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Timothy H. Dixon, Stefano Robaudo, Jeffrey Lee, Marith C. Reheis

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Timothy H. Dixon
University of Miami, thd@usf.edu

Stefano Robaudo
University of Miami

Jeffrey Lee
California Institute of Technology

Marith C. Reheis
U.S. Geological Survey

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Constraints on present-day Basin and Range deformation from space geodesy

Timothy H. Dixon and Stefano Robaudo[1]
Rosenstiel School of Marine and Atmospheric Sciences, University of Miami
Miami, Florida

Jeffrey Lee[2]
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena

Marith C. Reheis
U.S. Geological Survey, Lakewood, Colorado

Abstract. We use new space geodetic data from very long baseline interferometry and satellite laser ranging combined with other geodetic and geologic data to study contemporary deformation in the Basin and Range province of the western United States. Northwest motion of the central Sierra Nevada block relative to stable North America, a measure of integrated Basin and Range deformation, is 12.1±1.2 mm/yr oriented N38°W±5° (one standard error), in agreement with previous geological estimates within uncertainties. This velocity reflects both east-west extension concentrated in the eastern Basin and Range and north-northwest directed right lateral shear concentrated in the western Basin and Range. Ely, Nevada is moving west at 4.9±1.3 mm/yr relative to stable North America, consistent with dip-slip motion on the north striking Wasatch fault and other north striking normal faults. Comparison with ground-based geodetic data suggests that most of this motion is accommodated within ~50 km of the Wasatch fault zone. Paleoseismic data for the Wasatch fault zone and slip rates based on seismic energy release in the region both suggest much lower slip rates. The discrepancy may be explained by some combination of additional deformation away from the Wasatch fault itself, aseismic slip, or a seismic rate that is anomalously low with respect to longer time averages. Deformation in the western Basin and Range province is also largely confined to a relatively narrow boundary zone and in our study area is partitioned into the eastern California shear zone, accommodating 10.7±1.6 mm/yr of north-northwest directed right-lateral shear, and a small component (~1 mm/yr) of west-southwest - east-northeast extension. A slip rate budget for major strike-slip faults in our study area based on a combination of local geodetic or late Quaternary geologic data and the regional space geodetic data suggests the following rates of right-lateral slip: Owens Valley fault zone, 3.9±1.1 mm/yr; Death Valley-Furnace Creek fault zone, 3.3±2.2 mm/yr; White Mountains fault zone in northern Owens Valley, 3.4±1.2 mm/yr; Fish Lake Valley fault zone, 6.2±2.3 mm/yr. In the last few million years the locus of right-lateral shear in the region has shifted west and become more north trending as slip on the northwest striking Death Valley-Furnace Creek fault zone has decreased and is increasingly accommodated on the north-northwest striking Owens Valley fault zone.

Introduction

It has long been recognized that Basin and Range extension is an important component of deformation within the Pacific-North America plate boundary zone [*Atwater*, 1970]. In the last decade space geodetic techniques have helped to clarify the kinematics of Basin and Range deformation and its role in Pacific-North America plate interaction [*Minster and Jordan*, 1984, 1987; *Ward*, 1990; *Argus and Gordon*, 1991]. There are nevertheless some remaining puzzles. For example, why do recent space geodetic estimates of the rotation vector describing Sierra Nevada block-stable North America relative motion [*Argus and Gordon*, 1991], a measure of integrated deformation across the Basin and Range province, differ in direction from geological estimates of Basin and Range deformation averaging over longer times [Minster and Jordan, 1987; Wernicke, 1988]? Does this imply rapid evolution in deformation geometry? Which faults accommodate surface deformation associated with the recently recognized eastern California shear zone, and what is the total slip rate [*Sauber et al.*, 1986; *Dokka and Travis*, 1990; *Savage et al.*, 1990; *Sauber et al.*, 1994]? What is the relation between the eastern California shear zone and overall deformation of the Basin and Range? Is the Basin and Range province deforming as a continuum, or is deformation largely restricted to the boundary zones? In this paper we address these questions with new space

[1]Now at Ecology and Environment, Ft. Lauderdale, Florida.
[2]Now at Department of Geology, Central Washington University, Ellensburg.

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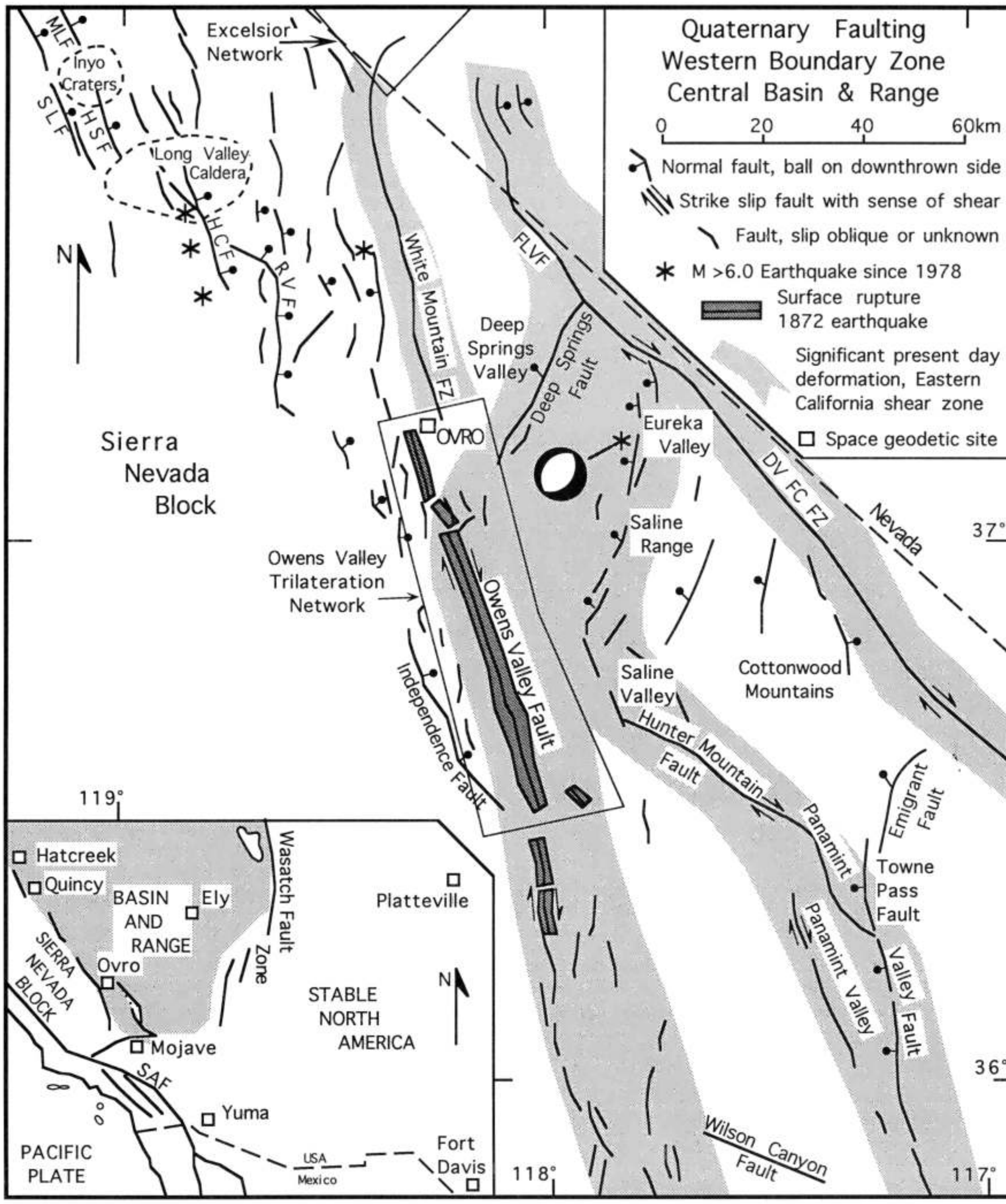

Figure 1. Major Quaternary faults and selected earthquakes for the boundary zone between the Basin and Range province and the Sierra Nevada block near Owens Valley Radio Observatory (OVRO). Surface rupture of 1872 earthquake and outline of Owens Valley and southern Excelsior trilateration networks [*Savage and Lisowski*, 1980, 1995] are also shown. Fault abbreviations are DVFCFZ, Death Valley-Furnace Creek fault zone; FLVF Fish Lake Valley fault; HSF, Hartly Springs fault; HCF, Hilton Creek fault, MLF, Mono Lake fault, RVF, Round Valley fault; SLF Silver Lake fault. SAF, San Andreas Fault. Focal mechanism is shown for the May 17, 1993, Eureka Valley earthquake from Harvard Centroid Moment Tensor (CMT) solution [*Dziewonski et al.*, 1994]. Light stipple is postulated surface trace of major faults presently accommodating the eastern California shear zone. Inset shows location of most space geodetic sites used in this study. Figure 1 is modified from *Hill et al.* [1985] and *California Division of Mines and Geology* [1992].

geodetic data combined with other geodetic and geological data.

Space Geodetic Data

Previous space geodetic studies of Basin and Range deformation [*Ward*, 1990; *Argus and Gordon*, 1991] were based on very long baseline interferometry (VLBI) data collected by NASA's Crustal Dynamics Project (CDP) up to the end of 1989. Our study improves on earlier studies by having a longer time span of data and by incorporating additional data types. We use VLBI data collected by the CDP from 1979 to the end of 1991 (GLB 868) [*Ryan et al.*, 1993] and incorporate satellite laser ranging (SLR) data to the Lageos satellite from 1976 to the end of 1990 (University of Texas long arc solution LLA 9101) [*Watkins*, 1990]. Where appropriate we also incorporate geological observations and local ground geodetic data to help interpret the velocities of the space geodetic sites. This allows us, for example, to better relate the velocity of Owens Valley Radio Observatory (OVRO), located in Owens Valley east of the eastern Sierra Nevada range front fault and also east of the surface trace of the Owens Valley fault zone (Figure 1), to the motion of the stable Sierra Nevada block to the west.

For analysis of the space geodetic data, we combine baseline length and (for VLBI) transverse rates of change for a global network of stations, similar to the technique described by *Ward* [1990] and *Argus and Gordon* [1991] for VLBI data only. Details of the analysis are given by *Robaudo and Harrison* [1993]. Velocities of sites of interest, Ely (Nevada), Hat Creek, Quincy, OVRO, and Mojave (California) (Figure 1, Table 1), are determined relative to stable North America by minimizing in a least squares sense the velocities of six stations: Fairbanks (Alaska), Platteville (Colorado), Fort Davis (Texas), Yuma (Arizona), Westford (Massachusetts), and Richmond (Florida). Platteville, Fort Davis, and OVRO have both SLR and VLBI data; the remaining stations have VLBI data only. A preliminary version of these results was presented by *Dixon et al.* [1993]. This paper expands and updates the earlier interpretation and corrects an error in the uncertainty assigned to the station velocities.

The space geodetic data have two important characteristics. First, they describe deformation relative to an external reference frame. This will allow us to link local deformation estimates based on geological and ground geodetic observations to more regional data and processes. Second, they define integrated deformation over a broad region. For example OVRO's velocity relative to stable North America approximates integrated Basin and Range deformation, absent only a small component of extension across the eastern Sierra Nevada range front fault to the west (Figure 1). The velocity of Ely defines integrated deformation across the eastern Basin and Range and by vector difference with OVRO provides information on the magnitude and style of present day deformation in the western Basin and Range between OVRO and Ely. Thus we can describe Basin and Range deformation in a transect roughly orthogonal to a small circle describing Pacific-North America motion, connecting the Wasatch front in the eastern Basin and Range to the San Andreas fault in central California (Figure 1, inset).

In a study like this it is important to determine the influence of the reference frame on the site velocity estimates. While our choice of reference frame ("stable North America") is logical, the ensemble of stations used to define it is arbitrary and necessarily introduces random and possibly systematic error. For example, our six-station reference frame encompasses regions undergoing differential postglacial rebound and includes three sites (Fairbanks, Platteville, and Yuma) arguably close to deforming zones. We opted to use this larger group of reference frame-defining stations in order to minimize the influence of errors at any one station, but it is useful to ask how results might vary with different combinations of reference frame stations. In an otherwise similar analysis of VLBI data from 1979 to 1991, *Gordon et al.* [1993] used a different definition of stable North America, eliminating all stations west of the Mississippi River and fixing only two

Table 1. Velocity of Selected Sites in Western United States Relative to Stable North America

	North and West Velocities*		Rate, Azimuth and Error Ellipse*†				
	North, mm/yr	West, mm/yr	Rate, mm/yr	Azimuth, deg	σ_1, mm/yr	θ_1, deg	σ_2, mm/yr
Ely	-0.7±1.1	4.9±0.7	4.9±1.3	262	1.2	12	0.9
Hatcreek	4.5±0.4	7.7±0.3	8.9±0.5	300	0.7	343	0.6
Mojave	7.5±0.3	4.2±0.2	8.6±0.4	331	0.7	342	0.6
OVRO	8.0±0.4	6.2±0.3	10.1±0.5	322	0.7	347	0.6
Quincy	3.6±0.4	8.1±0.3	8.9±0.5	294	0.8	338	0.6

*Uncertainties are one standard error.
†σ_1 and θ_1 are the length and orientation (degrees clockwise from north) of the semimajor axis of the velocity error ellipse at one standard error; σ_2 is the length of the semiminor axis. For 95% confidence ellipse, multiply σ_1 and σ_2 by 2.45.

eastern seaboard stations, Westford and Richmond. Their results are generally similar to ours within uncertainties. For example their velocity for Ely (5.6 mm/yr±1.0 mm/yr at an azimuth of 274° or N86°W) overlaps our result (4.9±1.3 mm/yr at an azimuth of 262° or W8°S; Table 1; all errors quoted at one standard error) within uncertainties. This suggests that the reference frame definition we have chosen has not unduly influenced the site velocities of interest.

Our results for most stations are also similar to those of *Ward* [1990] and *Argus and Gordon* [1991] within uncertainties. The azimuth of OVRO's velocity obtained in our study (322° or N38°W; Table 1) is 10° more westerly compared to earlier results [*Argus and Gordon*, 1991] (332° or N28°W) though not as westerly as that obtained by *Gordon et al.* [1993] (314° or N46°W). Results for Ely have not been discussed in any detail previously because of few observations and corresponding large error. However, there are now sufficient data to warrant analysis. Our velocity estimate for Ely is based on 12 observations taken between April 1984 and October 1990.

Discussion

Argus and Gordon [1991] used data then available to predict north-northwest motion of the Sierra Nevada block relative to stable North America, approximately parallel to the block's eastern boundary with the Basin and Range, and suggested that Basin and Range deformation reflected this motion via a right-lateral simple shear model. In other words, west-northwest - east-southeast extension in the Basin and Range, taken as a continuum, was a direct result of right lateral shear on the western boundary. There are three important implications of this model. First, while motion of the Sierra Nevada block predicted by the *Argus and Gordon* [1991] model (N28°W at OVRO) would yield a maximum stretching direction oriented ~N70°W, in agreement with geological indicators of Basin and Range extension, it also predicts orthogonal shortening for which there is no geological evidence. Second, a right-lateral simple shear model for Basin and Range deformation predicts no crustal thinning. However, elevated heat flow, gravity and seismic reflection and refraction data all suggest that relatively thin crust is characteristic of much of the Basin and Range province [e.g., *Smith*, 1978; *Eaton*, 1982; *Knuepfer et al.*, 1987]. Third, the amount of extension possible in right-lateral simple shear is fairly limited, difficult to reconcile with the large magnitude extension characteristic of the province on geological timescales [*Wernicke et al.*, 1988]. Either the rate or geometry of Basin and Range deformation has recently changed such that geodetic observations do not agree with longer-term geological indicators of deformation, or there is a problem in one or both data sets or their respective interpretations.

Several observations suggest that it is worthwhile reexamining the space geodetic data and some assumptions concerning local site geology and strain distribution within the Basin and Range province in order to better understand comparisons between geologic and geodetic measures of Basin and Range deformation. First, the kinematic boundary condition for Basin and Range deformation (Pacific-North America relative plate motion) has been essentially constant for at least the last 3.4 million years [*Harbert and Cox*, 1989], confirmed by good agreement between geologic and geodetic estimates of the plate motion vector within their joint uncertainties [e.g., *Ward*, 1990; *Argus and Gordon*, 1990; *Dixon et al*, 1991; *Feigl et al.*, 1993]. Second, the present-day state of stress as indicated by earthquakes indicates least principal stress directions between east-west and east-southeast - west-northwest for most of the Basin and Range province [*Zoback*, 1989] in agreement with longer-term geological indicators of extension direction [Zoback and Zoback, 1980; *Minster and Jordan*, 1987; *Wernicke et al.*, 1988]. Third, there are several problems with a right-lateral simple shear model for Basin and Range extension, noted in the previous paragraph. Motivated by these observations, we reexamine the space geodetic data and relevant terrestrial data and consider implications for deformation on the eastern and western boundaries of the Basin and Range and the location, kinematics, and evolution of the eastern California shear zone. We then define a vector (valid in the general vicinity of OVRO) describing motion of the Sierra Nevada block with respect to stable North America, a measure of integrated Basin and Range deformation, for comparison to geological estimates and consider some tectonic implications.

Deformation in the Eastern Boundary Zone

Ely's westward motion is consistent with previous suggestions that the north striking Wasatch range front fault (Figure 1, inset) and related eastern boundary faults primarily experience dip slip motion [*Best and Hamblin*, 1978; *Minster and Jordan*, 1984; *Zoback*, 1989]. However, the rate estimate for Ely (4.9±1.3 mm/yr) suggests faster extension across the eastern Basin and Range than is indicated by most other data (see below). If correct, the new space geodetic data have important implications for seismic hazard and earthquake process in the region.

Before comparing our result to other data, we first assess the possible impact of our choice of reference frame on the extension rate estimate. *Gordon et al.* [1993] discuss an apparent east-west lengthening of ~ 2 mm/yr across eastern North America based on VLBI data. Whether this represents a physical process or a systematic error in the VLBI data is beyond the scope of this paper, but it clearly impacts our interpretation of Ely's velocity. The same physical process or data artifact manifested in the *Gordon et al.* [1993] result will affect our results as well since we used essentially the same data. *Gordon et al.'s* [1993] velocity for Ely (5.6 mm/yr) is faster than ours because they defined stable North America by fixing two sites on the eastern seaboard. If lengthening across the stable interior of the United States is occurring, it would add to the westward velocity of Ely relative to the reference frame by an amount unrelated to extension across the eastern boundary zone of the Basin and Range province. Thus our choice of reference frame may be more appropriate for investigating Basin and Range deformation, as the effect of this lengthening is reduced with a reference frame of widely separated sites including sites in both eastern and central North America. But we are still left with the question of reference frame dependence; that is, how much is our rate for Ely affected?

One way of minimizing this frame dependence is to look at the velocity of one station with respect to another. While this is generally avoided because the station velocities of interest are unduly sensitive to errors at the single reference station, it does get around the reference frame problem noted above. The velocity of Ely with respect to Platteville (Figure 1) in our solution (see also *Gordon et al.* [1993]) is 3±1 mm/yr to the west, still significantly higher than most previous estimates for deformation in the region (next paragraph). We conclude that our choice of reference frame does not affect the basic result, and because of the beneficial effect of using six broadly distributed stations to define a reference frame, we take our velocity for Ely with respect to this reference frame as the most appropriate estimate available at this time for investigating eastern Basin and Range deformation.

Rates of seismic energy release based on summing seismic moment tensors in a given region over a given period can be used to infer recent deformation rates. This approach estimates brittle strain release, i.e., strain release associated with earthquakes, but underestimates total strain if aseismic deformation is occurring. Studies in the general vicinity of the Wasatch fault zone on the eastern boundary of the Basin and Range province (Figure 1) where modern seismicity is concentrated indicate very low rates of seismic energy release, equivalent to deformation rates <0.5 mm/yr, except for one area (Hansel Valley) west of the northern Wasatch fault zone where the rate is 1.5 mm/yr [*Eddington et al.*, 1987]. These rates are significantly less than the total extension rate observed at Ely by space geodesy. The discrepancy between the higher geodetic rate and lower seismic rates could be explained if aseismic strain release accounts for a significant fraction of overall deformation. Alternately, or in addition, there may be an anomalously low rate of seismicity during the short period covered by historical data compared with longer time averages. In fact, modern earthquakes predict anomalously low rates of slip along most of the Wasatch front even compared to the paleoseismic record (itself low compared to the space geodetic result; see below), which has important implications for future seismic activity and hazard [*Smith*, 1978; *Eddington et al.*, 1987].

Paleoseismic studies on the Wasatch fault zone suggest Holocene rates of horizontal extension less than about 1.0 mm/yr [*Schwartz and Coppersmith*, 1984; *Eddington et al.*, 1987; *Machette et al.*, 1992; *McCalpin et al.* 1994], again significantly less than the space geodetic result which integrates across a broader region. One explanation is that the paleoseismic studies underestimate slip rate because some fraction of slip is accommodated by nonbrittle coseismic mechanisms such as warping and rotation which do not lead to discrete, easily measured offset [*Salyards et al.*, 1992]. Given that paleoseismic studies have been conducted at numerous locations along the Wasatch fault zone and give consistent results, this seems unlikely. Another possibility is that significant strain is accommodated aseismically and thus is not recorded in the paleoseismic sites. A third possibility is that other active but less well studied faults accommodate significant extension in the eastern Basin and Range. Numerous faults with late Pleistocene offset have been mapped both east and west of the Wasatch fault [e.g., *Nakata et al.*, 1982], most lying within about ±100 km of the Wasatch fault itself. Ely lies about 250 km west of the Wasatch front, thus its velocity relative to stable North America integrates across roughly the eastern third of the province and would include slip on these additional faults if they are presently active. Other geodetic data discussed below suggest strain accumulation in the general vicinity of the Wasatch fault zone (distances <50 km) at rates sufficient to explain our data assuming simple elastic strain models. Assuming no systematic error in either the space or ground geodetic data, this agreement would seem to limit the location of the most active faults to no more than about 50 km from the Wasatch fault.

Ground-based trilateration data indicate about 2 mm/yr of extension across a ~ 70-km-wide network roughly centered on the central Wasatch fault [*Savage et al.*, 1992]. However, fitting these data to an elastic strain accumulation model and solving for fault slip and horizontal extension at depth (the latter for comparison to the "far-field" horizontal rate measured at Ely) implies significantly faster rates of horizontal extension. *Savage et al.* [1992] fit the trilateration data to two models (planar and listric normal faults) and obtained east-west extension rates of 5.3±2.0 and 7.6±1.6 mm/yr respectively. Both results agree with our space geodetic data at Ely within one standard error. If correct, this implies that all surface deformation manifested by Ely's velocity with respect to stable North America can be accommodated within a relatively narrow region centered on the Wasatch fault zone. Additional active faults near the Wasatch fault are allowed by these data, but they would have to be located within the ~70-km aperture of the trilateration network, or less than ~50 km from the Wasatch fault.

Preliminary Global Positioning System data spanning a broad aperture that includes the Wasatch fault zone also support the concept of rapid extension (4±1 mm/yr) across this region [*Martinez et al.*, 1994]. In summary, all recent geodetic data are in rough agreement and are consistent with relatively rapid (3.0-7.6 mm/yr) east-west extension across the Wasach fault zone and eastern Basin and Range. The discrepancy between high geodetic rates and low rates inferred from both paleoseismicity on the Wasatch fault zone and seismic moment tensor summation in the region may be explained by active faulting away from the Wasatch fault zone itself, aseismic deformation, and/or anomalously low rates of current seismic activity compared to long-term rates.

Deformation in the Western Boundary Zone

Data. The following four sets of geological and geodetic observations are relevant to our discussion of the

VLBI/SLR data for the western boundary zone of the Basin and Range province:

1. Geological evidence suggests that the eastern California shear zone has accommodated northwest trending right lateral shear since late Miocene time (~10-6 Ma) with a significant fraction accommodated along the Death Valley-Furnace Creek fault zone (6-12 mm/yr [*Dokka and Travis*, 1990]). Geomorphic evidence indicates this fault zone is still active, but present day rates are poorly constrained. Other active fault zones in the region accommodating right-lateral shear include the Hunter Mountain-Panamint Valley fault zone [*Smith*, 1979; *Burchfiel et al.*, 1987], the Owens Valley [*Lubetkin and Clark*, 1988] and White Mountains fault zones, and the Fish Lake Valley fault zone [*Reheis*, 1994a] (Figure 1). *Zhang et al.* [1990] report a Holocene slip rate of 2.4±0.8 mm/yr for the southern Panamint Valley fault. *Beanland and Clark* [1995] report a late Quaternary slip rate of 2.0±0.5 mm/yr for the Owens Valley fault zone. North of OVRO, geologic mapping indicates that both the Fish Lake Valley fault zone [*Reheis et al.*, 1995] and White Mountains fault zone [*dePolo*, 1989] are active. *dePolo* [1989] reports a Holocene slip rate of 0.5-1.2 mm/yr for the White Mountains fault zone (Figure 1). *Reheis* [1994b] suggests a minimum Holocene slip rate of 4 mm/yr for the Fish Lake Valley fault zone.

Note that the rate and direction of individual faults or even the shear zone as a whole do not define motion of the Sierra Nevada block relative to stable North America; the geological indicators only describe relative motion in a local reference frame.

2. Ground geodetic data led *Savage et al.* [1990] to suggest that the southern part of the shear zone in the Mojave Desert presently accommodates ~8 mm/yr of north-northwest directed right-lateral shear and extends north from the Mojave Desert into Owens Valley, west of both the Death Valley-Furnace Creek and Hunter Mountain fault zones. A recent analysis of these and other geodetic data from the Mojave Desert suggests that the rate may be as high as 12 mm/yr [*Sauber et al.*, 1994]. A recent analysis of the Owens Valley data suggests that ~7 mm/yr is accommodated here [*Savage and Lisowski*, 1995]. New data from the Excelsior trilateration network (the southernmost part of which is shown in Figure 1) and other networks north of Owens Valley along the central Nevada seismic zone show strain rates about 50-75% of those observed in Owens Valley, with orientations consistent with north-northwest trending right-lateral shear [*Savage et al.*, 1995]. Thus right-lateral shear continues north of Owens Valley, perhaps at reduced rate, or perhaps is partitioned differently compared to regions to the south, with some shear occurring in regions not covered by trilateration. These data also indicate that unlike the Owens Valley area where most right-lateral shear is accommodated within ~100 km of the eastern Sierra range front, significant right-lateral shear is accommodated in central Nevada 150 km or more east of the range front.

Note that slip rates estimated from ground geodetic data in Owens Valley (~7 mm/yr; *Savage and Lisowski* [1995]) are significantly faster than geological estimates for slip rates on the Owens Valley (2.0±0.5 mm/yr *Beanland and Clark,* 1995]) or White Mountains (0.5-1.2 mm/yr [*dePolo*, 1989]) fault zones. As with the geological estimates, the ground-based geodetic data describe only local relative motion. The space geodetic data will allow us to link these local data sets to an external reference frame such as stable North America.

3. Deformation along the western boundary of the Basin and Range province in the vicinity of OVRO at the present time is apparently partitioned into nearly orthogonal strike-slip and extensional components on subparallel faults, as suggested by the simultaneous occurrence of dominantly right-lateral displacement on the Owens Valley fault and nearby active normal faulting along the eastern Sierra range front [e.g, *Stewart*, 1988; *Zoback*, 1989; *Jones* and *Wesnousky*, 1993]. However the partitioning is not perfect. For example, vertical as well as horizontal offset occurred along the surface break of the 1872 earthquake with a ratio of about 1:6 [*Beanland and Clark*, 1993]. Differences in the thickness of valley fill on either side of the Owens Valley fault zone [*Hollett et al.*, 1991] indicate that this fault has accumulated significant vertical offset in the past. Note that OVRO lies east of both the Owens Valley fault zone and the eastern Sierra Nevada range front faults (Figure 1). The White Mountains fault zone, immediately north of OVRO, has a right stepping, en echelon relation with the Owens Valley fault zone (Figure 1) but differs somewhat in character. While both are oblique slip faults, the White Mountains fault zone has a higher normal component compared to strike-slip component [*dePolo*, 1989] in contrast to the Owens Valley fault zone where the strike-slip component dominates.

4. A series of north to north-east striking normal faults cuts across the White and Inyo Mountains, the Cottonwood Mountains and the Saline Range (Figure 1). These faults may have acted in the past as transfer faults linking a series of en echelon, right stepping, northwest to north-northwest striking right-lateral strike-slip faults. Geomorphic and seismic evidence suggest that the northernmost of the normal faults are active. Fresh, steep fault scarps, vertically offset drainages, and offset Holocene alluvial fans indicate recent activity on the Deep Springs fault [*Bryant*, 1989] (Figure 1). The May 17, 1993, M=6.1 Eureka Valley earthquake similarly indicates active normal faulting immediately south of Deep Springs Valley (Figure 1). We suggest that the normal faults in Eureka Valley provide a kinematic link between the Hunter Mountain-Panamint Valley fault system and the Fish Lake Valley fault zone (we are aware of no other faults that might transfer slip northward from the Hunter Mountain fault; see Figure 1). If correct, this linkage implies a minimum rate for the Fish Lake Valley fault zone of 2.4±0.8 mm/yr. This rate is a minimum because it does not account for any slip transferred from the Death Valley-Furnace Creek fault zone southeast of Fish Lake Valley nor for any slip transferred from the Owens Valley fault zone via the Deep Springs fault (Figure 1).

Strain concentration in the western boundary zone: Evidence and implications. The kinematic model presented in this section attempts to reconcile the different observations listed above, using the new space geodetic data as an additional constraint. OVRO's northwest velocity relative to stable North America (10.1±0.5 mm/yr) is roughly comparable to the expected rate of shear for the eastern California shear zone [*Savage et al.*, 1990; *Sauber et al.*, 1994; *Savage and Lisowski*, 1995], but to make a rigorous comparison we must first account for the fact that OVRO's velocity is defined relative to stable North America and thus includes deformation in the interior of the Basin and Range plus the eastern boundary zone, whereas the terrestrial survey data describe only local deformation within part of the western boundary zone in a reference frame defined by the local network. Also, we must correct for elastic strain accumulation since OVRO is located near seismically active faults comprising the shear zone (Figure 1).

If A, B, and C represent points in stable North America, the central Basin and Range (e.g., Ely) and the western Basin and Range (e.g., OVRO), respectively, then vector **AC** (motion of OVRO relative to stable North America) equals the sum of vector **AB** (motion of Ely relative to stable North America) plus vector **BC** (motion of OVRO relative to Ely) (Figure 2). Vector **BC** (8.8±1.3 mm/yr at N9°W±5°, i.e., north-northwest directed right-lateral motion) reflects motion associated with the eastern California shear zone. Because of elastic strain accumulation it does not exactly represent the far-field rate, i.e., the rate that should be compared to geologic rates which average over many earthquake cycles, although the uncorrected and corrected values are actually very similar (see next section). The general similarity between vector **BC** (or its value corrected for elastic strain accumulation) and the rate and direction of shear (8-12 mm/yr north-northwest) for the eastern California shear zone inferred by *Savage et al.* [1990] and Sauber et al. [1994] from ground geodetic data is important and suggests two key points. First, the relatively narrow aperture of the ground geodetic networks, including the one outlined in Figure 1, apparently captures a significant fraction of the deformation associated with the shear zone. This is consistent with the observation by *Savage et al.* [1994] of negligible strain accumulation in the Yucca Mountain trilateration network in western Nevada, just east of the shear zone. Second, most of the deformation between Ely and OVRO must in fact be restricted to the shear zone. This suggests that deformation across the western half of the Basin and Range province is not uniformly distributed but rather is restricted to a relatively narrow western boundary zone. The deformation represented by **BC** (motion of OVRO relative to Ely) must include virtually all deformation associated with the eastern California shear zone and little else (we argue below that some extension likely occurs west of OVRO, but this is a relatively small effect). Since OVRO apparently records all or most of the motion characterizing the shear zone, we also surmise that the shear zone must lie entirely to the east (perhaps just east) of OVRO. The OVRO-Ely velocity also indicates negligible east-west extension between Ely and OVRO. Other data described below limit extension on the eastern Sierra Nevada range front (the western boundary of the Basin and Range) to about 1 mm/yr. Apparently, significant Basin and Range extension at the present time is limited to a region close to

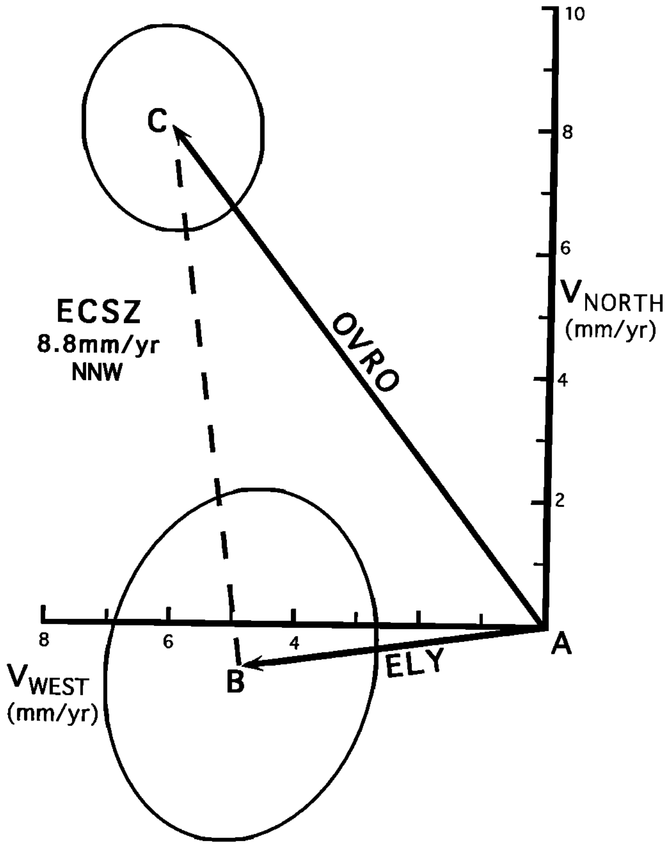

Figure 2. Velocity of Ely, Nevada (**B**), and OVRO, California (**C**), relative to stable North America (**A**). Ellipses are at 95% confidence. **BC** (8.8 mm/yr at N9°W) represents integrated deformation between Ely and OVRO (absent only a small amount due to elastic strain accumulation) and is similar to right-lateral shear deformation across the eastern California shear zone measured by ground-based geodetic data [*Savage et al.*, 1990; *Sauber et al.*, 1994].

the Wasatch fault zone on the eastern boundary of the province. This generalization does not apply to "pull apart" basins such as Death Valley or Panamint Valley associated with right steps in northwest striking strike-slip faults [*Burchfiel and Stewart*, 1966]. Finally, the fact that the shear zone at the latitude of OVRO maintains roughly the same rate recorded by geodetic data to the south suggests that the rate is not decreasing significantly northward. *Pezzopane and Weldon* [1993] trace shear zone-related deformation into Oregon and Washington, consistent with this observation, and discuss the regional tectonics.

The concentration of surface strain in the western boundary zone of the Basin and Range near OVRO is an important observation. It is consistent with the similar concentration of seismicity [*Eddington et al.*, 1987], but since the seismic record is short and perhaps anomalous with respect to longer time averages, geodetic evidence for strain concentration is important. Present-day strain concentration along this part of the western boundary zone is also consistent with concentration of late Quaternary faulting in the region [*Wallace*, 1984]. Perhaps this strain concentration is related to the anomalously low-velocity (hot and weak?) upper mantle observed here by *Biasi and Humphreys* [1992] using *P* wave travel times; that is, strain has concentrated in a weak zone.

The space geodetic data suggest that simple models of Basin and Range deformation such as unidirectional extension or right-lateral simple shear tell only part of the story; at least both these modes of deformation apparently occur simultaneously. Northwest motion of the Sierra Nevada block with respect to stable North America consists of two main components, with two corresponding styles of Basin and Range deformation: east-west extension on north striking normal faults in the eastern part of the province, probably concentrated near the eastern boundary, and right-lateral shear on northwest to north-northwest striking strike-slip faults concentrated in the western boundary zone.

Assuming these two modes of deformation have continued for several million years, we can see why it has been difficult to reconcile geologic indicators of extension direction with space geodetic measurements made on or near the Sierra Nevada block. Only the first (extensional) mode of deformation leads to creation of significant amounts of new crust, leaving a large areal fraction of the Basin and Range province with north-south striking normal fault scarps and north trending basins and ranges indicative only of the east-west extensional component. These data by themselves would lead to a biased view of Sierra Nevada-stable North America motion. Similarly, the integrated motion measured by space geodesy at OVRO by itself is not very descriptive of critical details of deformation in the interior of the province, especially the exensional component.

A Kinematic Model for the Eastern California Shear Zone. The OVRO-Ely velocity (8.8±1.3 mm/yr) is a minimum estimate for the total rate of shear across the eastern California shear zone because OVRO lies very close to one of the faults comprising the shear zone (the Owens Valley-White Mountains fault zone) and thus is affected by elastic strain accumulation. OVRO would also "miss" any right-lateral shear accommodated on strike-slip faults that lie to the west between OVRO and the Sierra Nevada block, but these are probably insignificant (Figure 1). Simple elastic half-space models for a locked vertical strike-slip fault [*Savage and Burford*, 1973] allow us to estimate the range of far-field rates for the eastern California shear zone consistent with the space geodetic data for comparison to geologic data averaged over many earthquake cycles. *Sauber et al.* [1994] modeled deformation in the Mojave Desert as a broad zone of shear. However, north of the Garlock fault, geologic evidence suggests that slip is concentrated on a few major faults. We model the deformation accordingly with discrete faults, albeit ones that are sufficiently close that their elastic strain fields overlap.

Because of ambiguities associated with the exact partitioning of slip among the active faults comprising the shear zone and uncertainties in the fault locking depths, the OVRO-Ely velocity data alone cannot distinguish between the lower (8 mm/yr) rate suggested by *Savage et al.* [1990] and the higher (12 mm/yr) rate suggested by *Sauber et al.* [1994]. As an aside, the rate need not be constant with latitude, though data to be presented suggest no significant rate variation from the southern Mojave desert to northern Owens Valley; below we make the assumption of constant rate over our limited study area.

If most slip is confined to the Owens Valley-White Mountains fault zone (Figure 1), then the OVRO-Ely velocity can be fit to an elastic strain model with a far-field rate of about 12 mm/yr. If, however, slip also occurs east of Owens Valley (Figure 1), the situation is more complicated, and the lower (8 mm/yr) rate is allowed by the data. Evidence discussed below suggests significant right-lateral motion on the Fish Lake Valley fault zone. We can fit the OVRO data to a model where slip is partitioned between the Owens Valley-White Mountains fault zone to the west and the Fish Lake Valley fault zone to the east, using additional information to help define some of the model parameters. For two locked, parallel strike-slip faults in an elastic half-space, the velocity field in a reference frame defined by the perpendicular distance from the first fault is given by:

$$v = \frac{1}{\pi}\left[v_a^0 \tan^{-1}\left(\frac{x}{D_a}\right) + v_b^0 \tan^{-1}\left(\frac{x-S}{D_b}\right)\right] \qquad (1)$$

where v is the velocity at perpendicular distance x from the first fault (a), v_a^0 and v_b^0 are the far field velocities of the first and second faults with locking depths D_a and D_b, respectively, and the faults are separated by distance S. Using the best estimate for slip partitioning on the faults (derived below) and assuming locking depths of 8 and 12 km for Owens Valley and Fish Lake Valley, respectively, we obtain an estimate of 10.7±1.6 mm/yr for the velocity of eastern California shear zone (Figure 3), 1.9 mm/yr higher than the measured OVRO-Ely velocity. The uncertainty is the root sum square (rss) of the space geodetic error (1.3 mm/yr) and additional uncertainty introduced by the model (estimated at 1.0 mm/yr). Our rate estimate is intermediate between other published geodetic estimates (~8 mm/yr; [*Savage et al.* 1990]; ~12 mm/yr, [*Sauber et al.* 1994]) and is equivalent to them within 95% confidence limits. In the kinematic models derived below for individual faults comprising the shear zone we arbitrarily assume that 10%±5% (1.1±0.5 mm/yr) of the total 10.7 mm/yr slip rate for the shear zone is accommodated east of Fish Lake Valley, since there is geological evidence for minor right-lateral faulting immediately east of Fish Lake Valley. Remaining slip (9.6 mm/yr) is assumed to be accommodated "locally," i.e., in the region between Fish Lake Valley and northern Owens Valley, or between Death Valley and southern Owens Valley (Figure 1).

The discrepancy between ground-based geodetic and geologic slip rate data in Owens Valley bears on the issue of where most of the deformation associated with the shear zone is presently concentrated. On one hand, geologic data indicate significant motion across the Death Valley [*Dokka and Travis*, 1990] and Hunter Mountain [*Zhang et al* 1990] fault zones (Figure 1) and lower rates of motion on

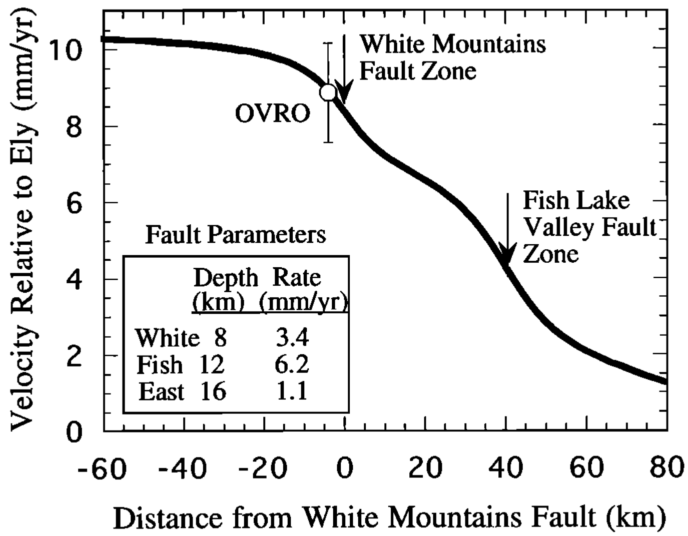

Figure 3. The measured velocity of OVRO relative to Ely (8.8 mm/yr NNW) is a function not only of the total slip rate across the eastern California shear zone but also, because of elastic strain accumulation, the distribution of slip on various faults comprising the shear zone and their respective locking depths. These effects can be approximated with elastic half-space models (1), see text. The models are non unique (1 data point, 6 adjustable parameters!), and various velocity distributions, with far-field rates totaling about 9 to 13 mm/yr, fit the space geodetic data equally well. The model shown here, with a total far-field rate of 10.7 mm/yr, is consistent with both the space geodetic data and other data, as discussed in text. Slip is partitioned between the White Mountain fault (3.4 mm/yr), the Fish Lake Valley fault (6.2 mm/yr), and a hypothetical fault (1.1 mm/yr) 80 km east of the White Mountain fault.

the Owens Valley fault zone [*Beanland and Clark*, 1995]. On the other hand, ground-based trilateration data suggest that the locus of present day right lateral shear is concentrated in Owens Valley [*Savage et al.*, 1990; *Savage and Lisowski*, 1995]. The fact that our space geodetic data require that OVRO lie west of the eastern California shear zone appears at first glance to agree with geological evidence for significant shear across the Furnace Creek-Death Valley fault zone and Hunter Mountain fault zones.

One complication in comparing the space and terrestrial geodetic data is that OVRO lies near the northern limit of the Owens Valley trilateration network. OVRO also lies at the northern limit of the surface rupture associated with the 1872 earthquake on the Owens Valley fault (Figure 1), consistent with a step or change in trend of the surface trace of the shear zone at this point. If strain was concentrated in the southern and central part of the Owens Valley trilateration network and the shear zone stepped east of OVRO, then at least the available ground- and space-based geodetic data could be reconciled (we would still have a discrepancy between ground-based geodetic rates and geologic rates in Owens Valley). *Dixon et al.* [1993] suggested that at the present time right-lateral shear was largely restricted to south-central Owens Valley fault zone and the Death Valley-Furnace Creek fault zone, and most of the Owens Valley component stepped east of OVRO to the Fish Lake Valley fault via the active Deep Springs normal fault (Figure 1). However, recent analyses of additional trilateration data [*Savage and Lisowski*, 1995] suggest no significant strain rate differences between the northern and southern halves of the Owens Valley network, limiting the amount of such shear transfer to less than about 1 mm/yr. Thus we need another explanation for the discrepancy between ground- and space-based geodetic results, preferably one that also addresses the difference between the ground-based geodetic rates and geologic rates in Owens Valley.

The trilateration data record 2.9±0.4 mm/yr of right-lateral shear across Owens Valley and strongly imply (via elastic models) a higher far-field rate [*Savage and Lisowski*, 1995], but it is useful to ask whether these data actually require that the major locus of shear be centered in Owens Valley. If right-lateral shear is distributed among the Death Valley-Furnace Creek, Hunter Mountain-Panamint Valley and Owens Valley fault zones, we can investigate how slip might be partitioned among these systems using available geologic and geodetic data combined with elastic strain models (1). Consider a model where right-lateral motion occurs on three parallel, locked faults, all with slip rates of 3 mm/yr, separated by 25 and 50 km, respectively, roughly similar to the situation for the Death Valley-Furnace Creek, Hunter Mountain-Panamint Valley, and Owens Valley fault zones (Figure 1). Clearly the situation is more complicated in our study area, since the three faults are not exactly parallel and extension as well as right-lateral motion is accommodated in the region. However, if oblique extension is largely partitioned into strike-slip and normal components, treating the strike-slip component independently is probably an adequate approximation. The key point is that a velocity gradient will be observed across the westernmost (Owens Valley) fault even though significant shear occurs to the east because of elastic strain effects. The magnitude of the observed velocity gradient depends on the actual slip distribution and the fault locking depth assumed in the models. For a locking depth of 15 km on all faults, the differential velocity across a distance of 25 km (the dimension of the trilateration network) centered on the westernmost fault is about 1.9 mm/yr, less than the 2.9±0.4 mm/yr observed by *Savage and Lisowski* [1995] across Owens Valley. However, Owens Valley has been the locus of abundant late Quaternary volcanism, and there is seismic evidence for anomalous crust consistent with magmatic activity at depth at some locations [e.g., *Sanders et al.*, 1988]. Thus it is reasonable to assume that the crust here is weaker, hence the fault locking depth should be shallower than regions to the east. Assigning a locking depth of 8 km to the Owens Valley fault and 12 and 16 km to the middle and eastern faults, respectively, again all with slip rates of 3 mm/yr, results in a differential velocity of 2.4 mm/yr across Owens Valley, still less than the observed value but equivalent within uncertainties.

We are now in a position to derive a slip rate budget for the major elements comprising the eastern California shear zone that better matches available data, with the space geodetic data constraining integrated slip rate and local geodetic or late Quaternary or Holocene geologic data constraining slip rates for individual faults. In constructing this model we ignore the small obliquities between major strike-slip faults, treating their slip rates as additive for comparison to the overall slip rate. Given other uncertainties, this approximation is reasonable. The model we derive is non unique, and other slip rate distributions could satisfy the data nearly as well. However, our example illustrates some key points and is a useful working hypothesis to be tested and revised with future data.

Assuming locking depths of 8 km, 12 km, and 16 km (west to east) and setting the rate for the middle (Hunter Mountain), fault equal to the Holocene estimate, then slip rates of 3.9 mm/yr (Owens Valley), 2.4 mm/yr (Hunter Mountain) and 3.3 mm/yr (Death Valley-Furnace Creek) fit the available data very well. Specifically, this slip distribution gives a velocity gradient across Owens Valley that exactly matches the trilateration data (2.9 mm/yr), minimizes the discrepancy between geologic and geodetic data in Owens Valley, and meets the geologic (Holocene) constraint for the Hunter Mountain fault. The slip rate for the Death Valley-Furnace Creek fault is constrained by the fact that the total slip rate across the three fault systems must sum to 9.6 mm/yr, based on the space geodetic data and assumptions outlined earlier. If our model is approximately correct, more than 50% of right-lateral slip associated with the eastern California shear zone is accommodated east of Owens Valley, but the Owens Valley fault zone is still the single most active fault in this part of the system.

Uncertainties are estimated as follows. For the Owens Valley fault zone, the uncertainty is the rss of the trilateration error (±0.4 mm/yr) and the model error, estimated at 1.0 mm/yr, for a total of 1.1 mm/yr. Thus our estimate for present-day slip on the Owens Valley fault zone (3.9±1.1 mm/yr) differs from the geologic estimate (2.0±0.5 mm/yr) at one standard error, but the values are equivalent at two standard errors (95% confidence). For the Death Valley-Furnace Creek fault zone, the total error depends on the error for the Owens Valley fault zone (1.1 mm/yr), the error for the Hunter Mountain fault (0.8 mm/yr), and the error in our estimate of total slip rate accommodated in the region (rss of 1.6 mm/yr and 0.5 mm/yr), for a total error of 2.2 mm/yr.

The slip rate model can be extended north if we assume that slip on the Hunter Mountain system is transferred completely to the Fish Lake Valley fault. This is a reasonable assumption since there are no other throughgoing faults in this region capable of accommodating the additional slip. Thus the slip rate on the Death Valley-Furnace Creek system must increase northward, to 5.7±2.3 mm/yr north of its intersection with the north striking system of normal faults in Eureka Valley (Figure 1) at the south end of Fish Lake Valley (here the Death Valley-Furnace Creek fault zone becomes the Fish Lake Valley fault zone; Figure 1).

Activity on the Deep Springs fault implies that additional slip may be transferred to the Fish Lake Valley fault zone north of its intersection with the Deep Springs fault, perhaps from the Owens Valley fault zone (Figure 1). However, precise slip rate estimates for the Deep Springs fault are not available. *Bryant* [1989] suggested that the minimum vertical rate through late Quaternary time was 0.24 mm/yr, based on offset stream channels containing deposits correlated with the Bishop Tuff. *Wilson* [1975] measured a 40° fault dip in the subsurface deposits of Deep Springs Lake, giving a minimum rate of horizontal extension for the Deep Springs fault of 0.29 mm/yr. Trilateration data limit the amount of slip rate reduction in northern Owens Valley to less than 0.8 mm/yr compared to the slip rate in central and southern Owens Valley [*Savage and Lisowski*, 1995; J.C. Savage, personal communication, 1995]. This suggests an upper limit to the horizontal component of extension on the Deep Springs fault, presuming a kinematic connection between this fault and the Owens Valley fault (Figures 1 and 4). We therefore assume that 0.5±0.3 mm/yr slip transfers from the Owens Valley fault zone to the Fish Lake Valley fault zone via the Deep Springs fault, implying that the slip rate on the White Mountains fault zone, north of the intersection of the Owens Valley fault zone and the southwest extension of the Deep Spring fault, decreases to 3.4±1.2 mm/yr, while the slip rate on the Fish Lake Valley fault zone northwest of its intersection with the Deep Springs fault increases to 6.2±2.3 mm/yr. Thus north of OVRO, our model requires that more than 50% of the right-lateral shear associated with the eastern California shear zone is accommodated east of Owens Valley, mainly in Fish Lake Valley. *Reheis* [1994a, b] and *Reheis et al.* [1995] found that the likely range of late Pleistocene and Holocene slip rates for the Fish Lake Valley fault zone is 4-7 mm/yr with an upper limit of 12 mm/yr, consistent with this suggestion.

Our model satisfies the space geodetic data at OVRO (it places most right-lateral shear to the east), satisfies the combined space geodetic data at OVRO and Ely (the total "far-field" rate of right-lateral shear accommodated between these stations is 10.7 mm/yr; we have accommodated 90%, or 9.6 mm/yr, within a relatively narrow zone), and eliminates the discrepancy between ground-and space-based geodetic data in Owens Valley. The model does not satisfy geological evidence for low (0.5-1.2 mm/yr) slip rates on the White Mountains fault zone [*dePolo*, 1989]. Coseismic disturbances associated with Long Valley activity beginning in 1979 limit the ability of ground geodetic data here to characterize the secular slip rate [*Savage and Lisowski*, 1995]. Perhaps several millimeters per year of slip are accommodated instead to the west, on faults closer to the eastern Sierra range front rather than the White Mountains fault zone.

Our model for slip distribution on major faults comprising the eastern California shear zone north of the Garlock fault includes an important kinematic role for north to northeast striking, west to northwest dipping normal faults such as the Deep Springs fault and faults in Eureka Valley, which accommodate right steps in the shear zone and transfer slip eastward from Owens Valley and Saline Valley to Fish Lake Valley. Right steps in the Death Valley and Panamint Valley fault zones are associated with the Death Valley and Panamint Valley pull apart basins, respectively [*Burchfiel and Stewart*, 1966; *Burchfiel et al.*, 1987]. The origin and kinematic development of Deep Springs Valley, north of and adjacent to Deep Springs fault (Figure 1), and Eureka Valley may be analogous to these better known basins.

Savage et al. [1990] note that the southern and central parts of the shear zone are right stepping with respect to a small circle about the Pacific-North America pole of rotation. Our proposed configuration suggests that the pattern of right steps continues northward. A right step between the Fish Lake Valley fault zone and the Walker Lane fault system to the north [*Stewart*, 1988], also accommodated by northeast striking normal faults, was noted by *Reheis and Noller* [1989] and *Kohler et al.* [1993]. We suggest that the northwest trending Walker Lane belt accommodates significant right-lateral shear based on its connection to the Fish Lake Valley fault zone and thus is the northern continuation of the most active part of the eastern California shear zone. Offset Holocene features [*Hardyman*, 1978] support our contention that this long-lived belt of deformation is still active. Earthquake data are also consistent with this interpretation. The 1932 Cedar Mountain earthquake (M=7.2) occurred within the Walker Lane belt and had a strong right-lateral component on a north-northwest striking fault plane [*Doser*, 1988]. In contrast, the 1915 Pleasant Valley earthquake (M=7.6) occurred 175 km northeast of the Walker Lane and was a normal fault earthquake on a north-northeast striking fault plane [*Doser*, 1988], similar to the 1993 Eureka Valley event (Figure 1). If our interpretation is correct, it suggests that some right-lateral shear also occurs east of Walker Lane, with normal right oblique faults of the central Nevada seismic zone accommodating the implied right step (see also *Pezzopane and Weldon* [1993]).

Evolution of the Eastern California Shear Zone over the Last Few Million Years. The present-day configuration of the shear zone, with significant shear in Owens Valley, can be reconciled with the observation of *Dokka and Travis* [1990] that the southern Death Valley-Furnace Creek fault zone was the principal locus of shear averaged over the last 5-10 million years, if the system is evolving rapidly and the shear zone is in the process of migrating west. This evolutionary model predicts that:

1. While activity still persists on the Death Valley-Furnace Creek fault zone, it has slowed in the last few million years as slip is increasingly taken up to the west, particularly on the Owens Valley fault zone.

2. North to northeast striking normal faults, accommodating right steps in the shear zone, should young to the northwest.

North to northeast striking normal faults between Owens Valley and the Furnace Creek-Death Valley fault zone include, from south to north, the Towne Pass and Emigrant faults, faults on the west side of the Cottonwood Mountains [*Reheis*, 1990], a group of faults in the Saline Range that connect Saline Valley with Eureka Valley, and the Deep Springs fault (Figure 1). We speculate that all of these faults have, at various times, transferred right-lateral slip from the Panamint Valley-Hunter Mountain fault or Owens Valley fault zone to the Death Valley-Furnace Creek or Fish Lake Valley fault zones, in a manner similar to the "displacement transfer" mechanism of *Oldow et al.* [1994]. Seismicity, geomorphic evidence for young slip, and preservation of surface fault traces increase northward from the Towne Pass area to Deep Springs Valley, consistent with our suggestion that as right-lateral shear migrated progressively west, right steps in the shear zone migrated progressively north. The Deep Springs fault would be very young in this model, consistent with available age constraints. *Reheis* [1993] points out that stream channels on present-day divides between Deep Springs and Eureka Valley (Figure 1), abandoned due to activity on the Deep Springs fault and consequent changes in topography, contain stream gravels overlain by reworked Bishop ash. This suggests that activity on the Deep Springs fault initiated or increased sharply sometime after 760,000 years ago, the age of the ash unit [*Izett and Obradovich*, 1994].

Dokka and Travis [1990] suggest that the shear zone in the south-central Mojave jumped west between 1.5 and 0.7 Ma, based on the initiation age of northwest striking faults in the San Bernardino Mountains [*Meisling and Weldon*, 1989]. *Hodges et al.* [1989] describe progressive westward migration of faulting and sedimentary deposition within the Emigrant, Towne Pass, and Panamint Valley fault systems, with movement of the earliest (Emigrant) fault bracketed between 6.1 and 3.6 Ma and the Towne Pass and Panamint Valley faults becoming active sometime after 3.6 Ma (Figure 4).

Finally, our model for the evolution of the shear zone is consistent in a qualitative way with large (40-100 km) right-lateral offset for the Death Valley-Furnace Creek fault zone [*Stewart*, 1967; McKee, 1968; *Saleeby et al.*, 1986; *Reheis*, 1993] compared with smaller (2-20 km) right-lateral offset suggested for the Owens Valley fault zone [*Stewart*, 1988; *Beanland and Clark*, 1995]. While Owens Valley may be the principal locus of right-lateral shear at present, it has not been active for nearly as long as

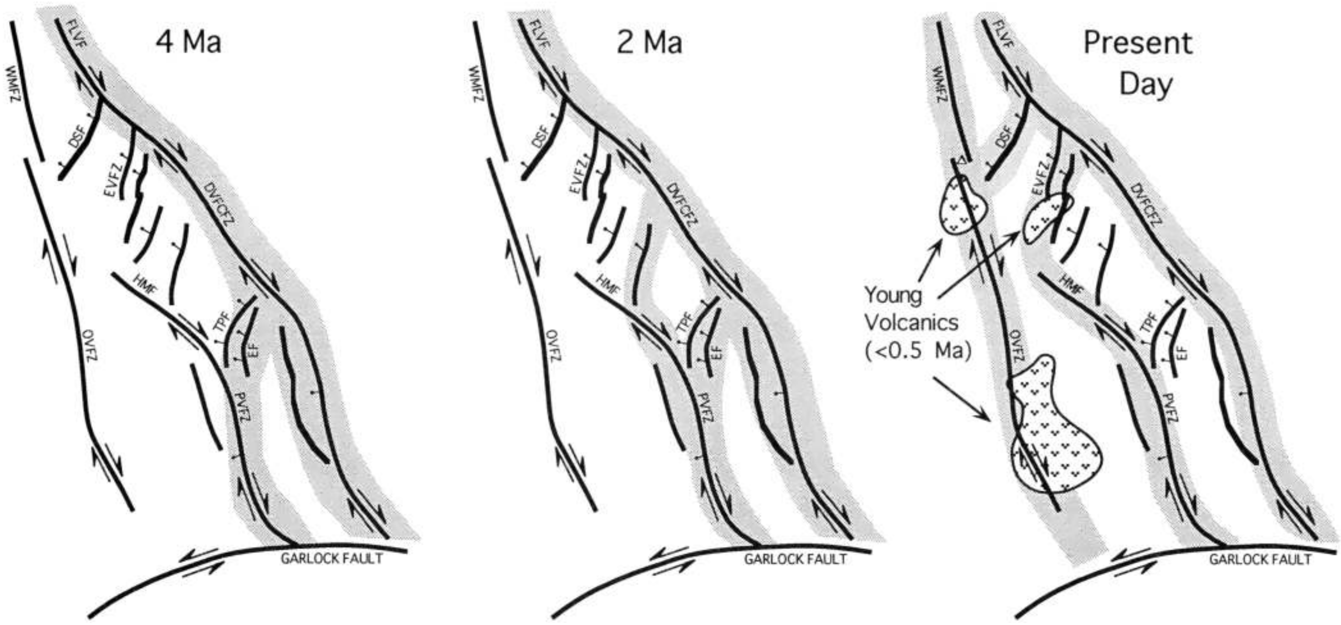

Figure 4. Cartoon summarizing possible evolution of the eastern California shear zone over the last few million years consistent with available data. Shading indicates most active faults at indicated time. Subsidiary slip undoubtedly occurs on numerous minor faults not shown. DSF is Deep Springs fault, DVFCFZ is Death Valley-Furnace Creek fault zone, EF is Emigrant fault, EVFZ is Eureka Valley fault zone, FLVF is Fish Lake Valley fault, HMF is Hunter Mountain fault, PVFZ is Panamint Valley fault zone, OVFZ is Owens Valley fault zone, TPF is Towne Pass fault, and WMFZ is White Mountain fault zone. On diagram for present-day configuration, we also indicate regions of extensive young volcanism (age less than 500,000 years) from *Jennings and Saucedo* [1994].

the Death Valley-Furnace Creek system and thus has not accumulated as much offset.

Why the shear zone should migrate rapidly west is unclear, but young igneous activity in Owens Valley (Figure 4) may be relevant. Perhaps upper crustal faults migrate such that slip is accommodated in the hottest, weakest crust. Another possibility discussed in the next section is that the migration is related to changes in overall plate motion.

Significance of Normal Faulting on the Sierra Nevada Range Front. Does the observation that OVRO lies west of the eastern California shear zone imply that OVRO lies on the stable Sierra Nevada block? We think not, primarily because active normal faults along the Sierra Nevada range front lie west of OVRO (Figure 1). OVRO also lies east of the Owens Valley fault, which experiences a minor dip-slip component. But what are the magnitudes of these effects? Can we correct the velocity of OVRO to reflect this dip-slip deformation? And what is the relation of this normal faulting to the eastern California shear zone?

A useful model for oblique extension in the western boundary zone is one in which deformation is largely partitioned into a strike-slip component, accommodated on faults such as the Owens Valley or Death Valley-Furnace Creek fault zones, and an extensional component, accommodated on north-northwest striking normal faults that mainly lie west of the strike-slip faults, such as the eastern Sierra Nevada range front (Figure 1). Due to its location at the step over between the Owens Valley fault zone to the southwest and the White Mountains fault zone to the northeast, east of any range front faulting but west of most strike-slip faulting, OVRO's velocity with respect to stable North America mainly reflects the strike-slip component of western boundary zone deformation but misses the extensional component (Figure 1). Any extension east of OVRO is already reflected in OVRO's velocity due to the reference frame we have chosen, except perhaps for a minor component associated with elastic strain accumulation on the White-Inyo Mountains frontal fault (Figure 1). *Savage and Lisowski* [1995] measured 1.0±0.3 mm/yr extension normal to the axis of Owens Valley across the ~25 km width of the Owens Valley trilateration network (Figure 1) and suggested that this mainly reflected extension on the Owens Valley fault and the eastern Sierra Nevada range front fault, both west of OVRO. This is consistent with the OVRO-Ely space geodetic data which preclude significant east-west extension across this baseline (Figure 2).

Because of elastic strain accumulation and the relatively narrow aperture of the Owens Valley trilateration network, it is difficult to determine the far-field extension rate from trilateration data alone. A model jointly fitting trilateration and leveling data and assuming dip-slip motion is divided between the Owens Valley fault and the eastern Sierra range front fault suggests a total of 3.6 mm/yr of normal slip west of OVRO, equivalent to about 1.2 mm/yr of far-field horizontal extension [*Savage and Lisowski*, 1995].

Geological estimates for late Quaternary extension are also available for the range front faults and the Owens Valley fault (Figure 1). *Gillespie* [1991] estimates that in the past as much as half of the total subsidence of Owens Valley may have occurred on the Owens Valley fault. Since OVRO is located near a transition in range front behavior, with the range front stepping west at the latitude of OVRO, and is also within the step over between the Owens Valley and White Mountains fault zones which partition normal and right-lateral slip quite differently, we separate our discussion accordingly. South of OVRO, *Martel* [1989] investigated one strand of the Owens Valley fault zone that had experienced mainly vertical motion and found the vertical rate to be 0.24±.02 mm/yr averaged over late Quaternary time. Assuming a 60° dipping fault, this is equivalent to 0.14±0.02 mm/yr of horizontal extension. The Independence fault southeast of OVRO is the range front fault. *Gillespie* [1982] suggested that it accommodates no more than 0.1 mm/yr extension at present. Thus south of OVRO, geological evidence suggests no more than 0.24 mm/yr extension summed across the Owens Valley and Independence faults; we take the value to be 0.2±0.1 mm/yr. The average of the geological and geodetic rate estimates for extension across the Owens Valley and eastern Sierra range front faults south of OVRO is 0.7 mm/yr.

Northwest of OVRO, the range front consists of en echelon, left stepping normal faults, including the Round Valley, Hilton Creek, and Mono Lake faults (Figure 1). *Clark and Gillespie* [1993] measured 2.3±1.3 mm/yr slip at McGee Creek on the Hilton Creek fault averaged over the last ~100,000 years. Assuming a 60° dip and that extension occurs perpendicular to the local strike of the normal faults (N20°W±10°) gives 1.2±0.7 mm/yr of horizontal extension oriented W20°S±10°. Extension across a single fault segment underestimates total extension across this part of the range front because of overlapping fault segments (Figure 1) and active normal faults just east of the Hilton Creek fault in the volcanic tableland [*Pinter*, 1995]. We have not included these in our estimates.

Since OVRO lies near the transition in range front behavior, we take 1.0±0.7 mm/yr in the direction W20°S±10° as our estimate of extension west of OVRO, intermediate between the geologic value northwest of OVRO and the mean of geodetic and geologic values southwest of OVRO. The sum of this vector and OVRO's velocity corrected for elastic strain accumulation on the eastern California shear zone (obtained by adding a vector 1.9 mm/yr oriented N9°W, the difference between the observed and calculated OVRO-Ely velocity; Figure 3) provides a good estimate of present-day motion of the Sierra Nevada block with respect to stable North America in the vicinity of OVRO. This vector is 12.1±1.2 mm/yr oriented N38°W±5° (Table 2). In computing this value we have ignored the effect of strain accumulation on the range front dip-slip faults, since the fault geometry is poorly known and the effect is very small.

Our rate estimate is equivalent within one standard error to the geological (primarily Holocene) estimate of *Minster and Jordan* [1987] for Basin and Range deformation (Model "A," Table 2). The corresponding azimuth estimates differ at the level of one standard error but are equivalent at two standard errors (Table 2). This is not to say that Basin and Range deformation is not evolving with time. For example, *Wernicke et al.* [1988] discuss a reduction in extension rate and a change in orientation over the last 10-15 million years. Rather, we cannot resolve the possibly subtle changes that may have occurred over the last 1-2 million years or less because of limitations in available data. For example, our discussion of the eastern California shear zone suggests that certain parts of the plate boundary zone actually evolve quite rapidly, with the main locus of right-lateral shear accommodated on more northerly faults compared to the mean trend several million years ago. Unfortunately, it is difficult say whether this evolving fault mosaic takes place in the context of more or less uniform far-field motion or may in fact be a response to changing far-field conditions. Below, we discuss one

Table 2. Estimates of Integrated Basin and Range Deformation Near OVRO

Source	Rate,* mm/yr	Azimuth,* degrees
Minster and Jordan [1987]† (Model A, Geological Data)	9.2±2.6	N64W±9
Argus and Gordon [1991] (VLBI to 1989)	11±1	N28W±3
This Study§ (VLBI/SLR to 1991)	12.1±1.2	N38W±5

* Uncertainties are one standard error

† Recalculated to a point on the eastern Sierra Nevada range front west of OVRO

§ OVRO data corrected for elastic strain accumulation and Sierra Nevada range front faulting.

possible scenario relating the evolving geometry of the eastern California shear zone to changing far-field plate motion.

Our revised estimate for Sierra Nevada block motion has implications for convergence normal to the San Andreas fault in California. The vector describing Pacific-North America motion can be compared to the vector sum of Basin and Range deformation and motion on the San Andreas fault. The resulting "discrepancy vector" [*Minster and Jordan*, 1984, 1987] can be resolved into components parallel and perpendicular respectively to the San Andreas fault. Using data then available and assuming that OVRO lies on the stable Sierra Nevada block, *Argus and Gordon* [1991] used their predicted value for motion of the Sierra Nevada block and the NUVEL-1 plate motion model [*DeMets et al.*, 1990] to predict convergence normal to the San Andreas fault in central California at a rate of 2±2 mm/yr. Our prediction of more westerly motion for the central Sierra Nevada block implies a higher rate of convergence in central California, but without an accurate Sierra Nevada-Pacific or Sierra Nevada-North America pole we can only make a crude estimate. Recent geodetic and seismic data seem to require fault-normal convergence in central California at rates of ~3-6 mm/yr [e.g., *Sauber et al.*, 1989; *Feigl et al.*, 1993, *Wakabayashi and Smith*, 1994] consistent with this suggestion. Lisowski et al. [1991] found no convergence within errors (<2mm/yr), but most of their trilateration networks are within about 30 km of the San Andreas fault, and geologic and seismic data suggest that convergence is often accommodated at larger distances. GPS data from a network northeast of San Francisco Bay also show no fault-normal convergence within errors (<2 mm/yr) [*Williams et al.*, 1994], but most of the stations are located west of the Coast Range-Central Valley Thrust, which *Wakabayashi and Smith* [1994] suggest is the locus of convergent deformation in the region.

The convergence rate normal to the San Andreas fault is sensitive to the mean azimuth of Basin and Range deformation. Over geologic time, Basin and Range deformation may evolve to minimize convergence in California, i.e., minimizing the fault-normal component of the San Andreas discrepancy and perhaps minimizing the work done in plate boundary zone deformation [e.g., *Lachenbruch and Thompson*, 1972], since rocks are weaker in shear than in compression. The change in absolute motion of the Pacific plate between 3.4 and 3.9 Ma [*Harbert and Cox*, 1989], which increased convergence in California, may be significant here. Relative plate motion has been essentially constant since then [e.g., *Argus and Gordon* 1990, *DeMets et al.*, 1990, *Dixon et al.* 1991; *Feigl et al.*, 1993] as has the orientation of the San Andreas fault in California [e.g., *Powell*, 1993]. Thus any subsequent kinematic changes in the plate boundary system in response to the change in Pacific plate motion likely involve the Basin and Range component. The western boundary of the Basin and Range province may be best able to accommodate changes since it is hotter and weaker compared to adjacent regions [*Biasi and Humphreys*, 1992]; (see Figure 4). The rapidly changing geometry of the eastern California shear zone over the last few million years, from exclusive exploitation of the northwest striking Death Valley-Furnace Creek fault zone to the present configuration that includes a major component on the north-northwest striking Owens Valley fault zone (Figures 1, 2, and 4), could make average Sierra Nevada block motion more northerly and reduce overall fault-normal convergence across the plate boundary. The beginning of the westward migration of the southern part of the shear zone (and thus the change to a more northerly trend) dates from the first movement on the Emigrant fault (between 6.1 and 3.6 Ma) and Towne Pass and Panamint Valley fault systems (both after 3.6 Ma) [*Hodges et al.*, 1989], consistent with the timing of Pacific plate motion change (3.4-3.9 Ma; [*Harbert and Cox* 1989]).

Conclusions

1. Combined SLR and VLBI data indicate that Ely, Nevada, is moving west with respect to stable North America at 4.9±1.3 mm/yr, while Owens Valley Radio Observatory (OVRO) in eastern California just east of the Sierra Nevada block is moving northwest at 10.1±0.5 mm/yr. OVRO's motion with respect to Ely is north-northwest at 8.8±1.3 mm/yr. Northwest motion of the Sierra Nevada block relative to stable North America consists of two main components, east-west extension in the eastern boundary zone of the Basin and Range province and right-lateral shear on north-northwest striking faults in the western boundary zone.

2. The space geodetic data for Ely suggest that east-west extension in the eastern Basin and Range is significantly faster than previous estimates based on paleoseismic data for the Wasatch fault zone or rates based on summing the seismic moments of earthquakes across the region. This suggests that there are other active faults accommodating significant extension, that current seismic slip rates on the Wasatch fault are anomalously low compared to longer-term averages, or that some deformation occurs aseismically. There is approximate agreement between our space geodetic data and ground geodetic data combined with an elastic strain model, consistent with locking and elastic strain accumulation on the Wasatch fault zone and nearby faults and strain concentration in the eastern boundary zone.

3. Most Basin and Range deformation west of Ely is accommodated within a relatively narrow (~50-150 km wide) western boundary zone. Most deformation associated with the eastern California shear zone lies east of OVRO, whose rate of motion with respect to Ely corrected for elastic strain accumulation is 10.7±1.6 mm/yr at N9°W±5°. Slow (~1 mm/yr) west-southwest extension across eastern Sierra Nevada range front faults and the Owens Valley fault zone occurs west of OVRO. We propose a kinematic model for the present configuration of the shear zone including a slip rate budget for the Owens Valley, White Mountains, Hunter Mountain-Panamint Valley, Death Valley-Furnace Creek, and Fish Lake Valley fault zones. One prediction of our model is relatively fast (6.2±2.3mm/yr) slip on the Fish Lake Valley fault zone. North to northeast striking normal faults such as the Deep Springs fault and faults in Eureka Valley accommodate

right steps in the north-northwest striking strike-slip faults and lead to development of pull-apart basins.

4. Motion of the Sierra Nevada block with respect to stable North America (a measure of integrated Basin and Range deformation) in the vicinity of OVRO occurs at a rate of 12.1±1.2 mm/yr oriented N38°W±5°, in agreement with previous geological estimates at the level of two standard errors.

5. Over the last few million years, the eastern California shear zone has evolved, with significant right-lateral shear migrating west from the southern part of the northwest striking Death Valley-Furnace Creek fault zone to the north-northwest striking Owens Valley fault zone. Activity on north to northeast striking normal faults has correspondingly migrated northwest to maintain connection with the northern Death Valley-Furnace Creek and Fish Lake Valley fault zones. These changes in geometry tend to make Sierra Nevada block motion more northerly, minimizing the rate of convergence normal to the San Andreas fault, possibly in response to a change in overall plate motion between 3.4 and 3.9 Ma.

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T.H. Dixon, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami FL 33149. (e-mail: tim@corsica.rsmas.miami.edu)

J. Lee, Department of Geology, Central Washington University, Ellensburg, WA 98926.

M.C. Reheis, U.S. Geological Survey, Mail Stop 913, Federal Center Box 25046, Lakewood, CO 80225.

S. Robaudo, Ecology and Environment, 1415E. Sunrise Blvd., Suite 800, Ft. Lauderdale, FL 33304.

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