

Evidence for an active shear zone in southern Nevada linking the Wasatch fault to the Eastern California shear zone

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ABSTRACT

Previous studies have shown that ~5% of the Pacific–North America relative plate motion is accommodated in the eastern part of the Great Basin (western United States). Near the Wasatch fault zone and other nearby faults, deformation is currently concentrated within a narrow zone of extension coincident with the eastern margin of the northern Basin and Range. Farther south, the pattern of active deformation implied by faulting and seismicity is more enigmatic. To assess how present-day strain is accommodated farther south and how this relates to the regional kinematics, we analyze data from continuous global positioning system (GPS) stations and model the strain rate tensor field using the horizontal GPS velocities and earthquake focal mechanisms. The results indicate an ~100-km-wide zone of ~3.3 mm/yr extension at 40.5°N that broadens southward from the Wasatch fault zone to a width of >400 km at 36°N. This broadening involves at least one zone of localized extension in northwestern Arizona that encroaches into the southwestern plateau, and an east-northeast–trending sinistral shear zone (the Pahrnagat shear zone) through southern Nevada. This shear zone may accommodate as much as 1.8 mm/yr, and is a key feature that enables westward transfer of extension, thereby providing a kinematic connection between the Wasatch fault zone and the Eastern California shear zone.

INTRODUCTION

The northern Basin and Range province and the Colorado Plateau are prominent, but very distinct, tectonic domains in the western United States. As the Pacific–North America plate boundary evolved, the Basin and Range became the locus of significant Cenozoic extension, while the adjacent Colorado Plateau remained largely intact (e.g., McQuarrie and Wernicke, 2005). Within uncertainty, the central part of the northern Basin and Range province (here referred to as the central Great Basin after Bennett et al., 2003) is geodetically rigid (Bennett et al., 2003; Hammond and Thatcher, 2004). Moreover, global positioning system (GPS) measurements have shown ~2–3 mm/yr of extension concentrated across the Wasatch and other nearby faults (here referred to as the Wasatch fault zone), which separate the northern Basin and Range from the northern Colorado Plateau (e.g., Chang et al., 2006; Hammond and Thatcher, 2004). To date, geodetic data have not revealed any significant extension across the southern Basin and Range (here referred to as the Basin and Range south of the Colorado Plateau; Bennett et al., 1999). Kinematic consistency suggests that, if the southern Basin and Range is currently not extending, the relative motion between the northern Basin and Range and Colorado Plateau needs to somehow transfer to the Eastern California shear zone between 35° and 39°N.

The only known major Quaternary faults south of the Wasatch fault zone are those within the Hurricane–Toroweap–Sevier fault system (Fig. 1A), within the Colorado Plateau–Basin and Range transition zone. The fault zone comprises a series of steep north-south–trending normal faults, the combined Quaternary slip rate of which is <0.4 mm/yr (e.g., Amoroso et al., 2004; Fenton et al., 2001). This rate is about one-fourth the post-6 ka rate across the Wasatch fault zone (Friedrich et al., 2003). The Wasatch fault slip rate has, however, changed considerably during the Cenozoic and the rate over the past 130–250 k.y. is ~0.3 mm/yr (Friedrich et al., 2003).

In this study, our aim is to elucidate how present-day localized extension is transferred southward and westward from the Wasatch Fault zone by (1) analyzing data from continuous GPS stations, and (2) modeling the present-day strain rate tensor field based on those GPS velocities and additional constraints from earthquake focal mechanisms. Considering the limited number of high-quality, long-running geodetic monuments, significant new insight can only be gained through integration of the complementary geodetic and moment tensor data sets. Our results provide new insight into the question as to whether strain is being accommodated along narrow zones separating rigid crustal blocks, such as farther to the north, or in a more diffuse manner, as it has over most of the history of the Basin and Range.

SEISMICITY AND EARTHQUAKE FOCAL MECHANISMS

The Intermountain seismic belt (e.g., Smith and Sbar, 1974) follows the Wasatch Front in Utah until it conspicuously turns westward at ~38°N as the southern Nevada transverse zone (Slemmons et al., 1965) (Fig. 1A). The roughly SSW-trending seismic zone in southern Nevada is puzzling, because it does not follow the dominant strike of faulting directly to the north or south. The largest recorded event in this zone was the 1966 $M = 6$ Caliente earthquake, which yielded an almost pure strike-slip focal mechanism, roughly similar to those of many other subsequent smaller events in southern Nevada (Fig. 1B). Until our study, the earthquake mechanisms were interpreted as right-lateral slip along the north-south nodal planes (Rogers et al., 1987).

A small number of events form a distinct seismic zone trending south-southeast from southwest Utah into northwest Arizona (between 113°W and 112°W) (Fig. 1B), east of the Hurricane–Toroweap–Sevier fault system. This seismic zone has been referred to as the Northern Arizona seismic belt (Brumbaugh, 1987), within which consistent normal faulting earthquakes (with EW- to NE-SW-oriented slip vectors) are observed (e.g., Brumbaugh, 2008; Kruger-Knuepfer et al., 1985). One of the largest recent events south of the Intermountain seismic belt, but outside the Northern Arizona seismic belt, was the 1992 $M_w = 5.3$ Saint George normal faulting event. This event appears to have occurred directly west of the Hurricane fault.

HORIZONTAL GPS VELOCITIES

We use data from regional continuous GPS stations that are part of the BARGEN, SCIGN, and EBRY networks, as well as from EarthScope's Plate Boundary Observatory. All data collected since 2002 are analyzed, and velocities relative to stable North America are presented for the 105 stations with >2.5 yr of data (velocities for 65 of these stations are presented here for the first time). Processing details and velocities are summarized in the GSA Data Repository.¹ Uncertainties in the velocities of the long-running stations are typically 0.1–0.2 mm/yr and can be as much as 0.6 mm/yr for stations with time series spanning only 2.5 yr. In the data collected since 2002 we find no systematic temporal changes in the GPS velocities that are similar to those reported by Davis et al. (2006)

¹GSA Data Repository item 2010127, earthquake focal mechanisms, GPS data analysis, GPS velocities, and strain rate modeling, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

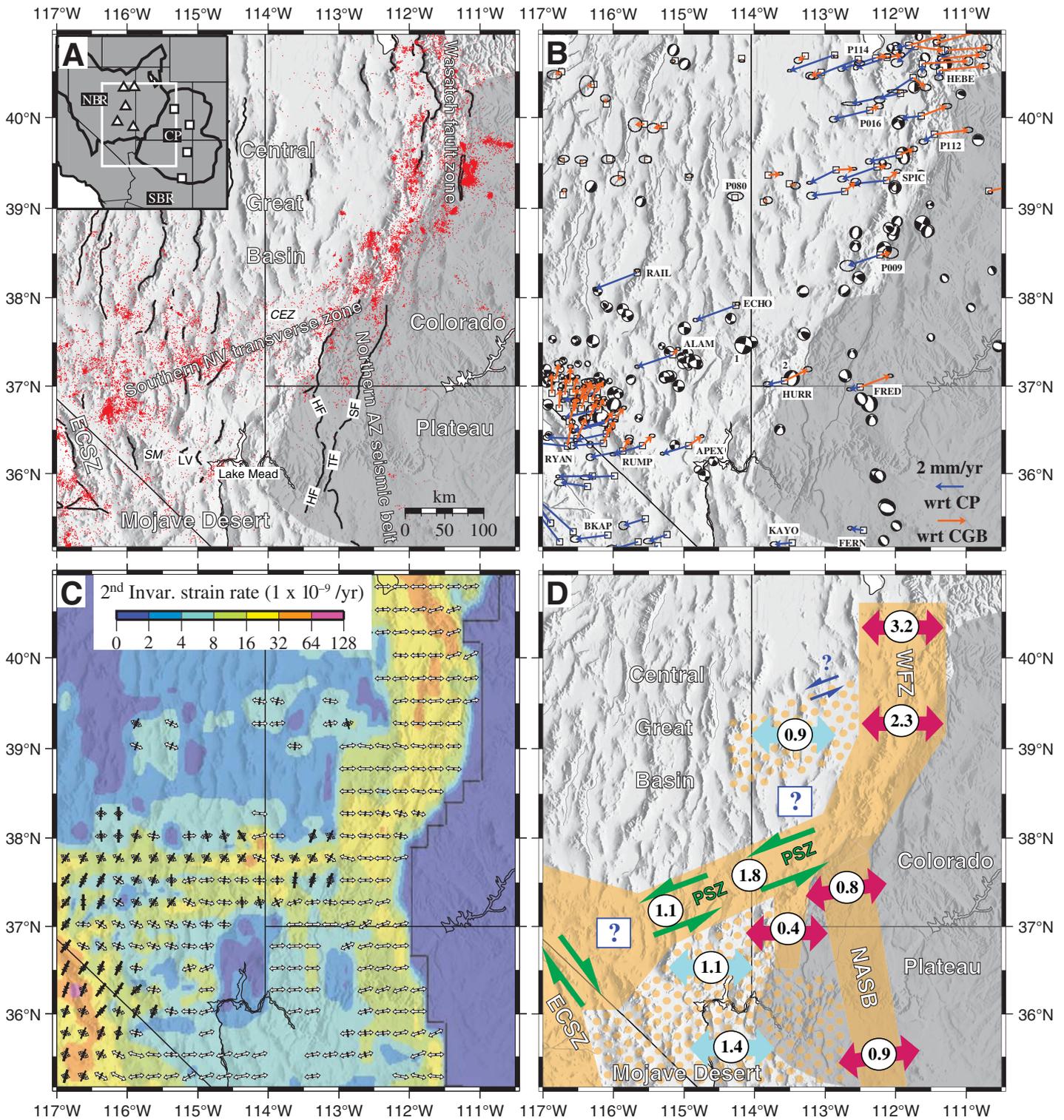


Figure 1. A: Red dots are epicenters for all events between 1964–2003 in Advanced National Seismic System catalog (<http://www.ncedc.org/cnss/>). Dark lines are faults from U.S. Geological Survey Fault and Fold Database (<http://earthquake.usgs.gov/hazards/qfaults/>) with known Quaternary slip rates. CEZ—Caliente-Enterprise zone; ECSZ—Eastern California shear zone; HF—Hurricane fault; LV—Las Vegas; SF—Sevier fault; SM—Spring Mountains; TF—Toroweap fault. Inset shows location of study area with outlines of Colorado Plateau (CP) and northern Basin and Range (NBR). SBR—southern Basin and Range. Triangles and squares are locations of global positioning system (GPS) stations used to determine central Great Basin (CGB) and CP reference frames, respectively. B: Focal mechanisms (scaled with magnitude) are for single events with $M > 2$ (see the Data Repository [see footnote 1]). 1—1966 $M = 6$ Caliente earthquake; 2—1992 $M_w = 5.3$ Saint George earthquake. GPS velocities relative to CP and CGB are in blue and orange, respectively. Error ellipses are 1σ uncertainty. Some velocities and most station names are excluded for clarity (full velocity fields are shown in Fig. DR1). C: Contours of second invariant of model strain rate with superimposed normalized principal axes for all areas with strain rate $> 5 \times 10^{-9}$ /yr. D: Interpretation of present-day deformation. Deformation is concentrated in solid orange areas, and more diffuse in orange dotted areas. Red versus light blue arrows indicate localized versus distributed extension, while green and dark blue arrows indicate shear. Question marks indicate areas where details of kinematics are unknown (values in mm/yr). PSZ—Pahrnagat shear zone; WFTZ—Wasatch fault zone; NASB—Northern Arizona seismic belt.

for continuous GPS stations in the northern Basin and Range. However, an absence of such variations within the past decade does not necessarily mean that present-day deformation rates are representative of the recent geologic past or more recent periods. Nonetheless, on most major fault systems geodetic rates agree with geologic rates to within uncertainty (e.g., Thatcher, 2009), and so without more detailed geologic data to the contrary, we will make that assumption.

To interpret the GPS velocities in terms of regional tectonics, we present the velocities relative to the central part of the Colorado Plateau, east of our area of interest, as well as to the central Great Basin (Fig. 1A). The GPS velocities indicate that there is 3.2 ± 0.3 mm/yr extension across the Wasatch fault zone at 40.5°N , between 112.5°W (e.g., station P114 in the central Great Basin) and 111.4°W (e.g., station HEBE, on stable Colorado Plateau). This rate appears higher and across a narrower zone than concluded from most previous geodetic studies. At 39.5°N , the extension across the Wasatch fault zone is only 2.3 ± 0.2 mm/yr (SPIC relative to Colorado Plateau), but gradually reaches 3.2 mm/yr through incremental extension across an area spanning southwest Utah (e.g., from P080 to the Wasatch fault zone). This result is consistent with previous findings that GPS, neotectonic, and seismic reflection data support the existence of a broad velocity gradient at this latitude (Niemi et al., 2004). However, this diffuse extensional zone is not expressed by the seismicity.

The two stations located on the southwestern Colorado Plateau (FRED and FERN) (east of the Hurricane-Toroweap-Sevier faults) show significant westward motion of 0.8 ± 0.2 and 0.9 ± 0.2 mm/yr, respectively, relative to the plateau's interior. Westward velocities increase roughly linearly away from the Colorado Plateau, to reach $\sim 2.3 \pm 0.3$ mm/yr at stations such as RUMP (in the Spring Mountains) and BKAP (in the Mojave Desert). There is 1.8 ± 0.4 mm/yr of $\text{N}64^\circ\text{E}$ -directed motion of station HURR with respect to the central Great Basin that needs to be accommodated in the ~ 115 km distance between HURR and ECHO. Station ALAM and APEX move at 0.5 ± 0.4 mm/yr toward $\text{N}41^\circ\text{E}$ and 1.1 ± 0.4 mm/yr toward $\text{N}54^\circ\text{E}$ relative to the central Great Basin.

STRAIN RATE TENSOR MODEL

A simple interpolation of the GPS velocities suggests a gently varying strain rate field, with a dominant east-west extension for most of the area (Fig. DR2; see footnote 1). To optimize the kinematic information in the geodetic and seismic data sets, we model the horizontal strain rate tensor field using the GPS velocities as constraints on deformation rates and directions of the crustal flow field, and we use focal mechanisms as additional constraints on the style of expected strain rate tensor and on the localization of the expected strain rates (e.g., Haines et al., 1998) (Fig. 1C; for details, see the Data Repository). The resulting strain rate model is sensitive to the geodetic and seismic data distribution, but nevertheless satisfies both data sets much better than the homogeneous isotropic model (Fig. DR2).

The strain rate model (Fig. 1C) indicates nearly uniform east-west extension all along the Colorado Plateau's western margin; the highest strain rates are along the Wasatch fault zone ($\sim 50 \times 10^{-9}/\text{yr}$). A zone of relatively high strain rates ($\sim 15 \times 10^{-9}/\text{yr}$) can be traced along the Northern Arizona seismic belt, the extension being directed more westward than implied by the focal mechanisms. A zone of high strain rates ($20\text{--}30 \times 10^{-9}/\text{yr}$) coincides with the southern Nevada transverse zone, which we interpret as accommodating left-lateral shear. We refer to this zone as the Pahranaagat shear zone (e.g., Gomberg, 1991). From the Pahranaagat shear zone toward the Eastern California shear zone, the strain rate field becomes more diffuse and complex in style. Although we find the highest model strain rates for the Eastern California shear zone ($\sim 110 \times 10^{-9}/\text{yr}$), strain rates there do not reflect shear, probably because the station distribution near the edge of our model gives a poor spatial sampling of the regional strain accumulation. Owing to a lack of rapid variation in GPS velocities and a dearth of seismicity in the central Great Basin or between

the Colorado Plateau and Mojave Desert, the modeled velocity gradient is diffuse, with strain rates $< 6 \times 10^{-9}/\text{yr}$.

DISCUSSION

We interpret the active deformation within the Colorado Plateau–Basin and Range transition to broaden from the Wasatch in the north to the Mojave Desert in the south (Fig. 1D). The key features of this broadening are (1) localization of deformation along at least one discrete extensional zones in the southwestern Colorado Plateau, (2) diffuse east-west extension across a few hundred kilometers between the Colorado Plateau and central Great Basin in the north ($\sim 39.5^\circ\text{N}$) and Mojave Desert in the south ($\sim 35.5^\circ\text{N}$), and (3) the E-NE–trending sinistral Pahranaagat shear zone. Some of these features were suggested by others based on the analysis of seismicity and faulting (e.g., Brumbaugh, 1987), but here we attribute displacement rates to them within a consistent regional context.

In our model the eastern limit of extension into the southwestern Colorado Plateau is east of the Hurricane-Toroweap-Sevier fault system, coincident with the Northern Arizona seismic belt. However, we have no geodetic data to exclude the possibility that extension is distributed farther east of the Northern Arizona seismic belt, nor are there any geologic data to confirm the strain localization. If present-day extension is indeed localized along the Northern Arizona seismic belt, it may reflect the most recent stage of eastward encroachment of extension (Brumbaugh, 1987) that has been corroborated by an eastward migration of magmatism (e.g., Nelson and Tingey, 1997; Wenrich et al., 1995). Given the lack of accompanying faulting, it is possible that the seismic strain localization along the Northern Arizona seismic belt is a transient phenomenon within a broader extending zone.

The Pahranaagat shear zone follows a N-NE–trending gradient in the regional gravity field and topography (Eaton et al., 1978) that separates a region to the south that had 1.5 times more extension than the region to the north (Wernicke et al., 1988) and that may provide a zone of weakness along which to localize deformation. There is independent geological and geophysical evidence for left-lateral motions in the Pahranaagat shear zone. Near 115°W there is a set of northeast-striking sinistral faults (e.g., the Maynard Lake and Kane Spring Wash faults) that have accumulated < 16 km of sinistral offset (Tschanz and Pampeyan, 1970) since perhaps as early as 7.7 Ma (Jayko, 1990). In the Caliente-Enterprise zone significant counterclockwise rotations have produced 40 km of sinistral offset along an east-west belt since 14–18 Ma (e.g., Hudson et al., 1998). There is no evidence that the faulting and rotations are still ongoing, but if they are, the reported values would be consistent with ~ 2 mm/yr of differential motion since inception of the shear zone, consistent with our present-day estimate.

The sinistral Pahranaagat shear zone is kinematically required to accommodate the different strain rates between the distributed zone of extension to its south (i.e., Mojave Desert and Northern Arizona seismic belt) and the much more rigid central Great Basin to its north. The difference in crustal motion north and south of the shear zone diminishes to the west, consistent with the observation of east to west decreasing sinistral motion. The Pahranaagat shear zone thus may act as a transfer zone, similar to how the sinistral Garlock fault originated (Davis and Burchfiel, 1973) and to how other transverse faults (or shear zones) in the Basin and Range may have functioned (e.g., Duebendorfer and Black, 1992). A contemporary example, symmetric to the Pahranaagat shear zone, was recently postulated for the northern margin of the northern Basin and Range, where the E-NE–striking dextral Centennial shear zone separates the actively extending Basin and Range in Idaho to the north from the nondeforming Snake River Plain (i.e., central Great Basin) to the south (Payne et al., 2008).

CONCLUSION

New GPS observations together with earthquake moment tensor data show that deformation is localized across the Wasatch fault zone, but is

distributed over a wider area south of 38°N. GPS velocities suggest that some of the widening of the extension zone may occur between 38°N and 39.5°N, but this is not supported by the contemporary seismicity. The Pahrana-gat shear zone forms a distinct boundary between the central Great Basin and the more diffusely extending area to the south. The only zone of possibly significant localized extension south of 37°N can be found east of the Hurricane-Toroweap-Sevier fault system and may reflect the most recent stage of Basin and Range encroachment into the Colorado Plateau. Our analysis suggests that the Pahrana-gat shear zone plays a key role enabling westward transfer of extension and thereby provides a kinematic connection between the Wasatch fault zone and the Eastern California shear zone.

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