

Strain rates and contemporary deformation in the Snake River Plain and surrounding Basin and Range from GPS and seismicity

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ABSTRACT

We used new horizontal global positioning system (GPS) velocities along with earthquakes, faults, and volcanic features to assess how strain is accommodated in the northern Basin and Range Province. We estimated horizontal velocities for 132 stations within the Snake River Plain and the surrounding Basin and Range from GPS phase data collected from 1994 to 2007. These velocities show regional-scale clockwise rotation suggestive of driving forces beyond those associated with the Yellowstone hotspot. Within the western Centennial tectonic belt, the GPS measurements indicate that the Basin and Range is extending at a rate an order of magnitude greater than the Snake River Plain, which explains its low seismicity. Between these two regions, we discern the “Centennial shear zone,” a NE-trending zone of right-lateral shear with estimated slip rates that increase northeastward from 0.9 ± 0.3 mm/yr in the SW to 1.7 ± 0.2 mm/yr in NE. We interpret the new GPS velocities to indicate: (1) right-lateral shear may be accommodated by strike-slip earthquakes on NE-trending faults in the Centennial shear zone; (2) three Basin and Range faults (Lost River, Lemhi, and Beaverhead) terminate at the Snake River Plain margin; and (3) extension in the Snake River Plain occurs at a much lower rate than the rate of normal faulting in the western Centennial tectonic belt.

Keywords: GPS, strain rates, continental extension, Snake River Plain, Yellowstone hotspot, Basin and Range.

INTRODUCTION

New horizontal global positioning system (GPS) velocities derived from campaign and continuous stations challenge our current understanding of how strain is accommodated in the northern Basin and Range Province. This region includes the Centennial tectonic belt (Stickney and Bartholomew, 1987) and northern Intermountain seismic belt (Smith and Sbar, 1974), which surround the Snake River Plain north of the Great Basin (Fig. 1A). The northern Basin and Range Province deforms under the confluence of crustal extension and hotspot volcanism (Armstrong et al., 1975; Pierce and Morgan, 1992). Investigators have proposed several hypotheses to explain the pronounced aseismic nature of the Snake River Plain surrounded by the seismically active Centennial tectonic belt and northern Intermountain seismic belt (Fig. 1A). Some of these hypotheses assume that strain rates are the same within the Snake River Plain and surrounding Centennial tectonic belt and northern Intermountain seismic belt Basin and Range zones, though this has not been demonstrated. Based on GPS, Puskas et al. (2007) suggested similar strain rates between the Centennial tectonic belt and Snake River Plain, whereas Chadwick et al. (2007) suggested they differed. Here, we present results of new GPS phase data collected during 2006–2007 in the Snake River Plain, Centennial tectonic belt, and northern Intermountain seismic belt and

merged with the Pacific Northwest velocity field of McCaffrey et al. (2007). We resolve significantly different horizontal strain rates between the Snake River Plain and Centennial tectonic belt and offer alternative interpretations that include right-lateral shear along the northwest boundary of the Snake River Plain.

GPS DATA

For this study, we analyzed GPS phase data collected at 132 survey-mode and continuous stations in the region from 1994 to 2007 (Table DR1 in the GSA Data Repository¹). Over this time period, several institutions acquired the GPS data, including the Idaho National Laboratory, Rensselaer Polytechnic Institute, National Geodetic Survey, University of Utah, and Idaho State University. We reoccupied 42 GPS survey-mode stations in 2006 and 2007 within the Snake River Plain, Centennial tectonic belt, and northern Intermountain seismic belt. We analyzed the data using the GAMIT/GLOBK software and the approach described in McCaffrey et al. (2007). The horizontal GPS velocities were referenced to stable North

¹GSA Data Repository item 2008155, GPS velocities and calculations of strain rates and slip rates, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

America. In the interpretation, we excluded horizontal GPS velocities with one-sigma uncertainties greater than 2.5 mm/yr in either component. Additionally, we did not use vertical GPS velocities, nor did we evaluate GPS velocities located northeast of the Snake River Plain (Fig. 1A) associated with recent volcanic deformation of the Yellowstone hotspot.

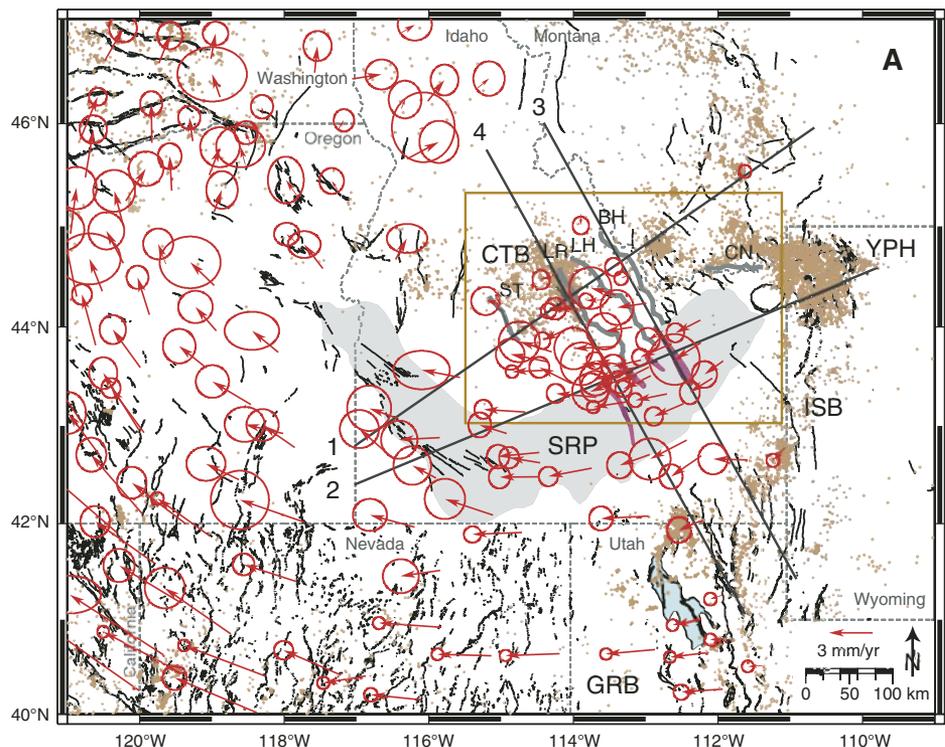
HORIZONTAL GPS VELOCITIES

In the northern Basin and Range Province, horizontal GPS velocities show components of both rotation and strain rates. Clockwise rotation is evident in the velocity gradient perpendicular to the directions of the velocities (Fig. 1A), increasing in magnitude in a radial direction outward from central Idaho across the Snake River Plain and into northern Utah and Nevada. The velocities in the northern Basin and Range Province are part of the regional-scale clockwise rotation observed over the Pacific Northwest. McCaffrey et al. (2007) suggested that the Snake River Plain and eastern Oregon rotate clockwise around nearby poles in central Idaho.

Normal and shear strain rates are evident in the changes of velocity magnitudes parallel to and perpendicular to, respectively, the directions of the horizontal GPS velocities. To estimate strain rates, we projected the velocities onto four profiles (Fig. 1A). Here, we discuss results for areas with the highest concentration of velocities in the eastern Snake River Plain and western Centennial tectonic belt. In the Basin and Range south of the Snake River Plain, we observed changes in magnitudes of the velocities across northern Utah and Nevada, which have been attributed to extension in the Great Basin (e.g., Hammond and Thatcher, 2004).

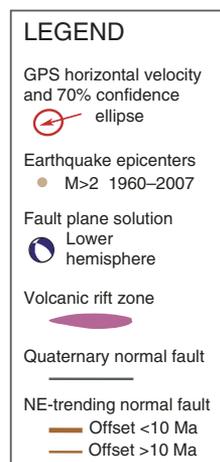
Two profiles oriented parallel to the direction of GPS velocities show extension at different average rates. Within the Centennial tectonic belt, profile 1 shows extension primarily across three Basin and Range faults. Using weighted least squares linear regressions of velocities over two different distance intervals in profile 1 (Fig. 2A), we calculated strain rates of $5.6 \pm 1.3 \times 10^{-9}$ yr⁻¹ for 11 velocities from 140 to 520 km and $12.2 \pm 4.7 \times 10^{-9}$ yr⁻¹ for 7 velocities from 280 to 350 km (Table DR2). The strain rate of $12.2 \pm 4.7 \times 10^{-9}$ yr⁻¹ across three Basin and Range faults is comparable to 10.4×10^{-9} yr⁻¹

Figure 1. Maps show horizontal GPS velocities in North American reference frame, Quaternary faults, distribution of seismicity, and fault-plane solutions. Abbreviations: CTB—Centennial tectonic belt, CSZ—Centennial shear zone, GRB—Great Basin, ISB—Intermountain seismic belt, SRP—Snake River Plain, and YPH—Yellowstone hotspot. Normal faults: CN—Centennial, BH—Beaverhead, LH—Lemhi, LR—Lost River, and ST—Sawtooth. (A) Cross-section locations are shown for profiles in Figure 2. Brown box shows location of map shown in B. (B) Global positioning system (GPS) velocities indicate that the Centennial tectonic belt extends (double-ended black arrow) at a higher rate than in the Snake River Plain (black arrow), which is an order of magnitude lower (see Figs. 2A and 2B). Right-lateral shear of 0.9 ± 0.3 – 1.7 ± 0.2 mm/yr (opposing black arrows) in the Centennial shear zone (blue shaded region labeled CSZ) is required to accommodate the different strain rates. Quaternary faults: U.S. Geological Survey (2007); NE-trending normal faults: modified from Zentner (1989); seismicity: Advanced National Seismic System (2007); and focal mechanisms: Zollweg and Richins (1985), Richins et al. (1987), Doser and Smith (1989), Jackson et al. (1993), Stickney (1997), and Saint Louis University (2007).



estimated by Eddington et al. (1987) for normal faulting earthquakes from 1900 to 1983 in central Idaho. In contrast, the velocities in profile 2 (Fig. 2B), which extends from the western to eastern Snake River Plain and crosses four volcanic rift zones, show much smaller slopes. We calculated two strain rates for the Snake River Plain: contraction at $-0.6 \pm 1.3 \times 10^{-9}$ yr⁻¹ for 16 velocities from 50 to 430 km and extension at $1.6 \pm 4.8 \times 10^{-9}$ yr⁻¹ for 9 velocities from 290 to 390 km (Table DR3). Hence, over similar distance intervals (long and short), the strain rates in the Snake River Plain are about an order of magnitude lower than those in the western Centennial tectonic belt (Figs. 2A and 2B).

Two NW-SE profiles perpendicular to the directions of the horizontal GPS velocities show gradients due to both regional rotation and right-lateral shear. Profiles 3 and 4 extend from the Centennial tectonic belt along the Beaverhead and Lost River faults, respectively, across the Snake River Plain, and into the Intermountain seismic belt (Fig. 1A). Both profiles show a decrease in eastward velocities (i.e., increase in the westward velocities) from NW to SE along the entire profile, indicating a component of regional-scale clockwise rotation. In each profile, we also see a negative step across a zone of variable velocities that is not consistent with the rotation rate (lines shown in Figs. 2C and 2D). The velocity steps indicate a localized zone of right-lateral shear in the Centennial tectonic belt along the northwest margin of the Snake River Plain. We estimated slip rates across the



right-lateral shear zone by taking the difference between weighted average velocities on either side of it (Table DR4). The calculated slip rates are 0.9 ± 0.3 mm/yr for the SW profile and 1.7 ± 0.2 mm/yr for the NE profile (Figs. 2D and 2C, respectively). Figure 1B shows that slip rates increase northeastward from the Lost River fault, where magnitudes of velocities are similar within the Centennial tectonic belt and Snake River Plain, to the Beaverhead fault, where magnitudes of velocities are higher within the Snake River Plain than in the Centennial tectonic belt.

DISCUSSION

Our GPS results have three significant implications for current hypotheses of how strain is accommodated within the northern Basin and

Range Province. First, the Centennial tectonic belt includes a zone of right-lateral shear along the northwest margin of the eastern Snake River Plain (Fig. 1B). Strike-slip faults in concert with a propagating rift have been postulated as an alternative to hotspot migration for formation of the Snake River Plain (e.g., Hamilton, 1987). To date, however, investigators have identified only NE-trending normal faults in the Centennial tectonic belt (Fig. 1B) based on geologic mapping (e.g., Janecke, 1992; Rodgers et al., 2002) and at some locations along the Snake River Plain's northwest margin based on geophysical observations (e.g., Pankratz and Ackerman, 1982). McQuarrie and Rodgers (1998), for example, interpreted these normal faults to represent Snake River Plain-parallel

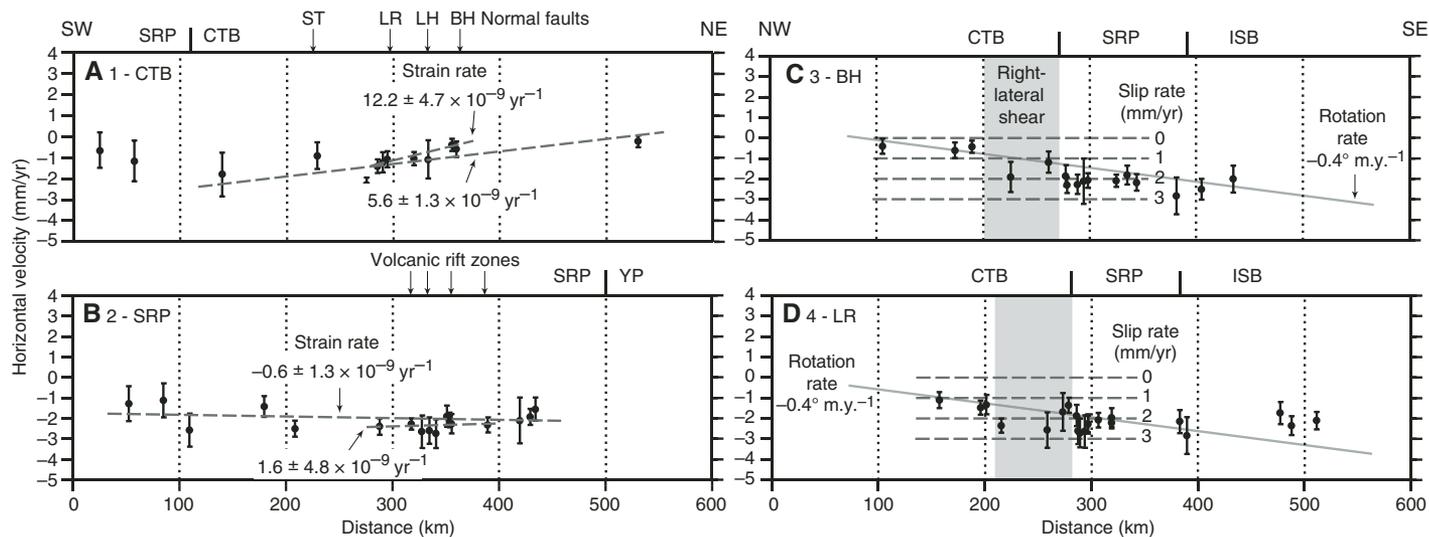


Figure 2. Profiles of horizontal global positioning system (GPS) velocities (dots; one standard deviation error bars) projected onto four lines shown in Figure 1A. Abbreviations are listed in caption of Figure 1. (A–B) Profiles are oriented parallel to GPS velocities so that positive increase of velocities indicates extension. Dashed lines are strain rates calculated using GPS velocities along these lines. (C–D) Profiles are oriented perpendicular to GPS velocities so a decrease of velocities indicates clockwise rotation or right-lateral shear or both. Gray lines show regional rotation rate of $-0.4^\circ \text{ m.y.}^{-1}$ (McCaffrey et al., 2007). Horizontal dashed lines are shown for slip rates of right-lateral shear (shaded region).

extension due to crustal flexure resulting from subsidence of the Snake River Plain. Focal mechanisms of recent earthquakes indicate predominately normal faulting in the Centennial tectonic belt and within the eastern Snake River Plain (Fig. 1B), although right-lateral strike-slip focal mechanisms have been observed along the E-trending Centennial normal fault (Stickney, 1997). Based on our GPS results and seismicity, we suggest that right-lateral shear may be accommodated by oblique slip distributed across the zone of NE-striking faults (e.g., Payne and Oldow, 2005) within what we refer to as the “Centennial shear zone.” Further, we propose that the Centennial shear zone may extend from Lost River fault northeastward as far as the Centennial fault (Fig. 1B).

Second, the significantly lower strain rate in the Snake River Plain implies that the three prominent Basin and Range normal faults (Lost River, Lemhi, and Beaverhead) terminate at the Snake River Plain (Fig. 1B). The mountain ranges adjacent to these normal faults end abruptly at the physiographic boundary of the eastern Snake River Plain. At the ends of the ranges, bedrock structural features, gravity data, and seismic reflection data suggest that significant seismogenic fault movements do not extend into the eastern Snake River Plain (Mabey, 1978; Bruhn et al., 1992; Jackson et al., 2006). Some investigators, however, suggest that the normal faults extend into the eastern Snake River Plain and may be covered over by Quaternary basalt flows (e.g., Rodgers et al., 2002). If normal faults do extend into the Snake River Plain, the slip rates on these normal faults will be an order

of magnitude lower than those located to the northwest in the Centennial tectonic belt.

Third, the GPS-derived difference in strain rates opposes hypotheses that require similar rates of extension within the Snake River Plain and western Centennial tectonic belt. In particular, the lack of observed extension in GPS velocities along the 380 km length of the Snake River Plain (Fig. 2B) contradicts the hypothesis that dike intrusion within Snake River Plain volcanic rift zones accommodates extension at a rate comparable to extension in the Centennial tectonic belt and Intermountain seismic belt (e.g., Rodgers et al., 1990; Parsons et al., 1998). Since dike intrusions (like normal-faulting earthquakes) produce localized deformation fields, the episodic nature of dike intrusions will not change the average strain rate along the 380 km length of the Snake River Plain. For example, satellite radar data of the 2005 Afar, Africa, basalt dike intrusion revealed that the deformation field was 50 km wide and centered about the rift along a 60 km length with a maximum opening of 6 m (Wright et al., 2006). Using this as an analogy, most GPS velocities along the 380 km length of the Snake River Plain will fall outside the localized deformation field of an individual dike intrusion (e.g., dike intrusion in the Great Rift 2 ka). Simply put, dike intrusion will not move the entire 380 km length of the Snake River Plain at one time. At distances of many tens of kilometers from the intruding dike, the lithosphere will move steadily and will be unaffected by the localized dike-induced deformation field. Hence, we argue that our GPS observations reveal the long-term motions of the Snake River Plain. Another

hypothesis offered by Pennington et al. (1974) suggested that the Snake River Plain is deforming rapidly by aseismic creep, presumably because the crust is too hot and weak to undergo brittle failure. Only infrequent, small-magnitude ($M < 2.0$) earthquakes have occurred within the Snake River Plain (Jackson et al., 1993). Our GPS results suggest that the low rate of seismicity may be simply due to low strain rates. Without knowing the stress on the Snake River Plain crust, we cannot say whether it is too strong to fracture, possibly due to repeated intrusions and crystallization of large volumes of basalt magma in it, as suggested by Anders and Sleep (1992), or if there is little stress acting on it. Borehole breakouts revealed little deformation, but without knowing the strength of the rocks, stress estimates from them are ambiguous (Moos et al., 1990). Thus, if processes such as dike intrusion, aseismic creep, and brittle fracture accommodate extension within the Snake River Plain, they do so at a much lower rate than the rate of normal faulting in the western Centennial tectonic belt.

CONCLUSIONS

We observe from GPS measurements that extension in the western Centennial tectonic belt occurs at an average rate of $5.6 \pm 1.3 \times 10^{-9} \text{ yr}^{-1}$ (over 380 km) and up to $12.2 \pm 4.7 \times 10^{-9} \text{ yr}^{-1}$ across three active normal faults. Here, normal-faulting earthquakes predominantly accommodate extension. In contrast, processes within the Snake River Plain, such as dike intrusion, aseismic creep, or brittle fracture, or a combination of them, may accommodate extension, but they do so at an order of magnitude lower rate.

From our GPS velocities, we calculated extension at an average rate of $1.6 \pm 4.8 \times 10^{-9} \text{ yr}^{-1}$ across four volcanic rift zones that are adjacent to the three active normal faults. Right-lateral shear in the Centennial shear zone occurs due to different rates of extension in the Snake River Plain and western Centennial tectonic belt. The slip rate within the Centennial shear zone increases from $0.9 \pm 0.3 \text{ mm/yr}$ near the Lost River fault to $1.7 \pm 0.2 \text{ mm/yr}$ near the Beaverhead fault and may extend further northeastward to the Centennial fault at an even faster rate. We suggest that within the zone of right-lateral shear, the major range-bounding normal faults (i.e., Lost River, Lemhi, and Beaverhead) terminate at the Snake River Plain, and strike-slip earthquakes may occur along NE-trending normal faults in the Centennial shear zone. Clockwise rotations observed in the horizontal GPS velocities within the northern Basin and Range Province are part of a large-scale rotation over the Pacific Northwest suggestive of driving forces possibly beyond those associated with the Yellowstone hotspot.

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