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Distributed Deformation across the Rio Grande Rift, Great Plains, and Colorado Plateau

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ABSTRACT

We use continuous measurements of GPS sites from across the Rio Grande Rift, Great Plains, and Colorado Plateau to estimate present-day surface velocities and strain rates. Velocity gradients from five east-west profiles suggest an average of ~1.2 nanostrains/yr east-west extensional strain rate across these three physiographic provinces. The extensional deformation is not concentrated in a narrow zone centered on the Rio Grande Rift but rather is distributed broadly from the western edge of the Colorado Plateau well into the western Great Plains. This unexpected pattern of broadly distributed deformation at the surface has important implications for our understanding of how low strain-rate deformation within continental interiors is accommodated.

INTRODUCTION

Global positioning system (GPS) monuments installed for the EarthScope Plate Boundary Observatory (PBO) and the Rio Grande Rift GPS experiment (Fig. 1) have greatly enhanced modern geodetic coverage of the physiographic regions of the Rio Grande Rift and the Colorado Plateau. More than 4 yr of continuous measurement at these sites provide a detailed map of the contemporary motion across the southwestern United States, where prior geodetic measurements are sparse and highly uncertain. Argus and Gordon (1996), using very long baseline interferometry (VLBI), found that the velocity of two sites on the Colorado Plateau differed from stable North America with upper bounds of ~4–5 mm/yr. At shorter spatial scales, classical trilateration across the Rio Grande Rift near Socorro, New Mexico, found no significant extension across the rift and gave an upper bound of ~1 mm/yr (Savage et al., 1980). Estimates of extension using geological methods in the Albuquerque Basin are on the order of 0.3 mm/yr (Woodward, 1977), while Golombek et al. (1983) estimated a rate of ~0.14 mm/yr across the Española basin in northern New Mexico for 5 Ma to present. More recently Kreemer et al. (2010) used PBO measurements to show that the western portion of the Colorado Plateau is moving westward ~1 mm/yr relative to stable North America. They did not detect significant extension across most of the Rio Grande Rift, except a possible ~0.5 mm/yr in the southernmost region.

Here we estimate horizontal velocities for 284 continuously measured GPS monuments in a region straddling the Rio Grande rift and bordered by the southern Basin and Range to the south, the Great Plains to the east, and the northern Basin and Range to the west. Using these velocities, we investigate the contemporary kinematic field and calculate deformation rates along east-west velocity profiles across the study area (Fig. 1).

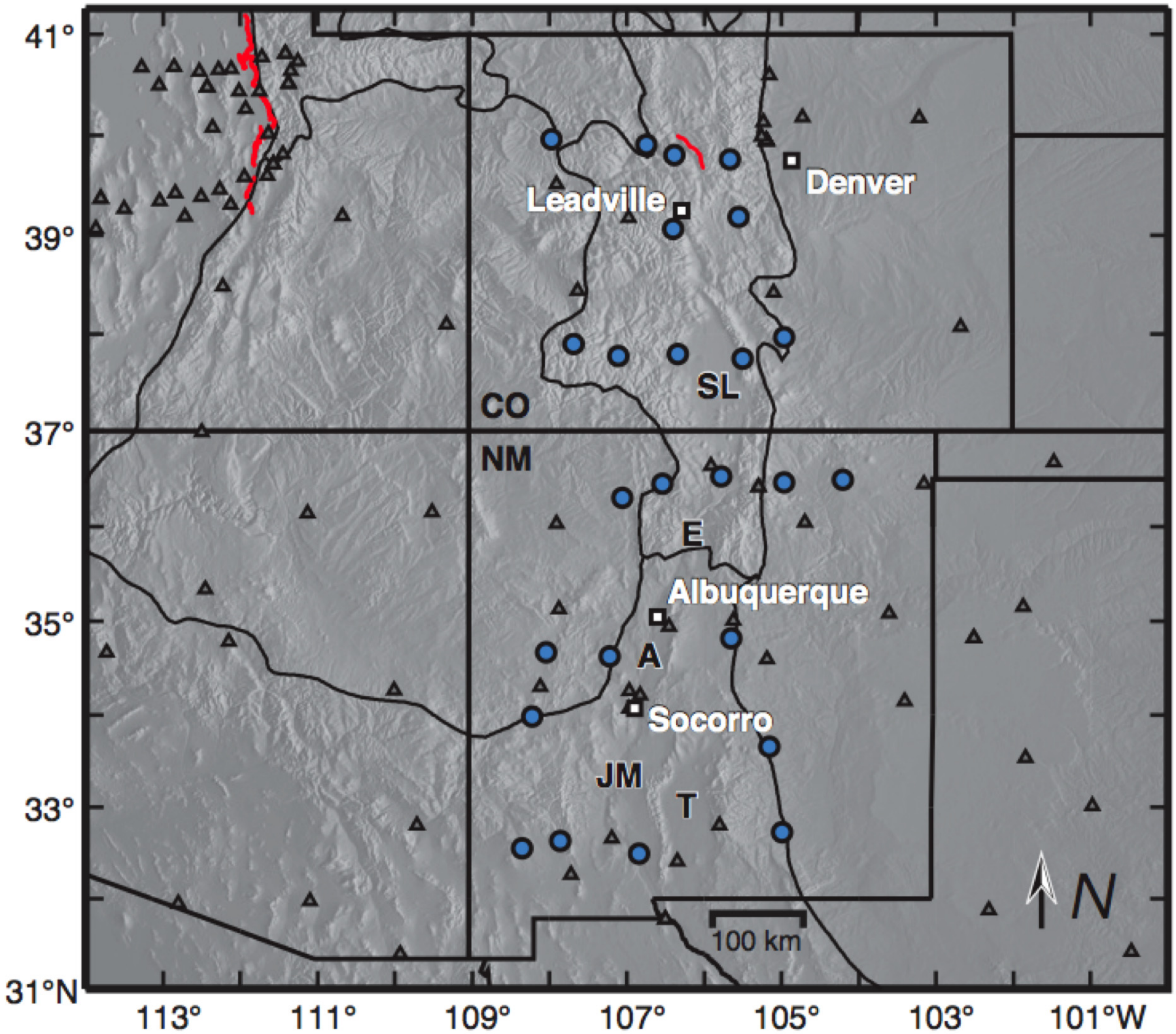

Figure 1. Global positioning system (GPS) monuments in vicinity of the Rio Grande Rift and southern Rocky Mountains. The Rio Grande Rift Earthscope GPS experiment included construction of 25 GPS monuments (blue circles) in Colorado and New Mexico in 2006 and 2007. Regional EarthScope Plate Boundary Observatory and Continuously Operating Reference Station monuments are shown by gray triangles. Black lines denote major physiographic boundaries (Fenneman and Johnson, 1946). Basins referred to in text: SL—San Luis, E—Espanola, A—Albuquerque, JM—Jornado del Muerto, T—Tularosa. Red traces show location of the Wasatch fault zone in north-central Utah and the Williams Fork Mountains fault in north-central Colorado (U.S. Geological Survey and Colorado Geological Survey, 2006).

TECTONIC SETTING

The surface expression of the Rio Grande Rift consists of a series of interconnected, north-south–trending asymmetrical grabens. Clearly defined rift grabens extend from Leadville, Colorado, in the north to Socorro, New Mexico, in the south, and include the San Luis, Espanola, and Albuquerque Basins. The rift's fault-bounded basins are narrower in Colorado and northern New Mexico and widen southward, with widths ranging from ~25 to 50 km (Cordell, 1978). In addition, the rift geometry changes southward from a linear chain of narrow grabens to multiple, adjacent basins (e.g., the Jornada del Muerto and Tularosa Basins) as the rift transitions into the southern Basin and Range province between profiles 4 and 5 (Fig. 2). At depth, the seismic data show anomalously slow upper-mantle seismic velocity in a broad zone around the rift, continuing beyond the geologically mapped boundaries well into the Colorado Plateau and extending north into the southern Rocky Mountains (Lee and Grand, 1996; Dueker et al., 2001; Gao et al., 2004; Burdick et al., 2009). Upper mantle seismic attenuation (Q) maps show narrow zones of low Q correlated with the zone of surficial grabens rather than the region of low seismic velocities (Boyd and Sheehan, 2005). If low effective viscosity in the upper mantle correlates with the seismic velocity picture, then kinematic extension in the Rio Grande Rift may actually be broader than the surficial geologic boundaries of the rift. In contrast, if low effective viscosity in the upper mantle correlates with the attenuation anomaly, then extension is likely to localize in a narrow region correlating with surficial grabens.

Contemporary crustal stress in western Colorado includes a roughly northeast-oriented extensional axis based on inversion of earthquake focal mechanisms (Bott and Wong, 1995). Seismicity within the Rio Grande Rift is dominantly normal faulting, with a minor amount of strike-slip (Keller et al., 1991; Herrmann et al., 2011). A disproportionate fraction of earthquake activity in New Mexico occurs in the middle of the Rio Grande Rift at Socorro, related to the Socorro magma body (e.g., Balch et al., 1997).

GPS RESULTS AND INTERPRETATION

We use data from 25 continuous GPS stations installed as part of the EarthScope Rio Grande Rift GPS experiment, supplemented by data from other GPS monuments in the southwestern United States, resulting in a data set of daily position estimates of 284 GPS monuments for the years 2006 through 2010. We use the GAMIT/GLOBK software (King and Bock, 1999) to obtain daily coordinates for the stations in the Rio Grande Rift GPS Experiment and for an additional 29 sites that are part of the Continuously Operating Reference Station (CORS) network (Snay and Soler, 2008; http://www.ngs.noaa.gov/CORS/). We combine the aforementioned position estimates with GPS coordinate estimates for 230 continuous sites available in the Solution Independent Exchange format (SINEX) from the PBO (http://pbo.unavco.org/data/gps). We constrain the rotation of North America by estimating six Helmert parameters (three translation, three rotation) for each day so that adjustments to a predetermined set of *a priori* values for a chosen group of stations are minimized. The *a priori* values for the stations that we use to constrain the rotation of North America are tabulated in Table DR1 in the GSA Data Repository[1]. We exclude sites located outside 28°N–65°N and 116°W–60°W from our analysis. We estimate velocities and uncertainties from the resulting position time series using the GAMIT/GLOBK software and account for annual and semi-annual sinusoidal terms in each time series. We restrict our analysis by excluding sites with <2.5 yr of data. The velocity estimates are tabulated in Table DR2 and shown in Figure 2.

Horizontal velocities, shown in Figure 2, increase in magnitude from east to west toward the Pacific–North America plate margin in California. Velocity estimates in Idaho, northern Utah, northern Nevada, Wyoming, and Montana show a smooth clockwise rotation. This rotational pattern is consistent with prior results showing large-scale rotation about an axis in eastern Oregon (e.g., McCaffrey et al. 2007). Sites east of the Rio Grande Rift in eastern Colorado, eastern New Mexico, Texas, Oklahoma, Kansas, and Nebraska move very slowly (~<1mm yr^{-1}) with respect to the North America frame.

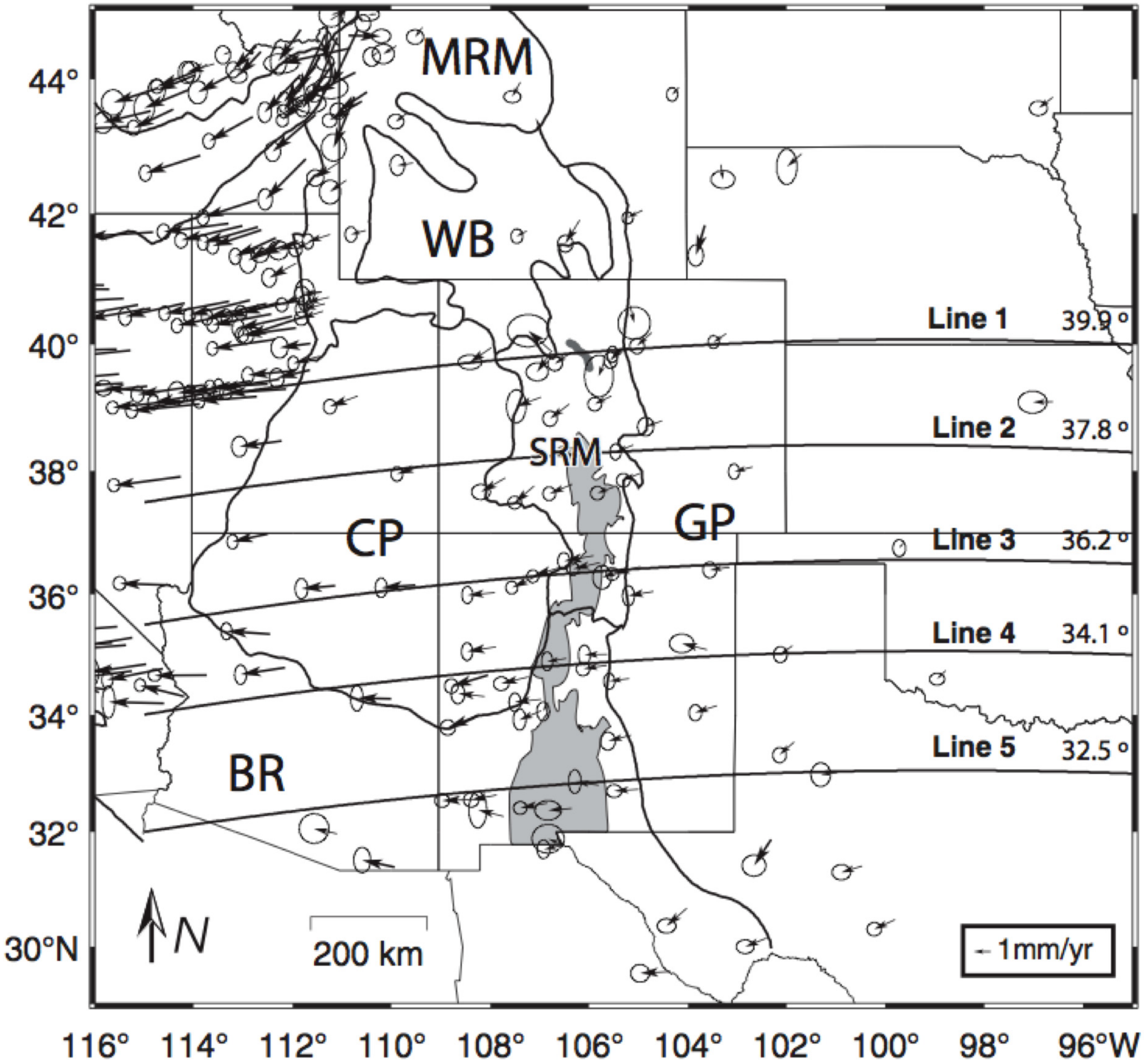

Figure 2. Locations of profile lines as numbered; west end of each profile line is the left side of Figure 3. Arrows indicate the direction and magnitude of GPS velocity estimates. Ellipses are 95% confidence. Thick black lines denote major physiographic boundaries (Fenneman and Johnson, 1946): MRM—middle Rocky Mountains, WB—Wyoming Basin, SRM—southern Rocky Mountains, CP—Colorado Plateau, GP—Great Plains, BR—Basin and Range. Light gray lines indicate state boundaries. Latitude at which each profile passes through 109°W is labeled on the right. Gray shaded region in Colorado and New Mexico indicates the rough extent of Rio Grande Rift basins. Williams Fork Mountains fault in north-central Colorado is indicated with a thick gray trace.

To estimate strain rates, we project the observed GPS velocities onto five profiles (Fig. 2). The five profiles are oriented approximately parallel to the azimuths of the GPS velocities (N87E) along great circles that pass through 109°W at the labeled latitude (Fig. 2). The velocity components parallel to each profile are related to their distance along the profile (Fig. 3). Profiles include sites within ±100 km normal to each line (Fig. 2). We exclude sites with horizontal uncertainties >0.5 mm/yr from this analysis. Using weighted least squares linear regressions of the velocities, we calculate strain rates for several different distance intervals along profile lines 1–5. Thus, for each site along a given profile, we can express the profile-parallel velocity, v_i, as a function of distance along the profile, x_i, as

$$v_i = \dot{\varepsilon} x_i + c \tag{1}$$

where $\dot{\varepsilon}$ is the profile-parallel strain rate. The parameters $\dot{\varepsilon}$ and c can then be determined using a linear model to fit the profile-parallel velocities.

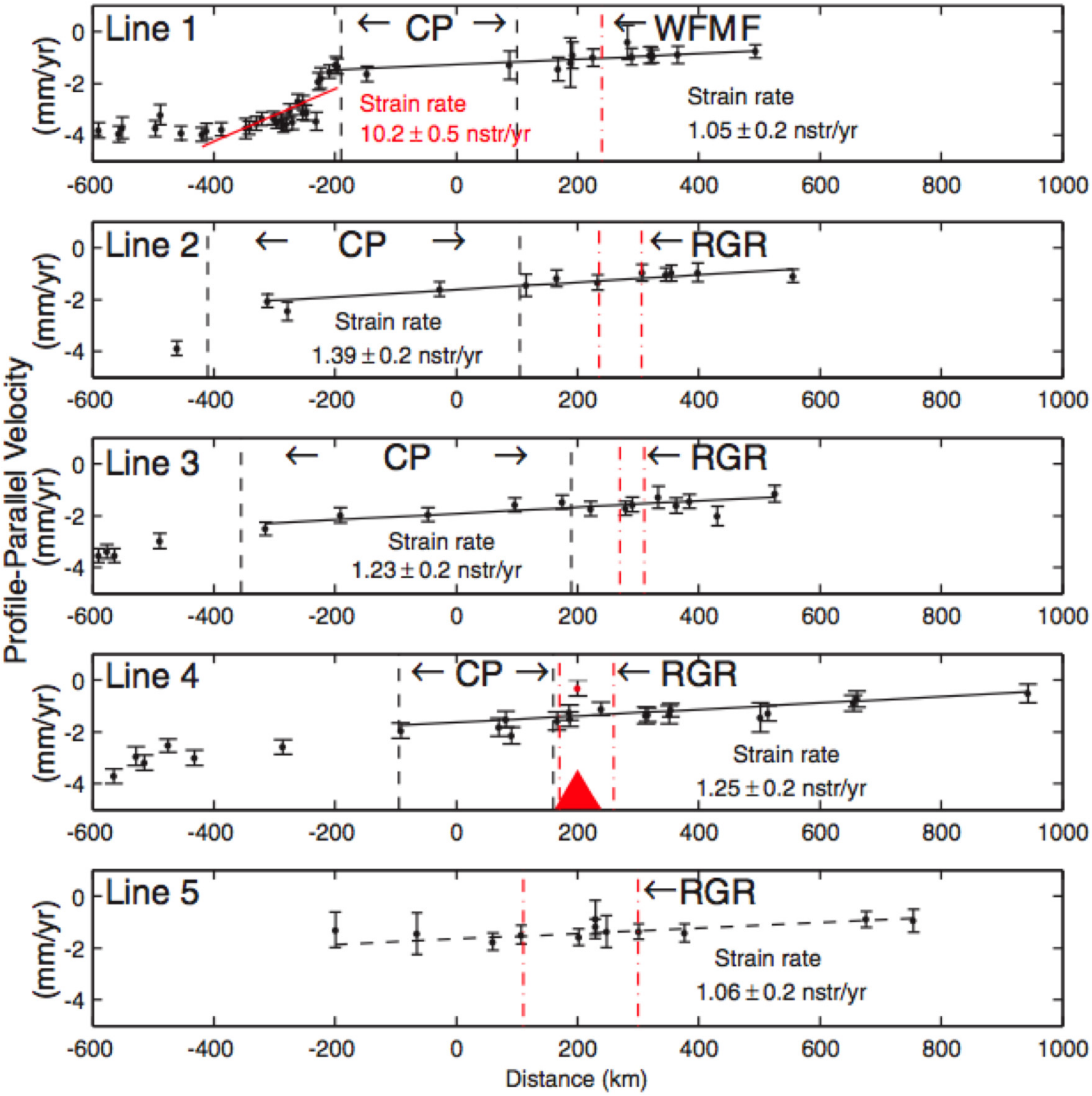

Figure 3. Horizontal GPS velocities projected onto five profiles. Black circles represent horizontal GPS velocity components parallel to the profile line. Error bars are 95% confidence. Approximate boundaries of the Colorado Plateau (CP), and Rio Grande Rift (RGR) are shown with dashed black lines and dashed red lines, respectively. Williams Fork Mountains fault (WFMF) is indicated with a dashed red line in line 1. Horizontal axis is kilometers east from the 109th meridian, which is the western border of Colorado and New Mexico. Red triangle shows approximate location of the Socorro magma body on line 4. The site PDBG (red circle) was installed within the boundaries of the Socorro magma body. The unit (nstr/yr) is equal to one part per billion (10^{-9}) per year.

All of the profile-parallel velocity gradient estimates from lines 1–4 (Fig. 3) indicate significant extension. For the northernmost profile, which transects northern Colorado (line 1), we calculated strain rates of 1.05 ± 0.2 nanostrains/yr (nstr/yr) for 11 velocities from −200 to 500 km relative to the Colorado-Utah border (eastern part of line 1) and 10.2 ± 0.5 nstr/yr for 19 velocities from −420 to −145 km relative to the Colorado-Utah border (western part of line 1). The strain rate of 10.2 ± 0.5 nstr/yr, which encompasses the Wasatch fault zone and part of the eastern Basin and Range in Utah, is consistent with the ~10 nstr/yr east-west extension estimated by Niemi et al. (2004). The positive strain rate estimate of 1.05 ± 0.2 nstr/yr across the northern Colorado Plateau, the Williams Fork Mountains fault, and the western Great Plains is the smallest strain rate that we observe in lines 1–5, but it still indicates that significant extension occurs over the width of the profile. GPS site velocities at the western boundary of profile 1 approach −4 mm/yr, where east is defined as positive. The total velocity difference across the Wasatch fault zone is extensional and has a magnitude of ~2–3 mm/yr. Line 2, which transects southern Colorado, southern Utah, and Kansas, has a strain rate of 1.39 ± 0.2 nstr/yr using 11 velocities from −400 to 600 km. The calculated strain rate across the Colorado Plateau and Rio Grande Rift along profile line 3, which passes through northern Arizona, New Mexico, and Oklahoma, is 1.23 ± 0.2 nstr/yr. The extensional velocity gradient along line 3 deviates from a linear trend and increases at the western margin of the Colorado Plateau. The strain estimate across the Colorado Plateau and the Rio Grande Rift along profile line 4, which passes through Oklahoma, Texas, central New Mexico, and central Arizona, is 1.25 ± 0.2 nstr/yr. The strain estimate for the southernmost profile line 5 is 1.06 ± 0.2 nstr/yr for sites from −200 to 780 km relative to the New Mexico-Arizona border.

DISCUSSION AND CONCLUSION

Our velocity gradient estimates (Fig. 3) show that statistically significant contemporary east-west extension occurred between the Great Plains and the western margin of the Colorado Plateau over a period of ~4 yr. The average strain rate from lines 1–4, which transect the Colorado Plateau and extend into the Great Plains, is ~1.2 nstr/yr. Our strain estimates also show that significant extension occurred across the southern reaches of the Rio Grande Rift and into the southern Basin and Range. Using a linear model to estimate the strain rate from a velocity profile assumes that the deformation along a given profile is distributed evenly (on average, ~0.12 mm/yr of extension across every 100 km along a given profile). Over geological timescales, the locations of faults with Quaternary displacements (U.S. Geological Survey and Colorado Geological Survey, 2006) suggest that east-west extension at the surface during the Quaternary has not been distributed uniformly along the profiles, but rather occurred in discrete zones through brittle deformation in the crust.

Our observation of broadly distributed strain can be interpreted in several ways. If extension occurs as ductile deformation on shear zones at depth during interseismic periods, and fault slip occurs when accumulated stress exceeds the strength of the brittle crust, then we might expect to observe smoothed localized strain at or near the Rio Grande Rift with a length scale of <200 km during interseismic periods. A strain rate of 1.2 nstr/yr across a 1000 km profile implies that a total of ~1.2 mm/yr of extension occurs across a given profile. The average horizontal displacement error for this experiment is ~0.2 mm/yr. It is plausible that the smoothing effect from interseismic strain combined with the uncertainty in our measurements prevents us from resolving localized strain at the surface when the horizontal deformation is distributed into more than one or two areas.

Alternatively, our observation of nearly linear velocity profiles may indicate that contemporary east-west extension in Colorado and New Mexico is not focused in a localized zone of deformation (<200 km in width), but rather is broadly distributed and with uniform strain rates over widths exceeding 600 km. Broad and uniform extension across the Rio Grande Rift, Colorado Plateau, and Great Plains is a surprising result given the geological complexity of this region. To assess whether the data support an interpretation of broadly distributed contemporary strain over a given profile, we created a model of the strain along each profile that can be expressed in terms of three parameters: (1) a width W of a finite zone, centered at the rift, over which strain is occurring; (2) a constant velocity of V_1 east of the finite zone of strain; and (3) a constant velocity of V_2 west of the finite zone of strain. Those three parameters can be generalized into two by constraining V_1 to be equal to the easternmost velocity measurement in each profile and defining ΔV as the velocity V_2. The magnitude of ($\Delta V - V_1$) determines the slope of the velocity versus distance in the finite zone where strain is occurring. We then performed a grid search over those two parameters (W and ΔV) and estimated the misfit to determine the likelihood of strain occurring over varying widths. The results from this analysis rejected localized strain with 95% confidence for widths <100 km in profile line 1 and <200 km in profile lines 3–5. In addition, the optimal model width in terms of misfit was equal to the greatest model width in the search range (600 km) in four of the profiles (lines 2–5) and was >200 km in profile line 1. In contrast, our grid search results for deformation centered at the Wasatch fault zone (fault traces shown in Figure 1) in profile line 1, rather than at the Rio Grande Rift, show with 95% confidence an optimal model width (W) of 80–170 km, which implies strain focusing. A detailed description of the model used in this analysis and figures showing the misfit error norm and 95% confidence contours for each profile are available in the Data Repository.

Interestingly, our observation of distributed east-west extension over the past ~4 yr correlates better with a region of low uppermost-mantle seismic velocity (e.g., Schmandt and Humphreys, 2010) and high crustal quartz abundance (Lowry and Pérez-Gussinyé, 2011). Observation of strain focusing at the Wasatch fault zone in profile line 1 correlates well with an inferred band of high crustal quartz abundance, sandwiched between lower quartz abundances eastward into the Colorado Plateau and further westward into the Basin and Range (Lowry and Pérez-Gussinyé, 2011). The increased seismicity along the Intermountain Seismic Belt (Smith and Sbar, 1974) coincides well with our observations of strain focusing at the Wasatch fault zone in profile line 1. Strain estimates where profile lines 1–5 transect the Rio Grande Rift do not indicate a significant increasing or decreasing trend in the east-west extensional rates from the northern to southern profiles. We have observed episodic features in the data from the GPS site RG13; longer time series will help to resolve those features and reduce the velocity uncertainties in subsequent work.

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[1] GSA Data Repository item 2012014, model description, Table DR1 (*a priori* values used to constrain the rotation of North America), and Table DR2 (velocity estimates from our analysis), is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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