A possible "window of escape" in the southern Cascadia subduction zone

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Understanding the forces and factors that are responsible for deforming the continental lithosphere remains a fundamental issue in geophysics. Deformation in continental plate boundary zones occurs over length scales of hundreds to thousands of kilometers, in contrast to oceanic plate boundaries, where earthquakes are in most cases limited to much narrower zones. It is because of this typically diffuse nature that previous plate kinematic techniques have been limited in their ability to resolve surface motions within zones of continental deformation. However, with the proliferation of global positioning system (GPS) instrumentation over the past 20 yr, the kinematics and dynamics of these previously enigmatic regions are coming into focus.

One of the largest and most studied continental plate boundary zones is western North America, where the Pacific plate is grinding northwestward with respect to the North American plate, generating the San Andreas fault system (Fig. 1). Finding a complete explanation for the tectonics of this region is complicated by the subduction of the Juan de Fuca plate beneath the Pacific Northwest, and evidence that eastward of the San Andreas, the Basin and Range province (BRP) has undergone ~100% extension. The three proposed forces involved in driving such complex deformation (Richardson and Reding, 1991; Sonder and Jones, 1999) are 1) buoyancy forces associated with lithospheric density variations (Fleitout and Froidevaux, 1982; Fleitout, 1991; Jones et al., 1996); 2) boundary forces associated with the relative motions between the Pacific, Juan de Fuca, and North American plates (Atwater, 1970; Stock and Molnar, 1988; Bohannon and Parsons, 1995); and 3) tractions applied to the base of the lithosphere (McKenzie, 1969; Tovish et al., 1978)—some of these tractions likely result from mantle flow associated with the old subducted Farallon plate. To fully quantify the forces responsible for deforming the continental lithosphere, and to understand how deformation is being accommodated, a detailed knowledge of the surface motions is necessary.

Several researchers have used GPS to study surface kinematics in western North America (Shen-tu et al., 1999; Meade and Hager, 2005; McCaffrey, 2005; McCaffrey et al., 2007; Hammond and Thatcher, 2005; Flesch et al., 2007). Kreemer and Hammond (2007, p. 943 in this issue) took that analysis one step further to investigate the flux of material flowing in and out of the deforming region. By applying Gauss' divergence theorem to a modeled continuous surface velocity field, determined from 1477 GPS observations from Baja California to the Queen Charlotte Islands in Canada, they found that there was no net areal change within the plate boundary zone (within the uncertainty of GPS). This innovative result implies that within this zone of western North America, areas of contraction are completely balanced by areas of extension.

Kreemer and Hammond gain further insight into the balance of areal change by dividing the zone into four sub-regions. In doing this, they show that the San Andreas zone south of 38°N, and the Cascadia subduction zone and Juan de Fuca–Gorda Ridge systems, north of 42°N, have a complete balance of extension and contraction, with zero net areal change. However, there is a net areal decrease along a zone containing northwestern California (between 38°N and 42°N) (Fig. 1). Remarkably,
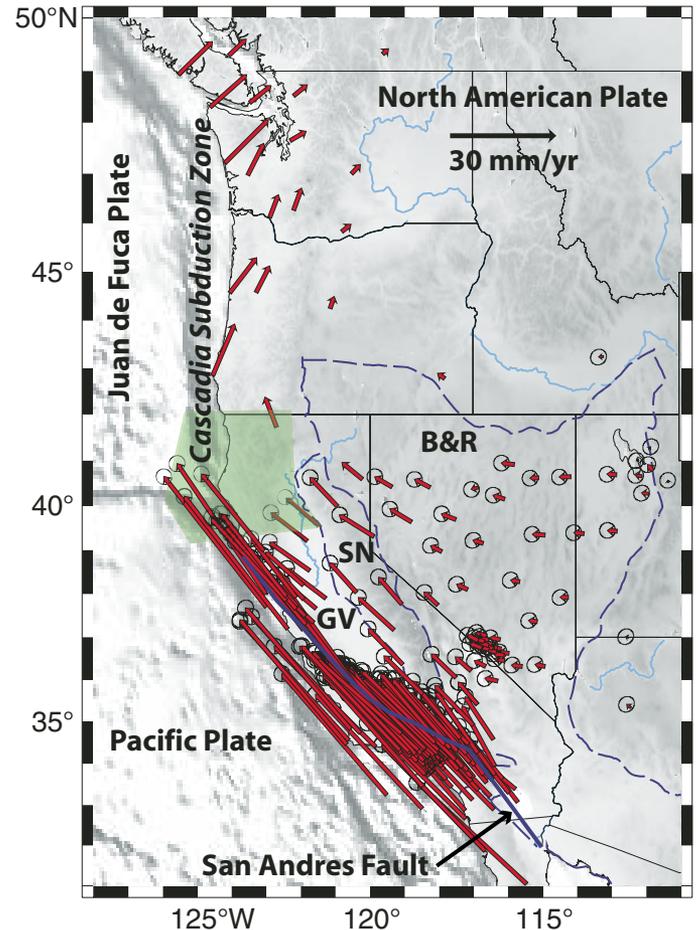
Figure 1. Western North American plate boundary zone. Red vectors are GPS observations from Bennett et al. (1999, 2003) plotted in the North American reference frame. Blue dashed lines show boundaries of the Basin and Range and Sierra Nevada provinces. Green zone represents region of areal reduction determined by Kreemer and Hammond (2007) that balances the extension occurring in the Basin and Range. SN—Sierra Nevada, GV—Great Valley, B&R—Basin and Range.

the areal growth within the BRP is equivalent to the areal reduction in this small region in Northern California. This interesting latter result indicates that there may be a kinematic relationship between the extension in the BRP and compression in Northern California. Kreemer and Hammond argue that the southern Cascadia subduction zone represents a "window of escape" for the BRP, guiding extension directions now and over the history of the BRP opening. Such a detailed kinematic analysis as that done by Kreemer and Hammond provides insight into the dynamics of BRP extension, and the nature of the transform-dominated plate boundary in general.

What forces are at work in driving extension in the BRP? Jones et al. (1996) argued that gravitational potential energy (GPE) differences, asso-

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ciated with density variations within the crust and upper mantle, are large enough to drive extension. Flesch et al. (2000) confirmed those results, but argued that the influence of Pacific–North America relative motion (Atwater, 1970) was of equal importance to GPE differences, and is necessary in order to produce the correct orientation of deviatoric tensional stresses in the BRP. However, Liu and Bird (2002) suggest that westward active mantle drag is needed to fit the GPS observations in the BRP.

Recently, two studies have used deformation indicators inferred from GPS observations (Flesch et al., 2007) and the World Stress Map data (Humphreys and Coblentz, 2007) to directly quantify the relative importance of deformational driving forces in the western North America plate boundary zone. Both studies found that GPE variations and plate interactions were the main deformational components, while effects from basal tractions were minimal. The findings of Kreemer and Hammond are consistent with these two studies. Additionally, Humphreys and Coblentz (2007) required a tensional load in the southern Cascadia subduction zone with stresses similar to that determined by Govers and Meijer (2001). Humphreys and Coblentz argued that this boundary condition was associated with the roll back of the Gorda slab and provides a suction that helps to drive both the Sierra Nevada and BRP motions. The "window of escape" observed by Kreemer and Hammond could be a result of this pull in the southern Cascadia zone guiding the BRP.

One must also consider lateral strength variations in the lithosphere (Flesch et al., 2000) when considering the dynamics of continental regions. For example, compression in Northern California has also been attributed to the northward motion of the Sierra Nevada–Great Valley block (Argus and Gordon, 2001), which is driven by the relative motion of the Pacific plate (Whitehouse et al., 2005). The stronger Sierra Nevada–Great Valley block may provide a barrier to BRP opening, forcing material to flow toward weaker regions at its northern end. Such a scenario is again consistent with the "window of escape" hypothesis of Kreemer and Hammond.

Although GPS observations have permitted the detailed kinematic and dynamic analyses discussed here, it is important to remember that GPS velocities represent interseismic velocity, which contains elements of elastic and transient components of deformation (Pollitz, 2003; Hetland and Hagar, 2004) that likely contribute to a deviation from the long-term motions. Such devations are likely to occur over relatively short wavelengths, whereas it is the much longer wavelength kinematics that are important in guiding the inferences of Kreemer and Hammond. As discussed by Kreemer and Hammond, some of the observed deformation in the Pacific Northwest may be non-permanent. If true, this may only expand the region of net areal loss to the north, but would not change the overall conclusion that the BRP and the southern Cascadia subduction zone are kinematically linked. Denser GPS coverage in Cascadia, and throughout western North America in regions of lower strain (e.g., the Rio Grande Rift, Yellowstone caldera, and Montana) will refine these types of kinematic relationships, and provide further insights into both the transient and permanent features in the kinematics and dynamics of the continental lithosphere in western North America.

REFERENCES CITED

Argus, D.F., and Gordon, R.G., 2001, Present tectonic motion across the Coast Ranges and San Andreas fault system in central California: Geological Society of America Bulletin, v. 113, p. 1580–1592, doi: 10.1130/0016-7606.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513–3536.

Bennett, R.A., Davis, J.L., and Wernicke, B.P., 1999, Present-day pattern of Cordilleran deformation in the western United States: Geology, v. 27, no. 4, p. 371–374.

Bennett, R.A., Wernicke, B.P., Niemi, N.A., Friedrich, A.M., and Davis, J.L., 2003, Contemporary strain rates in the northern Basin and Range province from GPS data: Tectonics, v. 22, p. 1008, doi: 10.11029/200ITC001355.

Bohannon, R.G., and Parsons, T., 1995, Tectonic implications of post-30 Ma Pacific and North American relative plate motions: Geological Society of America Bulletin, v. 107, p. 937–959.

Fleitout, L., 1991, The sources of lithospheric tectonic stress: Philosophical Transactions of the Royal Society B: Biological Sciences, v. 337, p. 73–81.

Fleitout, L., and Froidevaux, C., 1982, Tectonics and topography for a lithosphere containing density heterogeneities: Tectonics, v. 1, p. 21–56.

Flesch, L.M., Holt, W.E., Haines, A.J., and Shen-Tu, B.M., 2000, Dynamics of the Pacific-North American plate boundary in the western United States: Science, v. 287, p. 834–836.

Flesch, L.M., Holt, W.E., Haines, A.J., Wen, L., and Shen-Tu, B., 2007, The dynamics of western North America: Stress magnitudes and the relative role of gravitational potential energy, plate interaction at the boundary and basal tractions: Geophysical Journal International, v. 169, p. 866–896, doi: 10.1111/j.1365-246X.2007.03274.x.

Govers, R., and Meijer, P.T., 2001, On the dynamics of the Juan de Fuca plate: Earth and Planetary Science Letters, v. 189, p. 115–131.

Hammond, W.C., and Thatcher, W., 2005, Northwest basin and range tectonic deformation observed with the global positioning system, 1999-2003: Journal of Geophysical Research, v. 110, p. B10405.

Hetland, E.A., and Hager, B.H., 2004, Relationship of geodetic velocities to velocities in the mantle: Geophysical Research Letters, v. 31, p. L17604, doi: 10.1029/2004GL02069.

Humphreys, E.D., and Coblentz, D.D., 2007, North American dynamics and western U.S. tectonics: Reviews of Geophysics, v. 45, p. RG3001, doi: 10.1029/2005RG000181.

Jones, C.H., Unruh, J.R., and Sonder, L.J., 1996, The role of gravitational potential energy in active deformation in the southwestern United States: Nature, v. 381, p. 37–41.

Kreemer, C., and Hammond, W.C., 2007, Geodetic constraints on areal changes in the Pacific–North America plate boundary zone: What controls Basin and Range extension?: Geology, v. 35, p. 943–946, doi: 10.1130/G23868A.1.

Liu, Z., and Bird, P., 2002, North America plate is driven westward by lower mantle flow: Geophysical Research Letters, v. 29, p. 2164, doi: 10.1029/2002GL016002.

Meade, B.J., and Hager, B.H., 2005, Block models of crustal motion in southern California constrained by GPS measurements: Journal of Geophysical Research, v. 110, p. B03403, doi: 10.1029/2004JB003209.

McCaffrey, R., 2005, Block kinematics of the Pacific-North America plate boundary in the southwestern United States from inversion of GPS, seismological, and geologic data: Journal of Geophysical Research, v. 110, p. B07401, doi: 10.1029/2004JB003307.

McCaffrey, R., Qamar, A.I., King, R.W., Wells, R., Khazaradze, G., Williams, C.A., Stevens, C.W., Vollick, J.J., and Zwick, P.C., 2007, Fault locking, block rotation and crustal deformation in the Pacific Northwest: Geophysical Journal International, v. 169, p. 1315–1340, doi: 10.1111/j.1365-246X.2007.03371.x.

McKenzie, D.P., 1969, Speculations on consequences and causes of plate motions: Geophysical Journal International, v. 18, p. 1–32, doi: 10.1111/j.1365-246X.1969.tb00259.x.

Pollitz, F.F., 2003, The relationship between the instantaneous velocity field and the rate of moment release in the lithosphere: Geophysical Journal International, v. 153, p. 596–608.

Richardson, R.M., and Reding, L.M., 1991, North American plate dynamics: Journal of Geophysical Research, v. 96, p. 12,201–12,223.

Shen-Tu, B.M., Holt, W.E., and Haines, A.J., 1999, Deformation kinematics in the western United States determined from Quaternary fault slip rates and recent geodetic data: Journal of Geophysical Research, v. 104, p. 28927–28955.

Sonder, L.J., and Jones, C.H., 1999, Western United States extension: How the West was widened: Annual Review of Earth and Planetary Sciences, v. 27, p. 417–466.

Stock, J., and Molnar, P., 1988, Uncertainties and implications of the Late Cretaceous and Tertiary position of North-America relative to the Farallon, Kula, and Pacific Plates: Tectonics, v. 7, p. 1339–1384.

Tovish, A., Schubert, G., and Luyendyk, B.P., 1978, Mantle flow pressure and the angle of subduction—Non-Newtonian corner flows: Journal of Geophysical Research, v. 83, p. 5892–5898.

Whitehouse, P.L., England, P.C., and Houseman, G.A., 2005, A physical model for the motion of the Sierra Block relative to North America: Earth and Planetary Science Letters, v. 237, p. 590–600.