip model whereby 0.8–0.4 mm/yr of Pliocene to Pleistocene dextral fault slip was transferred northward from the White Mountains fault zone onto sinistral faults in the western Mina deflection via the dextral Coyote Springs fault (Fig. 2). The Adobe Hills, across which we have documented a minimum late Pliocene sinistral slip rate of 0.4–0.5 mm/yr, is located west of the northwest projection of the Coyote Springs fault (Fig. 2). The Pizona Springs area, located east and southeast of the Adobe Hills (Fig. 2), is at the northwestern tip of the Coyote Springs fault. In this area, geomorphically prominent sinistral faults are subparallel to and as well developed as the ones we have documented in the Adobe Hills, and cut basalt and andesite flows (J. Lee, 2010, personal observations and mapping; E. Hogan, 2012, personal commun.) (Fig. 2). We therefore speculate that the Pliocene sinistral slip rate along each sinistral fault in the Pizona Springs area is ~0.1–0.2 mm/yr, the same as we have documented along sinistral faults in the Adobe Hills. If the predicted ~0.8–0.4 mm/yr fault slip transfer rate is correct, and the Coyote Springs fault abuts these sinistral faults, then the Pizona Springs area of the western Mina deflection accommodated transfer of dextral slip from the White Mountains fault zone; those in the Adobe Hills did not.

This raises the question, what system of faults in the northern part of the ECSZ transfers slip onto the sinistral faults of the Adobe Hills? Based on the orientation of dextral and normal faults with respect to small circles about the Sierra Nevada–North American Euler pole and kinematic inversions of earthquake focal mechanisms, Unruh et al. (2003) postulated that normal faults in this region were the result of plate boundary–driven northwest translation of the Sierra Nevada microplate. Furthermore, Unruh et al. (2003) noted that major grabens along the
northeastern flank of the Sierra Nevada define a westward-stepping fault array, and thus a releasing step with respect to Sierra Nevada–North American motion. Following Unruh et al.’s (2003) ideas, we suggest that the normal faults exposed within the Volcanic Tableland extending northward into the southern part of Adobe Valley, west of the White Mountains fault zone, play a similar role and transfer dextral fault slip northward into the Adobe Hills (Figs. 2 and 10).

The Volcanic Tableland is characterized by east- and west-facing normal faults, with an average strike of N10–20°W (Pinter, 1995), that cut the 758.9 ± 1.8 ka Bishop Tuff (Sarna-Wojcicki et al., 2000). These faults strike ~25°–35° clockwise relative to motion of the Sierra Nevada microplate with respect to a fixed North American plate (Dixon et al., 2000), thus defining a releasing step. Locally within the Volcanic Tableland, normal faults curve westward, defining zones of en echelon faults that trend ~315°, subparallel to the Sierra Nevada–North American motion. This geometric configuration suggests that these faults accommodate dextral slip. The normal faults extend northward and east of the Long Valley Caldera into the Benton Range, Black Mountain, and the southern part of Adobe Valley (Krauskopf and Bateman, 1977; Rinahart and Ross, 1957; Crowder and Sheridan, 1972; Bateman, 1965; Nevin, 1963) (Figs. 2 and 10).

Pinter (1995) estimated 144–332 m of Pleistocene horizontal extension across the southern part of the Volcanic Tableland; this estimate combined with the age of the Bishop Tuff yields 0.2–0.4 mm/yr of ~N75°E–S75°W extension since its eruption. Nevin (1963) estimated ~1.94 km of horizontal extension to the north, across the southern part of Adobe Valley including Black Mountain and the Benton Range; here, north-northwest–striking normal faults cut Pliocene basalt flows that can be traced continuously into the Adobe Hills (Krauskopf and Bateman, 1977). This map relation suggests that the basalt flows exposed in the Black Mountain and the Benton Range are probably the same age as the ones we dated. Combining that age range with the magnitude of horizontal extension yields ~0.6 mm/yr of approximately east-northeast–west-southwest extension across the southern part of Adobe Valley.

The simple fault map in Figure 10 illustrates how normal faults straddling the southern part of Adobe Valley that accommodate approximately east-west extension transfer slip onto the sinistral faults we have documented. These north-northwest–striking normal faults accommodated ~0.6 mm/yr of east-northeast–west-southwest extension since the Pliocene. This slip was transferred to northwest-striking oblique-slip faults that bound the eastern margin

Figure 10. Simplified map highlighting the kinematic link between the Owens Valley fault and sinistral faults in the Adobe Hills. Map shows faults from the Bishop region northward to the Adobe Hills, where each major fault or fault zone is shown as a single fault (cf. fault maps in Figs. 2 and 7). Large arrow indicates motion of the Sierra Nevada microplate (SN) with respect to a fixed North American plate (NA) (Dixon et al., 2000). Colored arrows with adjacent numbers indicate fault slip vectors and slip rate (in mm/yr). Red arrows show the calculated 0.6 mm/yr approximately east–west extension across the southern part of Adobe Valley (Benton Range and Black Mountain). Blue arrows and adjacent slip rates indicate the partitioning of the 0.6 mm/yr vector into parallel and perpendicular vectors along northwest-striking oblique-slip faults in the eastern Adobe Valley and northeast-striking sinistral faults in the Adobe Hills. See text for discussion. Solid ball is on the hanging wall of normal faults, and paired arrows indicate relative motion across strike-slip faults. CF—Couldeau fault; CSF—Coyote Springs fault; OVF—Owens Valley fault; QVF—Queen Valley fault; WMFZ—White Mountains fault zone.
of Adobe Valley and are likely in the valley, although the latter are now mostly buried. Based on the geometric relationships, slip along this northwest-striking fault system is predicted to be oblique, dominantly normal (~0.5 mm/yr), with a lesser component of dextral slip (~0.3 mm/yr). The normal component is nearly parallel to the sinistral faults we mapped in the Adobe Hills, thus predicting ~0.5–0.6 mm/yr of sinistral slip in the Adobe Hills since the Pliocene, consistent with our preferred minimum sinistral slip rate of 0.4–0.5 mm/yr. The dextral component is almost perpendicular to the sinistral faults in the Adobe Hills, thus our simple kinematic model predicts ~0.2 mm/yr of extension across the sinistral faults. However, there is little, if any, extension accommodated along these faults. We suggest that the predicted 0.2 mm/yr northwest-southeast extensional component of slip was partitioned onto the approximately north-south–striking normal faults that have been documented throughout this region by our work and in the far western Adobe Hills (Reheis et al., 2002) as well as onto the northwest-striking dextral faults we documented.

The Pliocene east-northeast–west-southwest horizontal extensional rate across the Black Mountain and Benton Range could be closer to 0.4 mm/yr, the calculated east-northeast–west-southwest horizontal extension rate across southern Volcanic Tableland if (1) the basalt flows exposed in the Black Mountain and the Benton Range are somewhat older than the flows we studied in the Adobe Hills, (2) all of the Pleistocene east-northeast–west-southwest horizontal extension across the southern part of the Volcanic Tableland was transferred to normal faults exposed in the Black Mountain and Benton Range, and (3) fault slip rates have been constant through time. Using the same geometric relationships described here, the implications for slip rates in the Adobe Hills for a 0.4 mm/yr horizontal extension rate across Black Mountain and the Benton Range are 0.3–0.4 mm/yr of extension and 0.1–0.2 mm/yr of dextral slip along the northwest-striking oblique slip faults in the eastern part of Adobe Valley and 0.3–0.4 mm/yr of sinistral slip and 0.1–0.2 of extension across the northeast-striking sinistral faults in the Adobe Hills. We suggest that the predicted 0.1–0.2 mm/yr northwest-southeast extensional component of slip across the northeast-striking sinistral faults was partitioned onto the approximately north-south–striking normal faults and northwest-striking dextral faults exposed in the Adobe Hills region.

Figures 2 and 10 show a series of releasing steps between the dextral Owens Valley fault and faults bounding the eastern edge of Adobe Valley. The set of releasing steps from the northern end of the Owens Valley fault northward to Bishop indicate that dextral slip along the Owens Valley fault is transferred to both the White Mountains fault zone (Reheis and Dixon, 1996; Kirby et al., 2006, 2008; Sheehan, 2007) and the Volcanic Tableland. Releasing steps are common elsewhere within the dextral ECSZ-WLB, and have been described across the Towne Pass, Deep Springs, and Queen Valley normal faults and the Death Valley, Panamint normal faults, and Saline Valley pull-apart basins (Lee et al., 2001, 2009a, 2009b; Oswald and Wernousky, 2002; Stockli et al., 2000; Burchfiel et al., 1987; Burchfiel and Stewart, 1966). Fault slip transfer via releasing bends or extensional stepovers is also common, at a range of scales, within strike-slip fault systems worldwide (e.g., Cunningham and Mann, 2007) and has been documented in analog models (e.g., McClay and Dooley, 1995). Therefore, we are not surprised that a set of releasing steps, of varying scales, occur within the northern ECSZ and transfer slip from one major structure or set of structures to another.

Regional Tectonics

Geologic versus Geodetic Rates

The results from our studies in the Adobe Hills provide insight into whether there is an apparent discrepancy between summed geologic slip rates versus geodetic rates across the northern ECSZ (cf. Lee et al., 2009a; Frankel et al., 2007; Kirby et al., 2006; Bennett et al., 2003) and, combined with the results of several other studies along the eastern side Sierra Nevada, the forces that drive deformation along the western boundary of the Basin and Range Province. At lat ~36.5°N, cumulative long-term geologic dextral slip rates across the Owens Valley, Hunter Mountain, northern Death Valley, and State Line faults yield a net dextral slip rate that is the same, within error, as geodetic estimates (cf. Lee et al., 2009a; Bennett et al., 2003). In contrast, at lat ~37.5°N there is an apparent discrepancy between the summed late Pleistocene dextral geologic slip rates along the Fish Lake Valley and White Mountains dextral fault zones (Frankel et al., 2007; Kirby et al., 2006), which at 2.4–3.9 mm/yr (Frankel et al., 2007) is less than geodetic rates, assuming that the geodetic dextral strain rates for the northern ECSZ at lat ~36.5°N (9.3 ± 0.2 mm/yr) (Bennett et al., 2003) and central WLB at lat 38°–39°N (~10 mm/yr) (Hammond and Thatcher, 2007) are the same as at lat 37.5°N. This apparent discrepancy suggests that either (1) additional dextral slip was accommodated on structures to the east of these two faults, distributed across Owens Valley, and/or west of the White Mountains fault zone (Frankel et al., 2007; Kirby et al., 2006; Lee et al., 2009b), or (2) this part of the ECSZ underwent a strain transient, as has been observed in the Mojave Desert (Rockwell et al., 2000; Peltzer et al., 2001; Oskin and Iriondo, 2004; Oskin et al., 2007). As described in the following, we propose that additional dextral slip on faults both to the west and east of the Fish Lake Valley and White Mountains fault zones may account for the apparent discrepancy, although dextral slip rates along many of these faults have not yet been determined.

West of the White Mountains fault zone, normal faults across the Volcanic Tableland extending into the southern part of Adobe Valley account for some of the discrepancy (Fig. 10). To our knowledge, Bateman (1965) was the first to suggest that the en echelon geometry of faults across the Tableland and axes of warping (adjacent broad anticlines and synclines) were the result of a “rotational couple” or dextral shear. Moreover, most of the approximately north-south–striking normal faults strike clockwise with respect to Sierra Nevada–North America motion, thus defining releasing steps in a dextral shear zone (e.g., Unruh et al., 2003), and a few of these normal faults curve into parallelism with Sierra Nevada–North America motion, suggesting that slip along these segments is dominantly dextral. Others (e.g., Pinter, 1995; Phillips and Majkowski, 2011) attributed the development of normal faults across the Volcanic Tableland to the formation of an arch and flexure of the Bishop Tuff. It is possible that faults exposed across the Volcanic Tableland developed as a consequence of both processes that acted broadly simultaneously. Phillips and Majkowski (2011) documented a component of dextral slip, in addition to normal slip, farther west, along the northern Round Valley fault, although a dextral slip rate was not determined. The dextral slip here projects northward into the Long Valley Caldera. There may be other faults throughout this region that also accommodate a component of northwest dextral shear.

Frankel et al. (2007) suggested that dextral shear east of the Fish Lake Valley fault zone was accommodated via an extensional stepover through the Silver Peak–Lone Mountain extensional complex (Oldow et al., 1994; Hoef and Frankel, 2010) and vertical axis rotation (Petronis et al., 2002, 2007).

Geodynamic Implications

Major fault slip across the Adobe Hills occurred after the eruption of a sequence of 3.43–3.13 Ma basalt flows. Early to late Pliocene initiation of fault slip or renewed fault slip occurred throughout the western ECSZ-WLB–western Basin and Range between lat
CONCLUSIONS

New geologic map and structural and 40Ar/39Ar geochronologic data from the Adobe Hills, western Mina deflection, highlight a history of pre-Pliocene deformation, rapid basin flow emplacement during the late Pliocene, development of north-northwest-striking normal, northwest-striking dextral, and northeast-striking sinistral faults within a relatively short period of time, and a minimum late Pliocene sinistral slip rate of -0.4–0.5 mm/yr. The dominance of northeast-striking sinistral faults suggests that deformation across this part of the Mina deflection is characterized by a simple shear couple/fault block rotation, but paleomagnetic data are needed to test whether the blocks bounded by the sinistral faults rotated clockwise during fault slip. The sinistral faults in the Adobe Hills extend west of the predicted transfer of 0.8–0.4 mm/yr Pliocene to Pleistocene dextral fault slip from the northern ECSZ into the western Mina deflection (Lee et al., 2009a).

We propose that a component of dextral slip along the Owens Valley fault is transferred into the Adobe Hills via dominantly normal, and to a lesser extent dextral, faults exposed across the Volcanic Tablelands, Benton Range, and southern Adobe Valley. The kinematics of fault slip transfer into the Adobe Hills occur via a series of releasing bends in a zone dominated by dextral slip. This zone of dextral shear west of the White Mountains and Fish Lake Valley fault zones, along with other structures to the west and east of these fault zones, may account for the apparent discrepancy between summed long-term geologic dextral slip rates and geodetic strain rates across the northermost part of ECSZ. The fault history we documented in the Adobe Hills is part of a regionally extensive early to late Pliocene onset or renewed deformation event within the western Basin and Range. Deformation of this age extends from the northern WLB (-40°N) southward to the northern ECSZ (-36°N), and is not associated with changes in plate motion, but coincides with the estimated timing of lithospheric drip from beneath the Sierra Nevada. This temporal and spatial relationship suggests that the Pliocene deformation episode was driven by locally derived internal forces.

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