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Kinematics of the Eastern California shear zone: Evidence for slip transfer from Owens and Saline Valley fault zones to Fish Lake Valley fault zone

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ABSTRACT

Late Quaternary slip rates and satellite-based geodetic data for the western Great Basin constrain regional fault-slip distribution and evolution. The geologic slip rate on the Fish Lake Valley fault zone (the northwest extension of the Furnace Creek fault zone) increases northward from about 3 to 5 mm/yr, in agreement with modeled geodetic data. The increase coincides with the intersections of the Deep Springs fault, connected to the Owens Valley fault zone, and of other faults connected to the Saline Valley fault. The combined geologic and geodetic data suggest that (1) the northwest-striking faults of the Eastern California shear zone north of the Garlock fault are connected by north- to northeast-striking normal faults that transfer slip in a series of right steps, and (2) the amount and distribution of slip among the many faults of this broad, complex plate boundary have changed through time.

INTRODUCTION

Recent geologic (Dokka and Travis, 1990; Oldow, 1992) and geodetic (Sauber et al., 1994; Dixon et al., 1995) studies have shown that about 25% of the relative motion between the Pacific and North American plates (~46–48 mm/yr; DeMets et al., 1994; Humphreys and Weldon, 1994) is accommodated by dextral shear east of the San Andreas fault, mostly on faults in the Mojave Desert and western Great Basin. South of the Garlock fault, faults of the Eastern California shear zone accumulated ~65 km of dextral offset since the late Miocene (Dokka and Travis, 1990). To the north, several faults near Walker Lake (Fig. 1) in the Walker Lane belt have accumulated 60–75 km of dextral offset in the past 10 m.y. (Oldow, 1992). Other faults to the west have also been active (Dohrenwend, 1983). Between these two shear zones are three major northwest-striking dextral fault systems (Fig. 1): the Owens Valley and White Mountains fault zones, the Panamint Valley–Hunter Mountain–Saline Valley fault system, and the Death Valley–Furnace Creek–Fish Lake Valley fault system. Dixon et al. (1995) suggested that northeast-striking normal faults transfer slip among these fault systems. However, their geodetic data lack the resolution to verify slip transfer, and geologic proof was lacking. An important implication of the geodetic model is that significant dextral shear is concentrated on the Fish Lake Valley fault zone (FLVFZ), which has received little attention in studies of deformation of the Pacific–North American plate boundary zone. Temporal evolution of the complex fault system composing this zone has also received little attention.

Mapping of Quaternary deposits and faults in Fish Lake and Deep Springs valleys (Reheis, 1992; Reheis et al., 1995) documents the structural connection between the FLVFZ and the Deep Springs fault (Fig. 2) and provides Quaternary slip rates during different time periods. These data demonstrate slip transfer between the Owens Valley fault zone and the FLVFZ and suggest slip transfer from the Saline Valley fault to the FLVFZ. We compare geologic slip rates to geodetic data and discuss implications for kinematic evolution of the Eastern California shear zone.

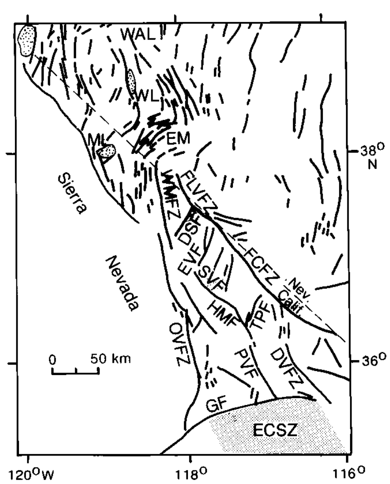

Figure 1. Map of late Cenozoic faults of western Great Basin, modified from Oldow (1992). Faults (F) and fault zones (FZ): WAL—Walker Lane; WMFZ—White Mountains; OVFZ—Owens Valley; DSF—Deep Springs; EVF—Eureka Valley; SVF—Saline Valley; HMF—Hunter Mountain; TPF—Towne Pass; PVF—Panamint Valley; FLVFZ—Fish Lake Valley; FCFZ—Furnace Creek; DVFZ—Death Valley; GF—Garlock; ECSZ—Eastern California shear zone. ML is Mono Lake; WL is Walker Lake; EM is Excelsior Mountains.

GEOLOGIC DATA

The right-oblique Fish Lake Valley fault zone extends north-northwest 80 km from the Furnace Creek–Death Valley fault system along the east side of the White Mountains (Fig. 1) and is characterized by large, steep fault scarps, offset drainages, and shutterridges (Brogan et al., 1991). Holocene alluvium filling the northern part of Fish Lake Valley is cut by many north-striking faults that transfer lateral offset eastward by an extensional right step to the Emigrant Peak normal-fault zone (Fig. 2). We suspect that this step is part of a larger step that transfers slip from the FLVFZ to faults of the Walker Lane northeast of the Excelsior Mountains (Reheis and Noller, 1989), but a kinematic connection has not yet been demonstrated.

Deep Springs Valley is a closed basin about 25 km long between the White Mountains and the Inyo Mountains (Fig. 2), bounded on the east by the north-northeast–striking Deep Springs normal fault. The fault is characterized by steep fault scarps in upper Pleistocene and Holocene deposits (Bryant, 1989). The FLVFZ is structurally linked to the northeast end of the Deep Springs fault by normal and sinistral faults (Fig. 2) (Reheis, 1992; Reheis et al., 1995). Although the connecting faults mostly offset basalt and granitic rocks, they also cut alluvium and fan deposits containing or overlying the 760 ka Bishop ash. The Deep Springs fault is probably also connected structurally with the Owens Valley and White Mountains fault zones (Fig. 2). Several short north-striking faults in upper Pliocene deposits within the Waucoba embayment step eastward from the junction (a right step) of the two fault zones and extend into a set of northeast-striking faults in bedrock that parallel or connect to the Deep Springs fault. The two southernmost of the bedrock faults probably have Quaternary offset, for they locally bound the sides of small, asymmetric topographic basins within the Inyo Mountains (Nelson, 1966, 1971).

Several normal faults in the Saline Range strike north-northeast from the north end of the Saline Valley fault toward the south end

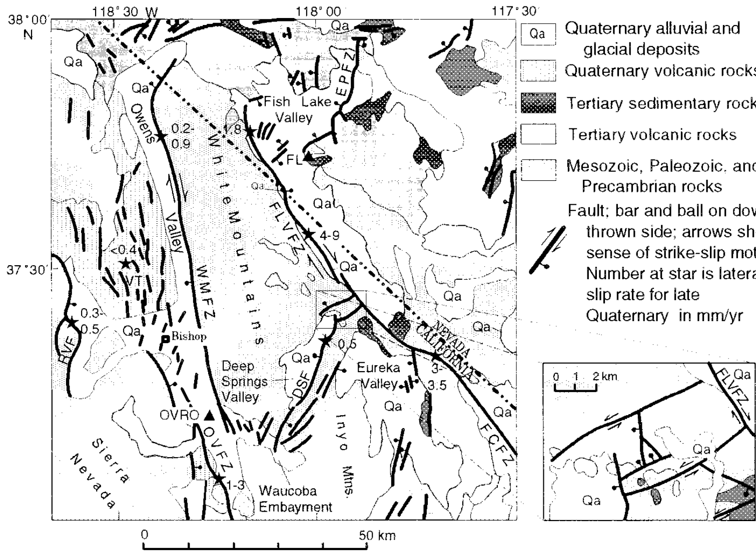

Figure 2. Geologic map of study area, showing Quaternary faults and slip-rate sites (star). RVF—Round Valley fault; DSF—Deep Springs fault; EPFZ—Emigrant Peak fault zone; geodetic stations are OVRO (Owens Valley Radio Observatory) and FL (Fish Lake); other abbreviations as in Figure 1. Sources of rates: Round Valley fault, Berry (1990); Volcanic Tableland (VT), Pinter (1995); White Mountains fault zone, DePolo (1989); Owens Valley fault zone, Beanland and Clark (1995); FLVFZ and Deep Springs fault, this paper.

of the FLVFZ (Fig. 1). These faults are buried by young alluvium in northern Saline Valley but probably are connected to the Saline Valley fault at depth. The westernmost fault (Fig. 2) has a scarp as much as 15 m high on upper Pleistocene(?) deposits and had an M = 6.1 normal-faulting earthquake in 1993 (Massonet and Feigl, 1995; Peltzer and Rosen, 1995). This fault and its pattern of aftershocks strike north toward a normal fault of the FLVFZ about 10 km away that has at least 15 m of late Pleistocene offset (Reheis, 1992).

Lateral Slip Rates on the Fish Lake Valley Fault Zone

Faulted middle and upper Quaternary fan and fluvial deposits in Fish Lake Valley were dated using radiocarbon, tephrochronologic, thermoluminescence, and surface-exposure techniques (Reheis et al., 1993, 1995, and references therein). Undated and dated deposits were correlated by using surface and soil characteristics. Fluvial deposits contain the 760 ka Bishop ash on divides north and east of Deep Springs Valley (Fig. 2). Fan unit Qpo, interbedded with and overlying the Bishop ash, is assigned an age of 760–600? ka. Fan unit Qpy is assigned an age of about 430–190 ka, assuming deposition during one or more interglacial periods. Fan unit Qpy is assigned a maximum age of 130 ka and is not younger than 50 ka. The oldest of the Holocene fan units (Qh) was deposited from 11 to 6.3 ka. We estimate 700–600 ka, 360–190 ka, 75–50 ka (as old as 100 ka at one site), and 8–6.3 ka as the surface ages of the four fan units.

A large shutterridge south of Furnace Creek consists of eroded deposits of upper middle Pleistocene unit Qpo that have moved southeast along the main faults of the FLVFZ (Fig. 3; Reheis et al., 1995). Comparison of clast lithology in deposits of unit Qpo west of the fault zone and the shutterridge indicates that the shutterridge moved about 4.5–7 km since deposition, yielding a post-early Pleistocene lateral slip rate of about 9 mm/yr (range 6–12 mm/yr).

Between Furnace Creek and the shutterridge, fans of upper Pleistocene unit Qpy are cut by two northwest-striking dextral faults and several north- to northeast-striking normal and sinistral faults (Fig. 3). A prominent debris-flow channel west of the two dextral faults is offset 56 m by the western fault (Reheis et al., 1995). The surface morphology and soils of five subdued channels on the fan surface east of the two faults suggest that channel age increases to the southeast; thus, the eastern block has moved progressively southeast. The youngest channel (~50 ka?) has been offset about 120 m across the two faults, yielding a slip rate of 2.4 mm/yr (range 1.5–2.5 mm/yr) (preferred slip rates are based on the best estimates of surface age and offset, which are commonly not the medians of the age and offset ranges). Including variation in the former position of the channel west of the faults, the oldest channel is offset about 400 m (245–465 m). This channel could be as old as about 100 ka (older than the surface age of this unit elsewhere), yielding a slip rate of about 4 mm/yr (2–9 mm/yr). The Qpy-Qpm contact has been offset about 550 m across the faults; assuming that this contact was created at the beginning of deposition of unit Qpy, the slip rate is 4.4 mm/yr (3–6 mm/yr). However, these values are minimum estimates of the total slip rate, because slip across nearby sinistral and normal faults that cut unit Qpy (Fig. 3) is not included. Thus, the actual late Quaternary slip rate for the fault zone could be as much as 5 mm/yr.

Debris-flow levees on the surface of unit Qpy are offset right laterally about 120 m near the north end of the FLVFZ (Fig. 2; Reheis et al., 1993), and the slip rate is 1.8 mm/yr (range 1.1–3.3 mm/yr), a minimum value because possible offsets across subparallel to oblique secondary faults at the two localities are not included. This site has a lower slip rate than that at Furnace Creek because it is north of the beginning of the eastward stepover to the Emigrant Peak fault zone.

Fan deposits south of the intersection of the FLVFZ with north-striking faults in Eureka Valley (Fig. 2) have beheaded drainages. Lateral offset is estimated by matching deposits of unit Qpy to tributary drainages across the fault zone. Allowable fits range from 110 to 180 m; the most likely offset is about 150 m. Thus, the late Quaternary slip rate here is about 3 mm/yr (range 1.5–3.6 mm/yr). The oldest Holocene fans have channels that are offset about 22 m (range 13–32 m), yielding a similar slip rate of about 3.3 mm/yr (range 1.2–5.0 mm/yr). These preferred late Quaternary slip rates are lower than those to the north at the Furnace Creek site.

Slip Rates on Other Faults

The hills bounding the east and north sides of Deep Springs Valley (Fig. 2) have wind gaps cut by streams flowing from the southern White Mountains into Eureka Valley (Reheis et al., 1995, and references therein). One wind gap 200 m above the valley floor on the footwall block of the northern Deep Springs fault contains Bishop ash and stream gravel. The depth of burial of the stream channel on the hanging-wall block is assumed to be less than the present scarp height. Thus, the vertical offset is 200–400 m, and the average slip rate on this part of the fault since 760 ka is about 0.3–0.5 mm/yr. The rate on the central part of the fault is probably higher. We estimate an extensional lengthening rate of 0.4–0.6 mm/yr using a dip of 40° ± 2° for the Deep Springs fault (Wilson, 1975). Bryant (1989) measured scarps about 5 m high on lower Holocene(?) deposits and about 24 m high on upper Pleistocene deposits; these data suggest a late Quaternary slip rate of about 0.3–1.0 mm/yr, in general agreement with the post-Bishop ash rate.

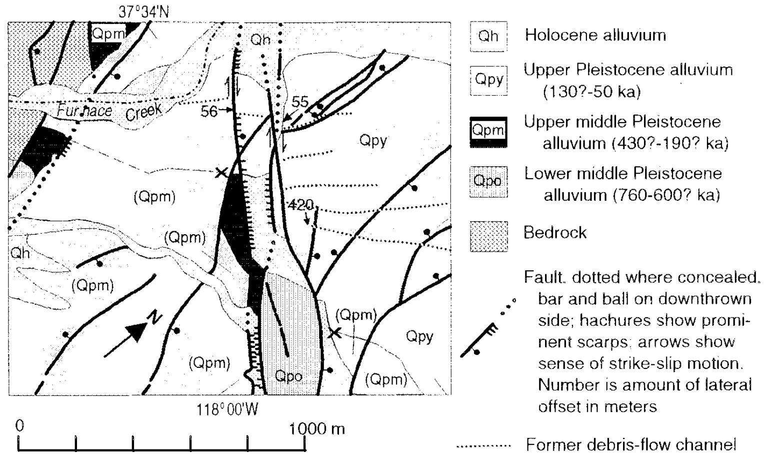

Figure 3. Map of Furnace Creek in Fish Lake Valley (slip-rate site on central part of FLVFZ in Fig. 2), modified from Reheis et al. (1995). Former debris-flow channels on surface of unit Qpy are progressively less distinct toward southeast, reflecting dextral offset. X is inferred offset of contact of units Qpy and Qpm. Parentheses indicate that unit Qpm underlies thin mantle of unit Qpy. Unit Qpo near bottom of figure is shutterridge described in text.

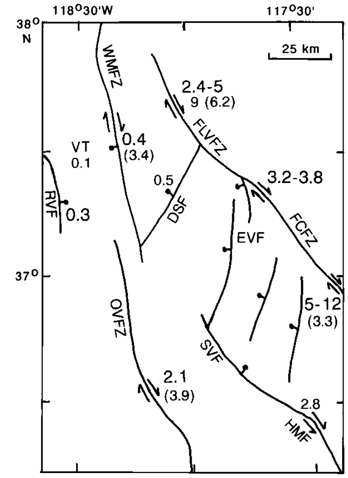

Figure 4. Tectonic map of Owens Valley–Fish Lake Valley area. Abbreviations as in Figures 1 and 2. Geologic slip rates (mm/yr), resolved to N30°W, shown adjacent to strike-slip or dip-slip symbols. Large type indicates late Quaternary rates; small type indicates post-early Pleistocene rates; parentheses indicate geodetic model rates (Dixon et al., 1995). Sources of geologic rates same as Figure 2, except: Owens Valley fault-zone rate (Martel, 1989) includes ~0.1 mm/yr combined extension from Sierra Nevada frontal fault (Gillespie, 1991); Hunter Mountain fault rate—Burchfiel et al. (1987); Furnace Creek fault-zone rate—Klinger (1994).

Late Quaternary slip rates for faults in Owens Valley apparently decrease from south to north. Lateral slip rates in the south on the Owens Valley fault zone and Sierra Nevada frontal fault sum to about 2.1 ± 0.6 mm/yr (Fig. 4, Table 1) resolved to a N30°W direction. Lateral slip rates in the north on the White Mountains fault zone, the Round Valley fault, and across the Volcanic Tableland sum to about 0.8 ± 0.3 mm/yr, an apparent decrease of about 1.3 mm/yr relative to southern Owens Valley. We chose N30°W because (1) using the mean regional trend of the major strike-slip faults simplifies calculations and (2) it is similar to the Dixon et al. (1995) value of N38°W ± 5° for movement of the Sierra Nevada relative to the Owens Valley Radio Observatory (Fig. 2).

COMPARISON TO GEODETIC DATA

The northward increase of late Quaternary lateral-slip rate on the FLVFZ, about 3 mm/yr at the southern end to at least 4 mm/yr in the central part (Fig. 2), agrees with available geodetic data within uncertainties. Trilateration data for Owens Valley suggest that southern and central Owens Valley is currently the principal locus of dextral shear for the Eastern California shear zone (Savage and Lisowski, 1995). Geologic and space-based geodetic data indicate that subsidiary shear also occurs to the east on the Death Valley–Furnace Creek and the Hunter Mountain–Panamint Valley fault zones. However, the space geodetic data relating Owens Valley Radio Observatory (Fig. 1) to stations east of the FLVFZ and elsewhere in the Great Basin require that significant dextral shear be accommodated to the east, most likely in Fish Lake Valley (Dixon et al., 1995). A model correcting the geodetic data for elastic strain-accumulation effects and consistent with other data suggests rates of 3.9 ± 1.1 mm/yr for the southern and central Owens Valley fault zone, 3.4 ± 1.2 mm/yr for the White Mountains fault zone in northern Owens Valley, 3.3 ± 2.2 mm/yr for the Furnace Creek fault zone, and 6.2 ± 2.3 mm/yr for the FLVFZ (Fig. 4; Dixon et al., 1995).

The northward increase in geologic slip rate from the Furnace Creek fault zone to the FLVFZ and corresponding decrease from the Owens Valley fault zone to the White Mountains fault zone (Fig. 4) is consistent with a simple slip-transfer model: the southern FLVFZ is joined by the Deep Springs fault (joined to the Owens Valley fault zone) and by faults in Eureka Valley (joined to the Saline Valley fault); hence, the northward increase in slip rate on the FLVFZ is the result of slip transfer via the Deep Springs fault and Eureka Valley faults. The geodetic-based model supports a northward increase in the present-day rate of dextral slip from the Furnace Creek fault zone to the FLVFZ. The Deep Springs fault has accommodated 0.5 mm/yr of slip by extensional lengthening since the middle Pleistocene. The post-3 Ma slip rate on the Hunter Mountain fault (Burchfiel et al., 1987), the Holocene rate on the Panamint Valley fault of 2–3 mm/yr (Zhang et al., 1990), and the seismicity in Eureka Valley suggest that the Eureka Valley faults also

TABLE 1. FAULTS AND SLIP RATES IN THE STUDY AREA

Name of fault or fault zone (f. z.)	Average strike	Source of data	Age range of slip rate	Extension rate (E) or lateral slip rate (L) (mm/yr)	Rate resolved to N30°W (mm/yr)
Volcanic Tableland	N15°W	Pinter (1995)	760 ka	<0.4 (E)	0.1
Round Valley fault	N10°W	Berry (1990)	20 ka	0.4 ± 0.1 (E)	0.3 ± 0.05
White Mtns. f. z.	N15°W	DePolo (1989)	<10 ka	0.2 ± 0.1 (E)	0.1 ± 0.05
White Mtns. f. z.	N15°W	DePolo (1989)	<10 ka	0.3 ± 0.2 (L)	0.3 ± 0.2
Owens Valley f. z.	N10°W	Martel (1989)	20 ka	0.1 ± 0.02 (E)	0.1 ± 0.01
Owens Valley f. z.	N30°W	Beanland and Clark (1995)	10 ka	2.0 ± 0.5 (L)	2.0 ± 0.5
Sierra Nevada fault	N20°W	Gillespie (1991)	<500 ka	0.1 (E)	0.02
Deep Springs fault	N30°E	This study; Bryant (1989)	760 ka	0.5 ± 0.1 (E)	0.4 ± 0.1
Fish Lake Valley f.z. (north)	N30°W	This study	100 ka	2.4 - 5.0 (L)	2.4 - 5.0
Fish Lake Valley f.z. (south)	N55°W	This study	100 ka	3.0 - 3.3 (L)	3.2 - 3.8
Hunter Mountain fault	N55°W	Burchfiel et al. (1987)	3 Ma	2.5 ± 0.5 (L)	2.8 ± 0.7

Note: See Figure 4 for locations.

transfer some slip to the FLVFZ. Hunter Mountain fault slip could also be partly transferred by Quaternary faults southeast of Eureka Valley (Fig. 4) that intersect the Furnace Creek fault zone. The ~3 mm/yr rate determined for the southernmost FLVFZ agrees with the rate based on limited geodetic data but conflicts with an estimate of 5–12 mm/yr on the central Furnace Creek fault zone in Death Valley (Klinger, 1994).

Much of the uncertainty in collating the geologic and geodetic slip rates lies in the different time scales of the techniques (Table 1) and the rapid evolution of the fault system. Few previous studies have been able to compare slip rates on a single fault zone during different time intervals and along the zone. Interval (rather than average) slip rates can be calculated for Furnace Creek in Fish Lake Valley by subtracting the best estimates of age and displacement for offset markers (i.e., the shutterridge and the debris-flow channels) to obtain the amounts of displacement during the intervals of time between the formations of the markers. These calculations suggest that the slip rate at this site may have been as much as 12 mm/yr during the middle Pleistocene and as little as 3 mm/yr during the latest Pleistocene and Holocene. Furthermore, lateral slip rates decrease and vertical slip rates increase as the strike along the FLVFZ changes from northwest to north (Fig. 2; Reheis et al., 1993, 1995), showing that extension here accommodates strike-slip deformation. Vertical slip rates also appear to have been higher during the middle Pleistocene than either before or after on both the FLVFZ and the Deep Springs fault. Gillespie (1991) suggested that rapid movement on the bounding faults of Owens Valley may have followed eruption of the Bishop Tuff and collapse of Long Valley caldera. Part of the temporal variation could also reflect a rapidly evolving fault mosaic even in the presence of a uniform far-field displacement rate. Understanding these relations will require careful assessment of offsets of temporally equivalent units and better spatial sampling of the present-day deformation field. We are hopeful that our ongoing geodetic studies in the area will provide better information on the present-day behavior of the major faults.

The combined geologic and geodetic studies suggest that the major northwest-striking faults of the Eastern California shear zone north of the Garlock fault (Fig. 1) are connected by short north-striking normal faults that transfer slip among the major faults via right steps. At present, the total slip rate of 10.7 ± 1.6 mm/yr (Dixon et al., 1995) across the shear zone around lat 36°15′ is distributed among the Owens Valley fault zone, the Hunter Mountain–Panamint Valley faults, and the Furnace Creek fault zone, but north of this latitude slip is increasingly transferred eastward to the FLVFZ. Similarly, at the north ends of the White Mountains fault zone and the FLVFZ, faults of the Mono Lake–Excelsior Mountains trend (Fig. 1) (Dohrenwend, 1983) and of the Emigrant Peak fault zone (Fig. 2) may serve to transfer slip to faults of the Walker Lane (Oldow, 1992). The slip-rate distribution to the south was probably different in the past, with more displacement accommodated by the Death Valley and Furnace Creek fault zones and less by the Owens Valley fault zone. If so, then deformation has apparently moved progressively westward and perhaps northward through time, a conclusion similar to that reached by Dokka and Travis (1990) for the Eastern California shear zone south of the Garlock fault. Furthermore, Quaternary slip rates on the FLVFZ and related faults suggest that (1) the relations among faults of this broad plate boundary change on a detectable scale of $<10^5$ yr and (2) extension in this area results from and in part accommodates strike-slip deformation.

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CORRECTION

Kinematics of the Eastern California shear zone: Evidence for slip transfer from Owens and Saline Valley fault zones to Fish Lake Valley fault zone: Correction

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The patterns in Figures 2 and 3 were lost in the printing process. They are reprinted here with all patterns intact.

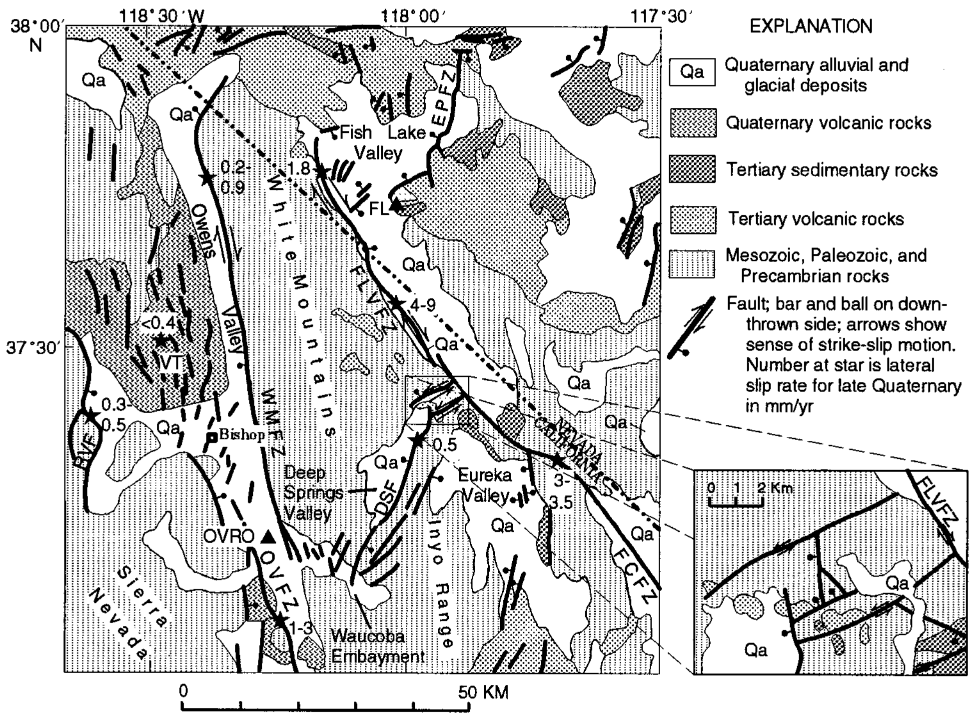

Figure 2. Geologic map of study area, showing Quaternary faults and slip-rate sites (star). RVF—Round Valley fault; DSF—Deep Springs fault; EPFZ—Emigrant Peak fault zone; geodetic stations are OVRO (Owens Valley Radio Observatory) and FL (Fish Lake); other abbreviations as in Figure 1. Sources of rates: Round Valley fault, Berry (1990); Volcanic Tableland (VT), Pinter (1995); White Mountains fault zone, DePolo (1989); Owens Valley fault zone, Beanland and Clark (1995); FLVFZ and Deep Springs fault, this paper.

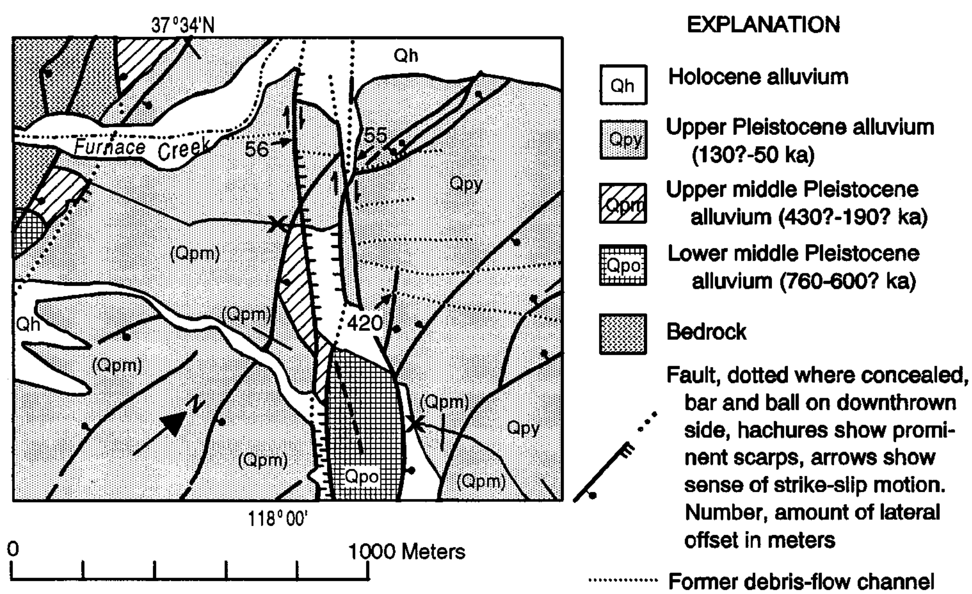

Figure 3. Map of Furnace Creek in Fish Lake Valley (slip-rate site on central part of FLVFZ in Fig. 2), modified from Reheis et al. (1995). Former debris-flow channels on surface of unit Qpy are progressively less distinct toward southeast, reflecting dextral offset. X is inferred offset of contact of units Qpy and Qpm. Parentheses indicate that unit Qpm underlies thin mantle of unit Qpy. Unit Qpo near bottom of figure is shutterridge described in text.