Quaternary faulting in Queen Valley, California-Nevada: Implications for kinematics of fault-slip transfer in the eastern California shear zone—Walker Lane belt

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ABSTRACT

New geologic map, tectonic, geomorphologic, and terrestrial cosmogenic nuclide (TCN) geochronologic data document the geometry, style, kinematics, and slip rates on late Quaternary faults within the Queen Valley, California-Nevada area. These data provide important insight into the kinematics of fault-slip transfer from the dextral White Mountains fault zone northward into the Mina deflection. Queen Valley is an ~16-km-long, NE-trending basin bounded to the south by the White Mountains and underlain by four major Pleistocene to Holocene alluvial-fan surfaces. Four different fault types and orientations cut and offset all but the youngest surfaces: (1) The normal-slip Queen Valley fault, which consists of a set of NE-striking, NW- and SE-dipping normal fault scarps that cut across the SE side of the valley and offset all but the youngest surfaces; (2) discontinuous NE-striking, sinistral faults exposed on the north side of the valley; (3) the NW-striking dextral Coyote Springs fault, which merges into (4) a set of E-W–striking thrust faults. Measured offsets across normal fault scarps developed within 9Be TCN-dated surfaces yield minimum late Pleistocene horizontal extension rates of 0.1–0.3 mm/yr. Documented fault geometries and slip orientations across Queen Valley suggest that fault-slip transfer models, such as the extensional displacement, block rotation, and simple shear models, within the dextral fault system proposed for the eastern California shear zone—Walker Lane belt are not applicable to this part of the Mina deflection. Rather, dextral fault slip is transferred by both a restraining westward step and a releasing eastward step. Restraining and releasing bends have been extensively documented at a range of scales in strike-slip fault tectonic settings globally, and they have been simulated in analog models; thus, it is not surprising to document both within the ~630-km-long dextral shear zone that makes up the northern eastern California shear zone—Walker Lane belt. Our results, combined with published slip rates for the dextral White Mountain fault zone and the eastern sinistral Coaldale fault, suggest that transfer of dextral slip into the Mina deflection is partitioned into three different components: horizontal extension along the Queen Valley fault, thrust faulting that merges into the dominantly dextral slip along the Coyote Springs fault, and dominantly sinistral slip along the Coaldale fault. A velocity vector diagram of fault-slip partitioning across Queen Valley predicts a small component of contraction across the Coyote Springs and western Coaldale faults. Contraction across the Mina deflection is consistent with global positioning system data. An observed reduction in late Pleistocene fault-slip rates at the northern end of the eastern California shear zone and across the southwestern part of the Mina deflection may be explained by distribution of slip across a much broader zone than generally thought.

Keywords: normal faults, strike-slip faults, thrust faults, terrestrial cosmogenic nuclide geochronology, fault-slip transfer, Walker Lane belt, Eastern California shear zone.

INTRODUCTION

Modern deformation between the North American and Pacific plates is distributed across a wide zone of the western margin of North America, from the San Andreas fault eastward into the western Basin and Range Province (e.g., Bennett et al., 1999; Thatcher et al., 1999) (Fig. 1). Geodetic and geologic studies indicate that the San Andreas fault system accommodates ~75%–80% of the total relative plate motion. The modern plate-boundary strain residual is transferred away from the San Andreas fault system via the eastern California shear zone northward into the Walker Lane belt and the Central Nevada seismic belt (Fig. 1). Geodetic data indicate that right-lateral shear, at a rate of ~9–13 mm/yr (Thatcher et al., 1999; Dixon et al., 2000; Gan et al., 2000; Bennett et al., 2003; Oldow, 2003; Hammond and Thatcher, 2007), dominates within the eastern California shear zone and Walker Lane belt, accounting for ~20%–25% of the total relative plate motion.

In the northern eastern California shear zone (north of the Garlock fault), dextral displacement is funneled through a relatively narrow zone of shear along four major subparallel strike-slip fault zones, the Stateline, Death Valley–Furnace Creek–Fish Lake Valley, Hunter Mountain–Panamint Valley, and White Mountains–Owens Valley fault zones (Figs. 1 and 2). At the northern end of the eastern California shear zone,
Individual NW-striking strike-slip fault systems abruptly swing eastward into an array of NE- to E-W-striking faults in the southern portion of the central Walker Lane belt, which is known as the Mina deflection (Figs. 2 and 3). The dramatic change in Cenozoic fault orientation that defines the Mina deflection is attributed to geometric control by the latest Precambrian–earliest Paleozoic rifting continental margin, which was mimicked by Phanerozoic depositional patterns and mid-Paleozoic through Mesozoic contractional structures (e.g., Stewart and Suczek, 1977; Speed, 1978; Oldow et al., 1989).

Fault-slip transfer by extension, contraction, and/or rotation is common within strike-slip fault systems worldwide (e.g., McKenzie and Jackson, 1983, 1986; Cunningham and Mann, 2007) and has been simulated in analog models (e.g., Wilcox et al., 1973; Hempton and Neher, 1986; McClay and Dooley, 1995; McClay and Bonora, 2001). Fault-slip transfer by extension or rotation has been postulated for the Mina deflection, which transfers dextral slip from fault zones that made up the northern end of the eastern California shear zone to the northern Walker Lane belt and Central Nevada seismic belt (e.g., Oldow, 1992; Oldow et al., 2001; Stockli et al., 2003; Wesnousky, 2005; Tincher and Stockli, 2008). The curvilinear Cenozoic faults in the Mina deflection form a z-shaped extensional relay zone that transfers dextral slip. Fault-slip transfer through this regional releasing bend results in the formation of multiple rhombooidal pull-apart structures. Oldow (1992) and Oldow et al. (1994) postulated that strike slip and transtensional slip across the dextral White Mountains fault zone to the broad deformation zone that defines the southern part of the Mina deflection (Figs. 2 and 3).

Fault-slip transfer from a relatively narrow (~25 km wide) and simple geometric zone of dextral shear northward into a broader (~60 km wide) and complex geometric zone of faulting styles and slip orientations is one of the distinctive structural characteristics of the Mina deflection. In this paper, we combine new geologic mapping and tectonic, geomorphologic, and terrestrial cosmogenic nuclide (TCN) geochronologic data from the Queen Valley area to determine fault geometries, slip orientations, and slip magnitudes that bear on the mechanism of fault-slip transfer from the relatively narrow dextral White Mountains fault zone to the broad deformation zone that defines the southern part of the Mina deflection (Figs. 2 and 3).

**QUEEN VALLEY**

**Geological Setting**

Queen Valley, located at the southwest corner of the Mina deflection and the northern end of the White Mountains, is an ~16-km-long, NE-trending basin (Figs. 2, 3, and 5). This geographic setting marks where the relatively narrow zone of
NW-striking dextral faults that define the northern eastern California shear zone abruptly swing into a broad zone of NE- to E-W–striking faults that define the Mina deflection (e.g., Oldow, 1992; Stockli et al., 2003). Paleozoic metasedimentary rocks, Mesozoic granitic intrusions, and Tertiary basalt lava and rhyolite tuff underlie the ranges surrounding the valley, and alluvial-fan deposits underlie the Queen Valley basin (e.g., Dalrymple and Hirooka, 1965; Everdend and Kistler, 1970; Crowder and Sheridan, 1972; Stockli et al., 2003; Tincher and Stockli, 2008). The SE side of the basin is bounded by the NE-striking, NW-dipping Queen Valley normal fault, which forms the northern termination of the NW-striking, dextral White Mountains fault zone (Fig. 3). Fault kinematic data are dominated by nearly pure down-to-the-NW dip slip along the Queen Valley fault; the extension direction is ~335° (Stockli et al., 2003). Near Montgomery Pass, the Queen Valley fault merges with the Coaldale fault, an E-W–striking, left-lateral strike-slip fault (Bradley, 2005; Tincher and Stockli, 2008) (Fig. 3).

Apatite (U-Th)/He thermochronological data from the footwall of the Queen Valley fault have yielded ages of ca. 3–5 Ma that decrease with decreasing elevation and exhibit an inflection point at ~2200 m, suggesting the existence of an exhumed Pliocene partial retention zone (Stockli et al., 2003; Tincher and Stockli, 2008).
et al., 2000). The concordant and invariant ages below ~2200 m directly date the onset of exhumation, initiation of normal slip, and the formation of the Queen Valley basin at 3.0 ± 0.5 Ma. Because the Queen Valley fault forms the northern termination of the dextral White Mountains fault zone, the opening of the basin at ca. 3 Ma reflects the onset of right-lateral strike-slip faulting. In addition, along the western range front of the White Mountains, apatite samples did not yield apatite (U-Th)/He ages younger than ca. 12 Ma, suggesting that Pliocene normal displacement decreased southward away from the Queen Valley fault (Stockli et al., 2003). Based on height of the escarpment and thickness of the Queen Valley basin fill (~200 m) (Black and Stockli, 2006), the minimum vertical offset across the Queen Valley fault is 1370 m.

ROCK UNITS AND AGES

Queen Valley is underlain by late Quaternary alluvial-fan deposits, which to the southeast are in fault contact with Paleozoic marine metasedimentary rocks (Crowder and Sheridan, 1972) that are in turn intruded by a variety of Jurassic and Triassic granitic bodies (Anderson, 1937; Harris, 1967; Evernden and Kistler, 1970; Crowder and Sheridan, 1972). To the east and northeast of the valley, late Quaternary alluvial-fan deposits are in fault contact with Paleozoic and Mesozoic rocks that are unconformably overlain by or fault-juxtaposed against Tertiary conglomerate, Oligocene to Pliocene rhyolite, andesite, and basaltic andesite (Dalrymple and Hirooka, 1965; Dincher and Stockli, 2008).

Tertiary Units

Unit Tb is exposed at the western end of the valley; it is composed of plagioclase ± olivine ± pyroxene phric basalt lavas (Fig. 5). We suggest that these lavas are Pliocene in age because they are similar to ca. 3–4 Ma basalt lavas that occur in the Benton Range and throughout the Queen Valley area (Dalrymple and Hirooka, 1965; Crowder and Sheridan, 1972; Bradley, 2005; Blackburn et al., 2007; Tinner and Stockli, 2008). Locally overlying unit Tb, there is unit Trt, a quartz + feldspar, lithic-bearing rhyolite tuff. In turn, this unit is overlain by unit Ts, a baking weathering, weakly bedded, basalt, granite, metasedimentary, and obsidian pebble-bearing quartz + feldspar tuffaceous sandstone.

Quaternary Units

The Queen Valley basin is underlain by four major Pleistocene to Holocene alluvial-fan surfaces. These surfaces have been subdivided into two groups, Qf surfaces, which cover the southwestern two-thirds of the valley, and Qqf surfaces, which cover the northeastern third of the valley (Figs. 5 and 6). Alluvial-fan surfaces in each group are further subdivided based on tone and fan surface morphology, including terrace height, presence or absence of bar and swale morphology, degree of fan dissection, and inset geometry (Figs. 6 and 7). The oldest Qf surface, Qf1, defined by its highly eroded ridge and ravine morphology, is preserved primarily in the southwestern part of the field area (Fig. 5). Relatively dense vegetation likely precludes desert pavement development (e.g., Quade, 2001), and desert varnish was not observed. The underlying alluvial-fan sediments, composed of granite, andesite, basalt, and metasedimentary rock–derived angular pebble-rich sand and typically weathered and fractured cobbles and boulders up to 2 m across, are deposited on pre-Tertiary bedrock or Tertiary basalt lava.

Qf2 surfaces appear light toned and relatively smooth in aerial photography (Figs. 6 and 7). Proximal to the range front, Qf2 deposits are composed primarily of sparse, ≤3-m-wide granitic boulders embedded in coarse, angular, granitic-derived pebble sand. Bouldery, ≤3-m-wide debris flows are locally present. Distal Qf2 surfaces are characterized by weakly developed, widely spaced (several meters) channels that dissect a relatively smooth surface. Deposits that underlie this part of the surface contain <1% angular, weathered dominantly granite boulders, with lesser basalt, andesite, and scarce metasedimentary boulders, embedded in an angular granite-derived pebbly sand.

Qf3 surfaces are darker than Qf2 surfaces in aerial photography and possess a moderately dissected surface composed of bar and swale morphology and bouldery debris flows adjacent (within ~2.5 km) to the range front (Figs. 6 and 7). Based primarily on inset geometry, the Qf3 surfaces are subdivided into three subunits (Figs. 5, 6, and 7). The oldest surface, Qf3a, possesses the most well-developed bar and swale morphology, whereas the younger Qf3b surface possesses moderately developed bar and swale morphology. Three ages of debris flows are found within or on Qf3b surfaces. The oldest are remnant pre-Qf3b debris flows that are partially buried by the Qf3b surface, Qf3b debris flows, and scarce, widely spaced, recent, single(?)-event younger debris-flow channels deposited on top of Qf3b surfaces (see TCN surface age dating section).

Qf3c surfaces are the most aerially extensive in Queen Valley (Fig. 5). These surfaces appear somewhat lighter in black-and-white aerial photographs compared to older Qf3 surfaces (Fig. 6). These surfaces possess well-developed plumeose texture and widely spaced, weak to moderately developed bar and swale morphology. Qf3c
Kinematics of fault-slip transfer, California-Nevada

Figure 5. Simplified geologic map of the Queen Valley area showing Tertiary volcanic rocks, Quaternary sedimentary deposits and alluvial-fan surfaces, and Quaternary faults. Locations and ages of cosmogenic radionuclide samples are shown; locations and magnitudes of measured offset across fault scarps are shown. TCN—terrestrial cosmogenic nuclide.
surfaces are underlain by angular, dominantly granite-derived pebbly sand containing <1% generally large (≤2 m across), angular granite cobbles and boulders embedded within.

The youngest surfaces, Qf4, are generally light toned in aerial photography and define active or recently abandoned stream channels cut into older surfaces. Active channels are commonly relatively densely vegetated, whereas abandoned ones are not. Channel deposits include unvarnished granitic and metamorphic boulders and cobbles, fresh boulder levee bars, and sand.

The Queen Canyon sequence of alluvial-fan surfaces is similar to surfaces elsewhere in Queen Valley, but the deposits underlying these surfaces can be traced to Queen Canyon (Fig. 6). The oldest alluvial-fan surface, Qf1, is exposed as remnants deposited on pre-Tertiary bedrock at the apex of ridge and ravine morphology (Fig. 5). The deposits underlying these surfaces are composed of angular granite, andesite, basalt, and metasedimentary rock-derived pebble-rich sandy matrix with typically weathered and fractured cobbles and boulders up to 2 m across. As observed on the Qf1 surface, desert pavement did not develop, probably because the density of vegetation is too high (e.g., Quade, 2001).

The next youngest surface, Qf2, is somewhat darker than Qf2 but lighter than Qf3a, and it

Figure 6. Aerial photograph of the central part of Queen Valley highlighting different alluvial-fan surfaces and prominent fault scarps (arrows). See Figure 5 for unit abbreviations.
possesses a smooth surface morphology with no channels (Fig. 6). These surfaces contain dominantly granite-derived, with lesser basalt and andesite, angular pebbly sand with scarce to ~5% strongly weathered and fractured primarily granite boulders up to 2 m across.

Based on inset geometry, Qf3 surfaces are subdivided into four different subunits (Fig. 5). The oldest, Qf3a, is darker compared to Qf2 surfaces. The surface morphology is smooth with no channels. These surfaces contain dominantly granite-derived, with lesser basalt and andesite, angular pebbly sand with <1% 15–60 cm embedded angular cobbles and boulders. The surface characteristics of the next two younger surfaces, Qf3b and Qf3c, are similar to Qf3a. These surfaces were mapped as independent units based on crosscutting and inset geometries. The youngest of the Qf3 surfaces, Qf3d, possess a moderately to well-developed plumose texture and weak to moderate bar and swale morphology, and it is underlain by dominantly granite-derived, angular pebbly sand.

In addition to the alluvial-fan deposits, landslide, playa, and eolian deposits are exposed within the valley (Figs. 5, 6, and 7). An ~2.7 km² landslide, Qls, exposed near the mouth of Morris Canyon, is characterized by hummocky topography underlain by dominantly granite-derived coarse angular sand and <1%–50%,
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### TABLE 1. SUMMARY OF $^{10}$Be MODEL AGES

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Surface unit</th>
<th>Lat. (°N)</th>
<th>Long. (°W)</th>
<th>Elev. (m)</th>
<th>Boulder thickness (cm)</th>
<th>Quartz Mass (g)</th>
<th>Be carrier Mass (g)</th>
<th>Prod. rate ($^{10}$Be/atom g$^{-1}$ yr$^{-1}$)</th>
<th>$^{10}$Be/Be error ($^{10}$Be/atom atom$^{-1}$)</th>
<th>Conc. Uncertainty (± s.e)</th>
<th>Age (ka)</th>
<th>Uncertainty (± s.e) (ka)</th>
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<tr>
<td>QV04</td>
<td>Qf1</td>
<td>37°54.60</td>
<td>118°22.00</td>
<td>2136</td>
<td>0.9</td>
<td>2</td>
<td>51.1483</td>
<td>0.4993</td>
<td>23.8</td>
<td>34.94</td>
<td>1.016</td>
<td>22.84</td>
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<td>QV01</td>
<td>Qf2</td>
<td>37°54.70</td>
<td>118°22.10</td>
<td>2133</td>
<td>0.9</td>
<td>2</td>
<td>46.0406</td>
<td>0.5096</td>
<td>23.6</td>
<td>16.54</td>
<td>3.323</td>
<td>12.26</td>
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<td>QV02*</td>
<td>Qf2</td>
<td>37°54.71</td>
<td>118°22.17</td>
<td>2124</td>
<td>0.7</td>
<td>3</td>
<td>60.2504</td>
<td>0.6431</td>
<td>23.2</td>
<td>23.09</td>
<td>4.456</td>
<td>16.51</td>
</tr>
<tr>
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<td>Qf2</td>
<td>37°54.60</td>
<td>118°22.00</td>
<td>2110</td>
<td>1</td>
<td>6</td>
<td>60.0088</td>
<td>0.4001</td>
<td>22.6</td>
<td>27.4</td>
<td>7.490</td>
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<td>118°22.25</td>
<td>1862</td>
<td>2</td>
<td>4</td>
<td>55.0888</td>
<td>0.3605</td>
<td>19.6</td>
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<td>QV08</td>
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<td>37°53.85</td>
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<td>1952</td>
<td>1.4</td>
<td>3</td>
<td>49.9321</td>
<td>0.5108</td>
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<td>23.13</td>
<td>4.448</td>
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<td>37°53.87</td>
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<td>1946</td>
<td>1.4</td>
<td>2</td>
<td>59.3973</td>
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<td>4.308</td>
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<td>2</td>
<td>48.4406</td>
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<td>20.5</td>
<td>16.41</td>
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<td>Qf2</td>
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<td>4</td>
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<td>2.2</td>
<td>3</td>
<td>51.1493</td>
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<td>3</td>
<td>59.3861</td>
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<td>2.622</td>
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<td>118°24.88</td>
<td>2008</td>
<td>2.4</td>
<td>4</td>
<td>59.6890</td>
<td>0.6500</td>
<td>21.3</td>
<td>4.732</td>
<td>2.693</td>
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<td>118°23.00</td>
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<td>2</td>
<td>23.7671</td>
<td>0.4093</td>
<td>23.1</td>
<td>4.557</td>
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<td>3</td>
<td>50.0017</td>
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<td>4.525</td>
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<td>118°23.05</td>
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<td>58.3805</td>
<td>0.6433</td>
<td>23.2</td>
<td>4.434</td>
<td>1.054</td>
<td>3.271</td>
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</table>

**Note:** Production rate at sea level, high latitude (≈ 5.1 atom g$^{-1}$ yr$^{-1}$) was scaled to site according to Lal (1991) as modified by Stone (2000), ignoring temporal variations in geomagnetic field, which do exist but for which there is no consensus for adjustment. Rates were averaged for sample thickness (2–6 cm, $ρ_0$ = 2.7 g cm$^{-3}$, $Λ_0$ = 160 g cm$^{-2}$), and less than 1% topographic shielding effect, but not for erosion, possible snow or ash cover, or inheritance. The $^{10}$Be% used (1.5 Ma) was recently shown to be 15% too high, but because the Accelerator Mass Spectometry standards (LLNL3000) were also calibrated to the 1.5 Ma half-life, there is no adjustment required (Nishizumi et al., 2007). Concentration of Be carrier was 10,000 atom g$^{-1}$, about 3× higher than the long-term average for the shielded beryllium crystal used as a carrier and measured at Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory. Sample QV015 was measured with a low precision (12%, 2σ) compared to the others (~4%, 2σ), and because the blank correction was ~25%, we cautiously report its age and recommend that it not be used in this or other studies. Considering all sources of error, the total systematic and random uncertainty in the ages is likely >20% 2σ.

*Sample not used in calculating mean age.

**σ.s.e.—standard error.**

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0.5–2.0-m-sized angular cobbles and boulders. In contrast to all other Quaternary surfaces, pebble-sized clasts are a minor (<1%) component. Playa deposits, Qp, are poorly exposed at the western end of Queen Valley and are composed of fine- to medium-grained, subrounded to subangular, granite-derived quartzite-feldspathic sand interlayered with fine sand and mud with detrital mica. Locally, sand horizons are tuffaceous, possessing pumice and obsidian grains. Horizontal bedding varies from 70-cm-thick sand beds at the base to a 40-cm-thick mix of mud and sand beds, which is capped by >2.5-m-thick massive playa muds. Subrounded granite pebble and cobble float suggests the presence of pebbly lens deposits, although these deposits are not exposed. Finally, medium- to fine-grained pumice-bearing eolian sand, unit Qe, is exposed along the western edge of the map area.

**TERRESTRIAL COSMOGENIC NUCLIDE (TCN) SURFACE EXPOSURE AGES**

Fifteen quartz-rich granite samples were collected from the top of the largest and best-preserved in situ boulders for $^{10}$Be TCN surface exposure age determination of five of the alluvial-fan surfaces (Fig. 5). Unfortunately, in many instances, three or fewer boulders were considered appropriate due to weathering or position. In all instances, the exposure ages were interpreted without correction for the possibility of inheritance (discussed later) or boulder erosion, snow cover, exhumation from the fan surface, or neutron loss due to small boulder geometry (possible 10% effect), and only in two instances were adjustments necessary for topographic shielding (<1% effect for both). Although some of the boulders were shorter than desired ($H = 0.7–2.4$ m) to minimize the possible influence of burial or exhumation, there was no apparent positive age covariance with boulder height and no geomorphic indication of burial or exhumation, indicating that partial burial may not have been important. Erosion has occurred on all boulders, yet none exhibited differential erosion greater than 5 cm. Nevertheless, the total amount of erosion could not be quantified. A 1 mm/k.y. boulder erosion rate would decrease the age of 15 ka boulders by ~1% and 85 ka boulders by ~7%. By avoiding boulders with evidence of significant erosion (for example, “sombrero shaped boulders”), granmas, and deep rillen), we minimized the effect of erosion on the exposure ages, and therefore the contribution of erosion to age error is <7%. Taking into account these errors, we report a conservative 20% error (2σ) in the accuracy of surface ages when calculating fault-slip rates (see Fault Scarps, Magnitude of Offset, and Slip Rates section).

**Morris Creek Catchment**

Five boulders from the Qf2 fan surface (Morris Creek catchment) were sampled to evaluate the possibility of inheritance. We interpret the low (5%) coefficient of variation about the mean age of those samples (Table 1) to indicate that this population of boulders does not contain inheritance—it would be very improbable for all five boulders to contain the same amount of inheritance. We cannot preclude inheritance from the other fan boulder samples; however, inheritance is unlikely on the basis of the low
coefficient of variation about the mean age of the Qf2 samples. The observed disparities among boulder ages on the same fan surfaces can be explained on the basis of field observations (see following).

Boulder samples collected from the Morris Creek Qf2 surface yield a mean age of 77.1 ± 0.8 ka (n = 5, standard error) (Fig. 5) and a range in ages between 72.6 ± 7.0 ka and 80.8 ± 3.1 ka. We interpret the mean age of these dates to indicate the timing of deposition of the faulted Qf2 fan surface. The mean age is consistent with a depositional event during oxygen isotope stage 4 glacial.

Two approximately contemporaneous Qf3 surfaces on the fan from the Morris Creek catchment yield exposure ages ranging from 70.6 ± 3.3 ka to 1.6 ± 0.2 ka. Field relations of boulders collected from the Qf3b surface clearly indicate that the 70.6 ka boulder is from a remnant debris flow and the 1.6 ka boulder is from the youngest debris flow in the field area, possibly revealing how some fans are characterized by punctuated aggradation over a long time interval. Note, however, that the 1.6 ka boulder sample was measured with low precision, and the age may be geologically meaningless (Table 1). Therefore, the only age that may be useful for constraining the age of the Qf3b surface is sample QV14 at 9.1 ka. Boulder samples collected from a Qf3c surface in the hanging wall of the Orchard Spring normal fault are undifferentiated pre-Tertiary bedrock, Tertiary basalt lava, rhyolite tuff, and tuffaceous sandstone, and the late Pleistocene alluvial-fan surfaces: (1) a series of NE-striking, NW- and SE-dipping normal faults and fault scarps cut and offset bedrock and Qf1, Qf2, Qf3, Qqf1, Qqf2, and Qqf3 surfaces along the south side of the valley; (2) a set of discontinuous NE-striking, sinistral faults cut Qf2 surfaces on the north side of the valley; (3) a NW-striking dextral fault cuts and offsets Tertiary basalt lava, and Qf1, Qf2, and Qf3 surfaces along the SW side of the valley; and this fault merges with (4) two, en echelon WNW- to E-W–striking, N-dipping thrust faults that cut Tertiary basalt lava and Qf1 and Qf2 surfaces (Figs. 5, 6, and 7).

Normal Faults

Exposed along the SE side of the valley, the NE-striking Queen Valley normal fault extends for ~14 km from southwest of Morris Creek to the NE end of the valley (Fig. 5). Between the southwestern end of the valley and Queen Canyon, the fault strikes NE, but it swings to a nearly N-S strike at the NE end of the valley. Fault geometry varies from a single, W-facing fault scarp along the southwestern portion that juxtaposes alluvial-fan deposits upon bedrock to a set of NW-facing, with subordinate SE-facing, en echelon fault scarps that cut alluvial-fan surfaces at the mouth of Queen Canyon. To the north of Queen Canyon, the fault geometry returns to a W- to SW-facing fault that juxtaposes alluvial-fan deposits upon bedrock. Here, older, smaller-offset, approximately E-W–striking normal faults are exposed in the footwall of the Queen Canyon fault (Tincher and Stockli, 2008). A few, discontinuous normal fault scarps that cut alluvial-fan surfaces are exposed within the southern two-thirds of the valley (Fig. 5). Height of the footwall escarpment ranges from a maximum of ~1810 m at Morris Creek to a minimum of ~620 m at the north end of the valley (Fig. 5). Recent slip along the Queen Valley fault is indicated by (1) well-developed geomorphic features, such as triangular facets (Fig. 8) and wineglass-shaped drainages, and (2) fault scarps developed across late Pleistocene alluvial-fan surfaces.

Normal fault scarps cut Qf1, Qf2, Qf3a, Qf3b, and Qf, Qqf1, Qqf2, and Qqf3a, Qqf3b, and Qqf3c surfaces but not younger surfaces. Where fault scarps offset small debris-flow channels or erosional escarpments cut into alluvial-fan surfaces, geomorphic evidence indicates normal dip slip but no dextral slip. Most scarps are mildly to moderately eroded and degraded and moderately vegetated (Figs. 8 and 9; see footnote 1). In profile, fault-scarp morphology varies from relatively short...
Figure 9. (A) Representative topographic profiles across normal fault scarps and calculated surface offset or scarp offset. See B for location of profiles and Table 2 for a complete list of measured profiles. (B) Simplified geologic map of a portion of the Queen Valley area highlighting location and magnitude of measured offset across fault scarps. Abbreviations: 3.6 (v7) indicates magnitude of vertical offset and profile number (see Table 2). See Figure 5 for location of map, map units, and symbols.
scars with a single sharp knickpoint, suggesting that these scars formed by a single earthquake event, to relatively tall scars with either one or two knickpoints, suggesting that one or two earthquake events resulted in their formation (Wallace, 1977) (Fig. 9). Measured surface offset or scarp offset across scars ranges from a few tens of centimeters to 14.0 m (Table 2). Transect A-A’ (Fig. 9B), perpendicular to the strike of fault scars cutting Qf2 surfaces at the mouth of Queen Canyon, yields a minimum 9.4 ± 4.4 m of horizontal extension (assuming a fault dip of 60° ± 10°) toward 282°. Combining this calculated horizontal extension measurement with the 10Be model Qf2 surface age of 53.6 ± 10.7 ka, we get a minimum horizontal extension rate of 0.2 ± 0.1 mm/yr. At Orchard Spring, Qf3c has been deposited across the Queen Valley fault, which offsets a Qf2 surface a minimum of 6.1 ± 0.3 m (Figs. 8 and 9). This offset measurement combined with 10Be model surface ages of 77.1 ± 15.4 ka for Qf2 in the footwall and 16.9 ± 3.4 ka for Qf3c in the hanging wall yields an estimated vertical slip rate bracketed between ~0.1 and 0.4 mm/yr and a horizontal extension rate bracketed between ~0.1 and 0.3 mm/yr (assuming a fault dip of 60° ± 10°) toward 300°. These late Pleistocene horizontal extension rates are the same, within error, to somewhat slower than the minimum 0.3 ± 0.1 mm/yr Pleistocene horizontal extension rate across the Queen Valley fault based on apatite (U-Th)/He age of 3.0 ± 0.5 Ma for onset of normal slip (Stockli et al., 2003) and minimum vertical offset of 1370 m across the fault.

**Strike-Slip Faults**

Exposed on the north-central side of the valley, there is a NE-striking, NW- and SE-facing, left-lateral strike-slip fault that cuts a distal Qf2 surface. Evidence for strike-slip faulting includes left-laterally offset channel edges, shutter ridges, and both NW- and SE-facing, ≤1-m-high fault scarps developed along the same fault trace. Two channel edges are left-laterally offset 48.9 ± 5.6 m and 51.7 ± 5.7 m across the same fault trace, yielding a weighted mean offset of 50.3 ± 4.0 m (Figs. 5 and 10; Table 3). This offset measurement combined with an age for the Qf2 surface of 77.1 ± 15.4 ka yields a sinistral slip rate of 0.7 ± 0.2 mm/yr. This estimated slip rate is unusually high because it is nearly twice that estimated for the sinistral Coaldale fault (cf. Bradley, 2005; Tincher and Stockli, 2008), a fault to which the ~50 m of offset is likely transferred (see following). Although this distal Qf2 surface morphology appears continuous with the proximal Qf2 surface we dated, they are separated by ~2.5 km. Because alluvial-fan surfaces may be time transgressive, we suggest that the distal part of the fan surface is considerably older than the dated proximal part, and, therefore, the calculated slip rate of 0.7 mm/yr is likely an overestimate.

Exposed along the western end of Queen Valley, there is a NW-striking, dominantly SW-facing with lesser NE-facing, ≤7.5-m-high fault scarp that we informally refer to as the Coyote Springs fault (Figs. 5 and 7). This fault cuts Tertiary volcanic rocks, Quaternary playa deposits, and Qf1, Qf2, Qf3a, and Qf3b alluvial-fan surfaces, although measurable offset markers are not present. An elevated, weakly convex-up Qf2 surface is located at a left step along the fault trace, which we interpret as a compressional ridge, thus indicating the fault is characterized by dextral slip.

**Thrust Faults**

To the southeast, the Coyote Springs fault merges into a set of ~WNW- to E-W-trending hills underlain by Tertiary basalt lava and Qf1 and Qf2 surfaces (Figs. 5 and 7). A sharp break in slope is exposed along the base of the S-facing side of the hills, which we interpret as the trace of N-dipping thrust faults. A break in slope is also exposed on the N-facing side of the hills, although this one is not as well developed as on the S-facing side. This break in slope may represent the trace of a S-dipping thrust fault. The morphology of the hills suggests that they define a hanging-wall anticline; however, poor exposure and absence of bedding in the basalt lava flows and alluvial-fan deposits make it impossible to determine if they are folded. If our interpretation of an uplifted antiformal structure bounded by thrust faults with opposite dips is correct, the set of hills may define a pop-up or positive flower structure in which oblique-slip thrust faults are characterized by a convex-upward shape and link down-dip (e.g., Sylvester, 1988; McClay and Bonora, 2001). Playa deposits (unit Qp) are exposed on the NE, upslope side of these hills, suggesting that these deposits ponded behind the developing hanging wall.

**KINEMATICS OF FAULT-SLIP TRANSFER ACROSS THE MINA DEFLECTION**

Queen Valley forms the southwestern part of the Mina deflection and the northern termination of the dextral White Mountains fault zone, and, therefore, the faults exposed in the Queen Valley area transfer slip from the White Mountains fault zone into the Mina deflection. Geomorphically, the Queen Valley normal fault is the best-developed fault in Queen Valley. Tincher and Stockli (2008) argued that since ca. 3 Ma, the magnitude of extension has decreased from southwest to northeast along the Queen Valley fault, implying that other structures within Queen Valley are accommodating transfer of slip to the Coaldale fault. Our tectonic geomorphic observations indicate that the southern half of the Queen Valley fault is active, whereas the northern half is not, consistent with Tincher and
Stockli’s interpretation. The sinistral slip faults we observed on the northern side of Queen Valley may be accommodating the missing strain.

The Queen Valley fault, and other major NE-striking, NW-dipping normal faults such as the Deep Springs and Towne Pass faults to the south, define right steps or releasing bends (e.g., Sylvester, 1988; McClay and Dooley, 1995) and transfer slip between the dextral White Mountains–Owens Valley, Hunter Mountain–Panamint Valley, Death Valley–Furnace Creek–Fish Lake Valley, and Benton Springs–Petrified Springs fault zones (Figs. 2 and 3). Right steps in the Death Valley and Hunter Mountain–Panamint Valley fault zones are associated with the Death Valley and Panamint Valley pull-apart basins, respectively (Burchfi el et al., 1987; Burchfi el and Stewart, 1966; Oswald and Wesnousky, 2002), and Queen Valley is, in part, analogous to these larger basins. However, in contrast to the Death Valley and Panamint Valley pull-apart basins, Queen Valley does not define a simple right-stepping extensional step between two dextral fault systems. Rather, sets of faults with different geometries and slip directions, including the NE-striking Queen Valley normal fault, ENE-striking sinistral faults, and a NW-striking dextral fault that merges into WNW- to E-W–striking thrust faults, transfer slip from the narrow White Mountains fault zone to the broad zone of faults that define the Mina deflection.

Three kinematic fault-slip transfer models have been proposed for the dextral slip–dominated eastern California shear zone–Walker Lane belt. In the extensional displacement fault transfer model (Fig. 4A), proposed for fault-slip transfer across the Mina deflection (Oldow, 1992) and across the Deep Springs and Towne Pass faults (Lee et al., 2001; Reheis and Dixon, 1996) (Figs. 2 and 3), the magnitude of extension along right-stepping normal faults is proportional to the amount of strike-slip motion transferred between subparallel dextral strike-slip faults. In the block rotation model (Fig. 4B), proposed for the central Walker Lane belt (Cashman and Fontaine, 2000) (Fig. 2), dextral strike-slip motion is accommodated by dominantly sinistral slip along faults that bound blocks that rotate clockwise within a zone of distributed deformation (McKenzie and Jackson, 1983, 1986). The simple shear couple model (e.g., Wilcox et al., 1973; Sylvester, 1988), in which the antithetic sinistral faults between subparallel dextral faults undergo clockwise rotation during slip, was proposed for the Mina deflection by Wesnousky (2005).

The range of fault styles, orientations, and slip directions exposed in the Queen Valley area precludes the extensional displacement transfer and block rotation models. On the other hand, the...
simple shear couple model, with the shear couple parallel to the White Mountains fault zone, predicts well the orientation, geometry, and style of faults documented in the Queen Valley area. Simple shear is associated with rotation, but we did not observe structural or geomorphic evidence for rotation along the Queen Valley fault, nor did Bradley (2005) or Tincher and Stockli (2008) observe structural or geomorphic evidence for rotation along the Coaldale fault. The absence of such observations suggests that either rotation did not occur within the Mina deflection or rotation occurred to the north of these faults within the Mina deflection (Petro- nis, 2005; Petronis et al., 2004) but not along faults that form the southern boundary of the Mina deflection. Thus, neither of these models can be applied to the range of fault types and geometries observed in the Queen Valley area. We suggest, therefore, that transfer of dextral slip from the NW-striking White Mountains fault zone into the Queen Valley area is partitioned into two primary components (Fig. 11): (1) a restraining bend to the west, resulting in development of contractional structures (pop-up structure) that merge into the dextral Coyote Springs fault, and (2) a releasing bend to the east, resulting in development of extensional structures (pull-apart basin) that merge into the sinistral Coaldale fault. Restraining and releasing bends have been extensively documented at a range of scales in strike-slip fault tectonic settings (e.g., Mann, 2007, and references therein), and they have been simulated in analog models (e.g., McClay and Bonora, 2001; McClay and Dooley, 1995). Thus, it is not surprising to document both restraining and releasing bends within the ~630-km-long dextral shear zone that makes up the northern eastern California shear zone–Walker Lane belt. The development of the broad deformation zone that defines the Mina deflection has been attributed to preexisting crustal heterogeneities (e.g., Stewart and Suczek, 1977; Speed, 1978; Oldow et al., 1989), one of many mechanisms proposed to explain the growth of restraining and releasing bends along strike-slip faults (e.g., Mann, 2007, and references therein). We postulate that small (relative to the Mina deflection) preexisting crustal heterogeneities, likely related to mid-Paleozoic through Mesozoic contractional structures, controlled the development of the restraining and releasing bends in Queen Valley.

We can estimate the magnitude of fault-slip partitioning across the Queen Valley region using a combination of calculated Pliocene to late Pleistocene slip rates along the normal Queen Valley fault (0.1–0.3 mm/yr; Stockli et al., 2003; this work), the sinistral Coaldale fault (0.4 mm/yr) (Bradley, 2005; Tincher and Stockli, 2008), and the dextral White Mountains fault zone (0.3–0.8 mm/yr) (Kirby et al., 2006). In particular, we can predict the style of faulting and slip rates along those faults, the Coyote Springs fault and the western end of the Coaldale fault, for which measurable offset geomorphic markers were not observed (Fig. 12). Based on field observations and structural data, we assign horizontal extensional slip rates (assuming a 60° dipping fault) along the Queen Valley fault of 0.3 mm/yr (Pliocene) to 0.1 mm/yr (late Pleistocene) toward 310° (this work) and a Pliocene pure strike-slip rate along the eastern part of the Coaldale fault of 0.4 mm/yr toward 70° (Bradley, 2005; Tincher and Stockli, 2008). For the northern part of the White Mountains fault zone, we extrapolated calculated slip rates from the southern part where Kirby et al. (2006) reported a middle Pleistocene dextral slip rate of 0.6–0.8 mm/yr toward 330° (this work) and a late Pleistocene transtensional slip rate of 0.3–0.4 mm/yr toward 320°–340°. We assume that the Pliocene strike-slip rate along the eastern part of the Coaldale fault and that the middle Pleistocene slip rate along the White Mountains fault zone have remained constant since the Pliocene.

Given these constraints, a horizontal two-dimensional (2-D) velocity vector diagram for Pliocene-fault-slip-rate transfer from the White Mountains fault zone into the Queen Valley area makes the following predictions (Fig. 12B). (1) The Benton block moved at a rate of 0.5 mm/yr toward 342° relative to the Queen Valley block. Motion of the Benton block was 20° clockwise with respect to the NW strike of the dextral Coyote Springs fault, suggesting that slip along this fault was dominantly dextral, with a lesser component of contraction. (2) The Benton block moved at a rate of 0.80 mm/yr due north relative to the Truman Meadows block. Motion of the Benton block was 38° clockwise with respect to the strike of the NW-striking, dextral Coyote Springs fault, suggesting that slip along this portion of the fault was also transpressional. (3) The Queen Valley block moved at a rate of 0.35 mm/yr toward 24° relative to Truman Meadows block. This vector was 46° counterclockwise with respect to the ENE-striking, sinistral Coaldale fault; therefore, slip is predicted to have been transpressional across the western end of this fault.

Fault-slip transfer of a calculated late Pleistocene transtensional slip rate of 0.35 mm/yr along the White Mountains fault zone—this slip rate is approximately half of the assumed Pliocene slip rate—yields predicted slip rates and orientations that are different from those predicted for the Pliocene (Fig. 12C). (1) The Benton block moved at a rate of 0.25 mm/yr, half the predicted Pliocene slip rate, toward 324° relative to the Queen Valley block. This vector was parallel to the NW-striking, dextral Coyote Springs fault, suggesting that slip along this fault was dextral. (2) The Benton block moved at a rate of 0.4 mm/yr toward 21° relative to the Truman Meadows block, also significantly slower than the Pliocene rate. This slip vector was oriented 59° clockwise with respect to the strike of the Coyote Springs fault, suggesting that slip along this fault was also transpressional but dominantly

Figure 11. Block model illustrating the transfer of dextral slip from the White Mountains fault zone into the Queen Valley area. Dextral slip is partitioned into two primary components: a west-stepping restraining bend, leading to the development of a flower or pop-up structure, and an east-stepping releasing bend, leading to the development of a normal fault and hanging-wall pull-apart basin.
Figure 12. Kinematic fault model for displacement transfer from the dextral White Mountains fault zone to faults within the Queen Valley region. (A) Simplified geometry of major Quaternary faults in the Queen Valley region (compare to geologic map in Fig. 5). Solid lines indicate Pliocene slip rates (mm/yr) based on measured offset markers and age of marker, and dashed lines are predicted slip rates based on the velocity vector diagram in B. Large arrow indicates motion of the Sierra Nevada microplate (SN) with respect to a fixed North American plate (NA) (Dixon et al., 2000). Solid ball is on the hanging wall of normal faults; teeth are on the hanging wall of thrust faults; arrow pairs indicate sense of relative strike-slip motion. (B) Pliocene horizontal velocity vector diagram for fault blocks Benton (B), Queen Valley (QV), Truman Meadows (TM), and White Mountains (WM) shown in A. Slip rates between fault blocks are in mm/yr. Solid lines indicate Pliocene slip rates (mm/yr) based on measured offset markers and age of marker, and dashed lines are predicted slip rates based on this velocity diagram. (C) Late Pleistocene horizontal velocity vector diagram for the fault blocks shown in A. Abbreviations and symbols same as in B. See text for discussion.
thrust slip, unlike the longer-term slip vector. (3) The Queen Valley block moved at a rate of 0.35 mm/yr relative to the Truman Meadows block, the same as the predicted Pliocene slip rate, toward 56°, 32° clockwise with respect to the predicted Pliocene slip vector. This slip vector was 14° counterclockwise with respect to the ENE-striking, sinistral Coaldale fault; thus slip is predicted to have been transpressional across the western end of this fault.

During the late Pleistocene, dextral slip rates appear to have decreased by ~50% across the northern eastern California shear zone. Along the White Mountains fault zone, dextral slip rates decrease from 0.7–0.8 mm/yr during the middle Pleistocene to 0.3–0.4 mm/yr during the late Pleistocene (Kirby et al., 2006) and along the Death Valley–Furnace Creek–Fish Lake Valley fault zone, late Pleistocene slip rates decrease northward from 4.2–1.9° to 4.7–0.9°/–0.6 mm/yr along the northern Death Valley fault (Frankel et al., 2007a) to 2.5–3.0 mm/yr along the Fish Lake Valley fault zone (Frankel et al., 2007b). Based on estimated horizontal extension rates along the Queen Valley normal fault, a minimum of 0.3 ± 0.1 mm/yr since the Pliocene and 0.1–0.3 mm/yr since the late Pleistocene, it is permissible that slip rates have decreased along this fault as well. Furthermore, the 2-D velocity vector diagrams show that the predicted dextral slip rates along the Coyote Springs fault decreased during the late Pleistocene as a result of the reduction in slip along the White Mountains fault zone and Queen Valley normal fault (Figs. 12B and 12C). The lack of fault scarps within Quaternary deposits along the eastern Coaldale fault (Bradley, 2005; Tincher and Stockli, 2008) may indicate a reduction in slip rate during the late Pleistocene. Assuming the sinistral slip rate along the Coaldale fault also decreased by ~50% to 2.0 mm/yr during the late Pleistocene, then predicted slip rates along the western Coaldale and Coyote Springs faults are somewhat smaller with a slightly different orientation to those just discussed. Nevertheless, as in the previous reconstructions, a small component of contraction is predicted across the western Coaldale and Coyote Springs faults.

In general, the predicted contractual component of slip across the Coyote Springs fault and western end of the Coaldale fault is smaller or nearly equal to the strike-slip component. This may explain why well-developed contraction-related structures were not observed along either of these faults (this work; Lee, 2003, personal commun.). Alternatively, the predicted contraction may be partitioned across the Mina deflection and accommodated along faults elsewhere in the region.

The NE-SW contraction perpendicular to the general NW trend of the eastern California shear zone–Walker Lane belt was observed in present-day global positioning system (GPS) data (Bennett et al., 1999) and fault kinematic models across the eastern California shear zone (Hearn and Humphreys, 1998). The competition between westward motion of the central Great Basin, driven by buoyancy (Sonder and Jones, 1999), and NW shear along the Pacific–North American transform boundary may explain this episode of contraction (Hearn and Humphreys, 1998; Bennett et al., 1999).

Late Pleistocene dextral slip rates have decreased by ~50% across the two major strike-slip faults, the White Mountains and Fish Lake Valley fault zones, in the northern eastern California shear zone. Horizontal extension rates may have decreased along the Queen Valley fault as well. This reduction in dextral fault slip rate has been attributed to either a strain transient, by accommodation of deformation along structures to the east of the Fish Lake Valley fault zone (i.e., the Silver Peak–Lone Mountain extensional complex), by distributed strain across Owens Valley, and/or deformation through Long Valley caldera (Frankel et al., 2007b; Kirby et al., 2006). The western ends of many of the EEN-WWS-striking sinistral faults within the Mina deflection are exposed on the north side of the valley. Discontinuous ENE-striking sinistral faults are exposed on the north side of the valley.

Queen Valley forms the southwestern part of the Mina deflection, a relatively broad, right step in the dextral slip–dominated eastern California shear zone–Walker Lane belt. Queen Valley also forms the northern termination of the dextral White Mountains fault zone, the dextral slip of which is partitioned across Queen Valley into two primary components: (1) a restraining bend to the west, resulting in development of contractional structures that merge into the dextral Coyote Springs fault, and (2) a releasing bend to the east, resulting in development of extensional structures that merge into the sinistral Coaldale fault. Restraining and releasing bends are typical in strike-slip fault zones worldwide and have been simulated in analog models of strike-slip fault systems. This geometry of slip transfer in the Queen Valley region precludes alternative fault-slip transfer models, such as the extensional displacement transfer, block rotation, and simple shear couple model, proposed for elsewhere in the eastern California shear zone–Walker Lane belt. Based on the fault-slip vectors for the White Mountains fault zone, the Queen Valley fault, and the eastern Coaldale fault, a small component of contraction is predicted across the Coyote Springs and western Coaldale faults. Present-day GPS data also predict a small component of contraction across the Mina deflection.

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CONCLUSIONS

New geologic mapping and 10Be alluvial-fan surface abandonment ages in the Queen Valley area yield numerical ages on alluvial-fan surfaces that range from 98.2 to 9.1 ka and geomorphic evidence that slip along faults that cut these surfaces includes normal, sinistral, dextral, and thrust slip components. The morphologically dominant fault in the area is the NE-striking normal-slip Queen Valley fault. East- and west-facing normal-slip fault scarps that cut alluvial-fan surfaces exhibit vertical offset of ~14 m to a few tens of centimeters. If we combine these data with the assumption of 60° ± 10° fault dip, we find late Pleistocene horizontal extension rates of 0.1–0.3 mm/yr across the Queen Valley fault, which are the same, within error, to the estimated Pliocene extension rate. Tectonic geomorphology indicates that slip along the NW-striking Coyote Springs fault is dextral and that this fault merges into approximately E-W-striking thrust faults that define a flower structure.