Geodetic constraints on areal changes in the Pacific–North America plate boundary zone: What controls Basin and Range extension?

Corné Kreemer
William C. Hammond
Nevada Bureau of Mines and Geology, and Seismological Laboratory, University of Nevada, Reno, Nevada 89557, USA

ABSTRACT

Using ~1500 geodetic velocities we model the present-day spatial patterns of areal changes inside the Pacific–North America plate boundary zone. From this model we show that between the central Gulf of California and the Queen Charlotte Islands there is no significant net change in surface area. This zero net areal-change result allows us to relate regions of areal growth to areas of equivalent contraction elsewhere within the plate boundary zone. We find that areal growth of the Basin and Range province (BRP) and its eastern margin (~5.2 ± 0.1 × 10^3 m^2/yr) is balanced by areal reduction near northwestern California between 38°N and 42°N. The San Andreas fault system south of 38°N and the plate boundary zone north of ~42°N (including the Juan de Fuca and Gorda Ridge systems) each have no significant net areal change. Our results suggest a kinematic relationship between extension in the BRP and contraction near the northern California Coast Ranges and Klamath Mountains. From these observations we propose that, although BRP extension may be caused by internal forces, the southernmost Cascadia subduction zone provides a "window of escape" that acts as a stress guide to BRP extension as well as northwestward Sierra Nevada motion. Such a dynamic model is consistent with independent findings that (1) the least principal horizontal stress orientations in the BRP are toward northern California, (2) extension directions in the BRP have changed orientation to track the northward migration of the Mendocino triple junction, and (3) the southernmost Cascadia subduction zone is a relatively weak plate boundary.

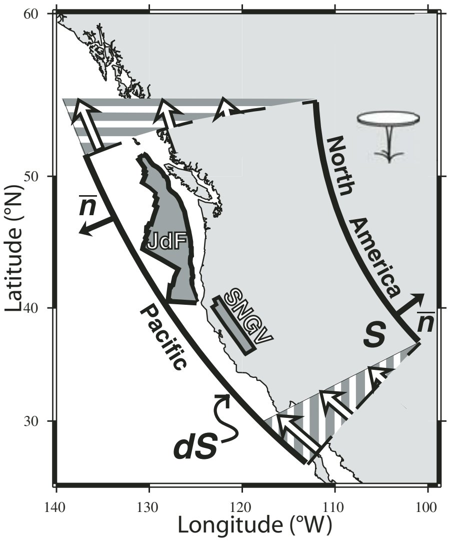

Figure 1. A partial annulus that encompasses the Pacific–North America (PA-NA) plate boundary in western North America is bounded by two small circles around the PA-NA pole of rotation (note that the small circles appear nonparallel because of the Mercator projection). If deformation within this partial annulus obeys no net areal change, then the crustal material flowing into the partial annulus (vertically hatched region) should equal the amount that flows out (horizontally hatched region). JdF—Juan de Fuca plate; SNGV—Sierra Nevada–Great Valley block.

Keywords: geodesy, dilatation, contraction, extension, plate boundary zone, Basin and Range, western United States, tectonics, lithospheric dynamics.

INTRODUCTION

The Pacific–North America (PA-NA) plate boundary zone in the western United States is predominantly a transform plate boundary (Atwater, 1970). This is evident from the fact that a large portion of the San Andreas fault system, which accommodates most of PA-NA motion, is oriented nearly parallel to the plate motion direction (Argus and Gordon, 2001). Despite this, the northern Basin and Range province (BRP), which encompasses a large part of the plate boundary zone, formed by progressive extension (Hamilton and Meyers, 1966; Stewart, 1978), which is still active today (e.g., Bennett et al., 2003; Hammond and Thatcher, 2004). The causes of BRP extension have been attributed to various mechanisms, including gravitational potential energy differences in the lithosphere, basal drag, mantle upwelling, plate boundary forces, or a combination of these (e.g., Flesch et al., 2000; Liu and Shen, 1998; Sonder and Jones, 1999). In the western United States, there is a dense and broad distribution of geodetic data that can place strong constraints on the style and magnitude of active crustal deformation, and are therefore valuable in the construction or validation of dynamic models of lithospheric deformation. Here we contribute to understanding the balance of regional-scale patterns of extension and contraction by quantifying the amount and extent of present areal growth in the BRP and surrounding areas.

ANNULUS KINEMATICS

The goal of this study is to clarify the kinematic relationship between BRP growth and the rest of the PA-NA plate boundary. To this end we consider a partial annulus *S* that encompasses the PA-NA plate boundary in western North America (Fig. 1). The width of the annulus is determined by the distance between two small circles around the PA-NA pole of rotation. The small circle nearest the pole is on stable North America, and the other is on the Pacific plate. According to Gauss' divergence theorem for a smooth two-dimensional flow, the integrated divergence of the velocity field ($\nabla\cdot\bar{v}$) inside *S* is equal to the integrated flux ($\bar{v}\cdot\bar{n}$) through the boundary around *S*, i.e., ∂S (Fig. 1). In our case $\bar{v}$ refers to the interpolated horizontal vector velocity field passing through ∂S that we have estimated from published geodetic measurements (see the GSA Data Repository[1]). On the surface of a sphere,

$$\oint_{\partial S}(\bar{v}\cdot\bar{n})\,dl = R^2\iint_{S}(\nabla\cdot\bar{v})\cos\theta\,d\theta\,d\varphi, \qquad (1)$$

where θ is latitude, ϕ is longitude, *R* is the radius of Earth, and $\bar{n}$ is the horizontal unit vector normal to ∂S. Gauss' theorem describes a purely kinematic relationship between horizontal dilatation and flux through ∂S on Earth's surface, and does not consider any material property (e.g., incompressibility, viscosity, strength, density). Therefore the mechanism of extension/contraction need not be specified and could, for example, be associated with crustal thinning/thickening, dike intrusions, faulting, or folding. Any height change that may be associated with $\nabla\cdot\bar{v}$ is not in violation with our two-dimensional treatment of Gauss' law.

With $\nabla\cdot\bar{v}$ equal to the dilatational strain rate, the net areal-change rate $\dot{A}$ can be directly inferred:

$$\iint_{S}\left(\dot{\varepsilon}_{\theta\theta}+\dot{\varepsilon}_{\varphi\varphi}\right)\cos\theta\,d\theta\,d\varphi = \dot{A}/R^2. \qquad (2)$$

When the same amount of material that enters *S* also leaves *S*, then $\dot{A} = 0$ (Fig. 2A). When, in that case, a subregion of *S* exhibits areal growth (e.g.,

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[1] GSA Data Repository item 2007232, geodetic velocities and references, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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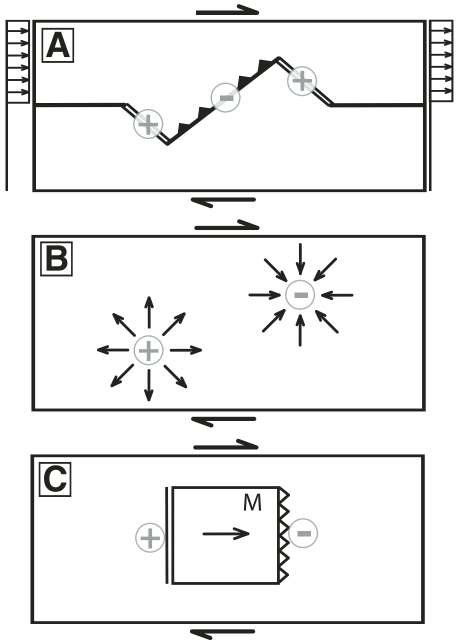

Figure 2. We show that for our study area (Fig. 3) the zero flux condition holds. Here are some examples of balanced dilatational kinematics. A: A transform plate boundary with sinuous fault geometry has local extension (i.e., areal growth, gray plusses) and contraction (i.e., areal reduction, gray minuses) that contribute equal and opposite quantities of dilatation. In this case, even though some of these faults are nonparallel to the plate motion direction, the velocity fluxes into and out of the box (arrows) are equal and opposite in sign. B: When the zero net flux condition holds, non-plate-boundary-derived sources and sinks inside the region also balance. This class of deformation is not associated with plate boundary processes. C: A specific instance of B where a microplate (M) moves inside the zone. Net zero dilatation occurs in the short-term (interseismic) and long-term (secular) time scales, and for any combination of recoverable and permanent deformation.

because of a fault not aligned with plate motion, or the presence of internal sources of deformation), then there must exist an equal amount of areal reduction elsewhere in the plate boundary zone to offset the areal growth (Fig. 2).

KINEMATIC MODEL

In order to quantify $\dot{A}$ (and the related flux $\oint(\bar{v}\cdot\bar{n})dl$) within the PA-NA plate boundary, we model the strain rate tensor field using the principles of continuum mechanics. A continuum description of the deformation field is appropriate for this study as it will capture the horizontal strain budget and its distribution. We use a velocity and strain rate interpolation method (Beavan and Haines, 2001) and a large set of 1477 geodetic velocities (see the GSA Data Repository) to obtain estimates of the strain rate tensor everywhere within the plate boundary zone. The model grid is aligned along small circles around the PA-NA Euler pole and consists of ~3000 0.4° by 0.4° grid cells. The grid extends from the central Gulf of California (~26°N) to the southern Queen Charlotte Islands (~52°N). For this choice of along-strike limits of the partial annulus, we find that the geodetic data indicate that inside *S*, $\dot{A}$ is indistinguishable from zero (see below). (Note that we do not constrain $\dot{A}$ to be zero.) The PA-NA Euler pole we use (50.0°N, 75.9°W, –0.758°/m.y.) for the plate boundary velocity constraint is obtained from the NA-ITRF2000 pole, as defined by the Stable North American Reference Frame Group (Blewitt et al., 2004), combined with the PA-ITRF2000 pole (Kreemer et al., 2006). As a boundary condition, we apply the above PA-NA motion to one side of the grid (corresponding to 51.2 mm/yr total plate motion), and hold the North America side fixed (Fig. 2A).

To account for the contributions from the Juan de Fuca plate and Sierra Nevada–Great Valley microblock, we assume that they are rigid elements that move within the plate boundary zone (Fig. 3). Motion of rigid blocks inside *S* does not alter the net areal change since the integral of extension and contraction caused by their motions is zero (Fig. 2C). We use the Juan de Fuca–North America motion of Wilson (1993), and the Sierra Nevada–Great Valley motion is constrained by the global positioning system (GPS) sites on this block.

Figures 3A and 3B show the patterns of the second $\left(\sqrt{\dot{\varepsilon}_{\theta\theta}^2+\dot{\varepsilon}_{\varphi\varphi}^2+2\dot{\varepsilon}_{\theta\varphi}^2}\right)$ and first $(\dot{\varepsilon}_{\theta\theta}+\dot{\varepsilon}_{\varphi\varphi})$ invariants of the model strain rate tensor field, respectively. The highest total strain rates can be found in the Gulf of California, along the San Andreas fault system, along the Cascadia subduction zone, and west of the Juan de Fuca plate. Because of the lack of any offshore constraints, the high dilatational strain rates west of the Juan de Fuca plate appear to be diffuse in our model, but in reality they are localized along the Juan de Fuca and Gorda Ridge systems. Contraction associated with the Cascadia subduction zone (blue areas in region "a" of Fig. 3B) is predominantly interseismic and recoverable strain accumulation related to locking along the plate boundary interface, but some of the strain is likely to be permanent (e.g., McCaffrey et al., 2000; Wells et al., 1998). Regardless of whether the strain is recoverable or permanent, however, the net dilatation in *S* associated with impingement of the Juan de Fuca plate onto North America is zero (Fig. 2C). Strain rates reach ~50 × 10^{-9}/yr in the Walker Lane belt, consistent with the ~10 mm/yr deformation that is accommodated across this zone (e.g., Hammond and Thatcher, 2004). Strain rates are insignificant east of the Central Nevada Seismic Belt, consistent with the central Great Basin acting as a geodetic microplate (Bennett et al., 2003; Hammond and Thatcher, 2005). Farther east, near the Wasatch Mountains, strain rates are elevated and almost purely dilatational, consistent with other studies (Martinez et al., 1998; Niemi et al., 2004). We do not see significant dilatation across the Rio Grande Rift; this may be a consequence of the current lack of data on the Colorado Plateau.

AREAL CHANGE

Inside the annular segment *S*, the net areal change $\dot{A}$ is not significantly different from zero (Table 1). Dividing by the length of the boundary ∂S, this areal change corresponds with 0.1 ± 0.2 mm/yr flowing out of the partial annulus. This net areal change is ~0.3% of the total amount of areal growth, and is thus not significant compared to the uncertainties in geodetic velocity data.

We first isolate the patterns of interseismic strain in the major tectonic provinces outside the BRP, i.e., Cascadia and the San Andreas fault (subregions *a* and *b* respectively, Fig. 3B), whose net areal changes are zero. For subregion *a*, the large extension west of the Juan de Fuca plate and large contraction along the Cascadia subduction zone and within the upper plate cancel out so that within *a*, $\dot{A} \approx 0$ (Table 1). The bend in the boundary between subregions *a* and *c* was designed to ensure that all offshore deformation was contained in *a* and that net dilatation in *a* is zero. The boundary between *b* and *c* was adjusted northward until contraction owing to the restraining geometry of the San Andreas fault canceled extension owing to rifting in the Gulf of California. Poor GPS constraint on the details of these strain patterns (e.g., near the Gulf of California or east of Cascadia) does not contribute significant bias, because net dilatation is not sensitive to the distribution of $\nabla\cdot\bar{v}$, except when the strain pattern crosses subregion boundaries, and we have designed the subregions to be minimally impacted by this change in strain distribution. Next we isolate in subregion *d* the extension that occurs within the BRP and interior western United States east of the San Andreas fault system and Sierra Nevada–Great Valley block. The net areal change in this region is ~5.2 ± 0.1 × 10^3 m^2/yr (Table 1), of which ~40% occurs along the eastern margin of the BRP (including the Wasatch Mountains), ~17% along Walker Lane, and a significant portion in areas where the geodetic coverage is limited. The areal reduction in the remaining area (subregion *c*), which covers northern California from 38°N to 42°N, equals the areal growth in the BRP (Table 1).

DISCUSSION AND CONCLUSIONS

Our estimates of the present-day areal-change budget in the PA-NA plate boundary zone suggest that extension in the BRP may be kinematically related to the present shortening in the northern California Coast Ranges and Klamath Mountains. A significant amount of permanent shortening appears to have occurred in northern California (e.g., McCrory, 2000) and is generally ascribed to the northwest motion of the

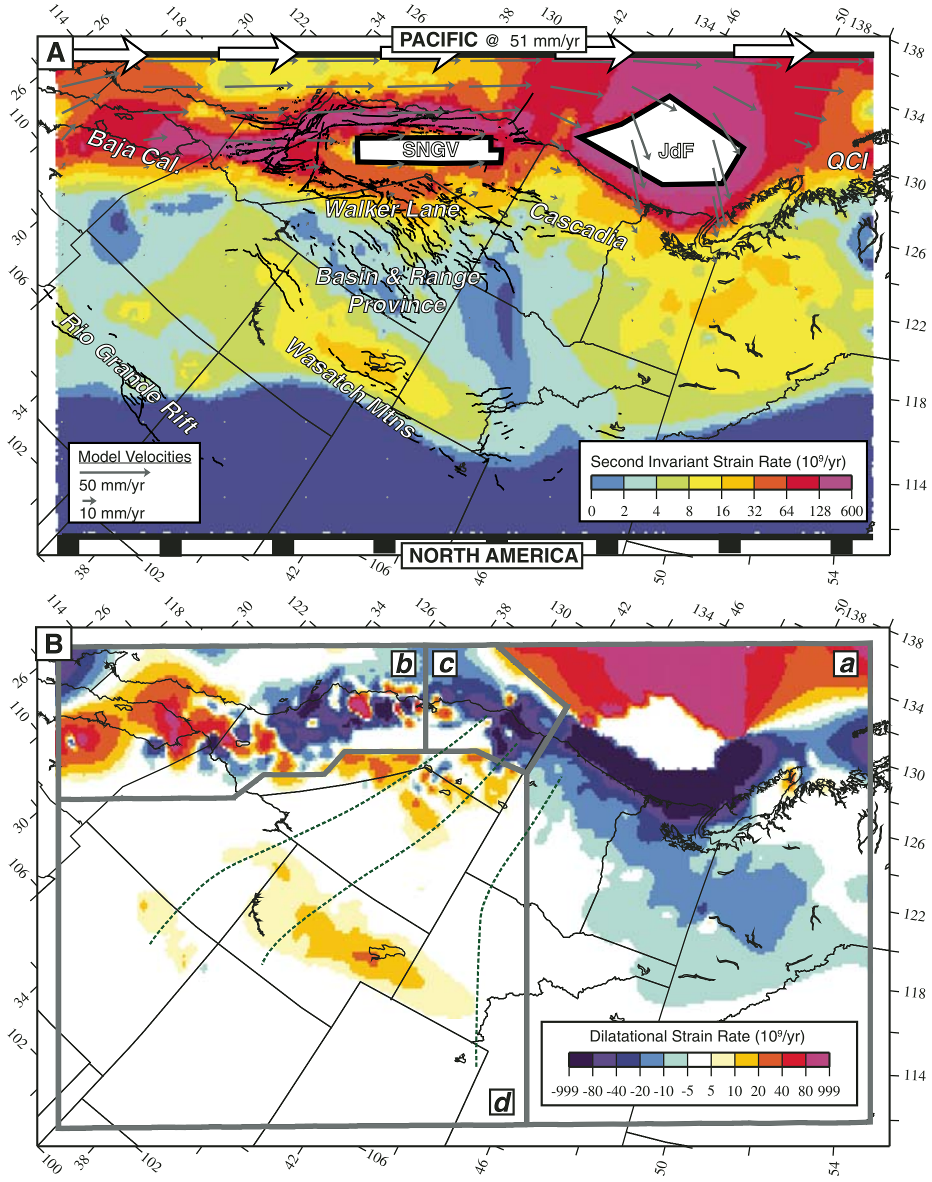

Figure 3. A: PA-NA plate boundary zone in western North America in an oblique Mercator projection around the PA-NA pole of rotation. North American model boundary is fixed, while the Pacific boundary is constrained to move at the full PA-NA rate. The Sierra Nevada–Great Valley block (SNGV) and Juan de Fuca plate (JdF) are modeled as rigid entities within the deforming grid. Black lines are Quaternary faults. Colors indicate second invariant of strain rate tensor field. Gray arrows are interpolated model velocities relative to North America. QCI—Queen Charlotte Islands. B: Contours of the dilatational strain rates. Red and blue colors indicate extension (i.e., areal growth) and contraction (i.e., areal reduction), respectively. The gray lines divide the plate boundary into four zones (Table 1). Dashed green lines are trajectories along (averaged) minimum principal stress observations for the greater BRP (Humphreys and Coblentz, 2007).

TABLE 1. AREAL CHANGE AND VELOCITY FLUX

Region	$\dot{A}$ ($m^2\ yr^{-1}$)	$\oint \bar{v} \cdot \bar{n}$ ($mm\ yr^{-1}$)
a. Cascadia–Juan de Fuca	221 ± 287	0.1 ± 0.2
areal reduction	–32,391	–19.2
areal growth	32,612	19.3
b. San Andreas fault system	–236 ± 172	–0.1 ± 0.1
areal reduction	–8355	–4.9
areal growth	8120	4.8
c. N. California–S. Cascadia	–5021 ± 101	–3.0 ± 0.1
areal reduction	–5391	–3.2
areal growth	369	0.2
d. Basin and Range province	5193 ± 125	3.1 ± 0.1
areal reduction	–227	–0.1
areal growth	5391	3.2
TOTAL	157 ± 372	0.1 ± 0.2
areal reduction	–46,364	–27.4
areal growth	46,521	27.5

$\dot{A}$ is the integrated areal change (positive is areal growth), which is proportional to velocity flux, $\oint \bar{v} \cdot \bar{n}$. Uncertainties are one standard deviation.

Sierra Nevada–Great Valley block (e.g., Argus and Gordon, 2001; Unruh et al., 2003; Williams et al., 2006). Our results suggest, however, that northern California's shortening may also be related to BRP extension, consistent with the conclusions of other studies (e.g., Hammond and Thatcher, 2005; Humphreys and Coblentz, 2007; McCaffrey, 2005). Our inference is corroborated by studies of western United States stress and lithospheric dynamics. For example, the observed minimum horizontal stress directions in the BRP are oriented toward northern California (Fig. 3B) and provide an incentive for deformation toward the southern Cascadia subduction zone (Zoback, 1989). From these and other stress observations on the North American continent, Humphreys and Coblentz (2007) derived an east-west minimum principal stress direction along the southern Cascadia subduction zone. A force balance study of the Juan de Fuca plate (Govers and Meijer, 2001) finds an east-west maximum principal stress along the Cascadia subduction zone north of 43°N but not south of there. These findings support the idea that the southern Cascadia subduction zone may provide a "window of escape" for a mobile continental interior. According to these models, the absence of large compressional stresses normal to the plate boundary, a condition exclusive to this part of the western North America margin (Humphreys and Coblentz, 2007), helps to accommodate (and perhaps guides) BRP extension and Sierra Nevada–Great Valley northwest motion, and allows permanent contraction in the upper plate above the southernmost Cascadia subduction zone. The post-Oligocene progressive clockwise rotation in the BRP principal stress orientations that coincides with the northward migration of the Mendocino triple junction (Bird, 2002; Zoback et al., 1981) suggests that this mechanism may have been in place since ca. 10–20 Ma.

The "window of escape" hypothesis suggests that BRP deformation is guided by plate boundary conditions. We note that the hinge line separating extension in the BRP and contraction in California remarkably follows that between "negative" and "positive" gravitational potential energy (Jones et al., 1996; Flesch et al., 2000), suggesting that the forces that drive deformation may have a gravitational origin. The relatively high strain rates along the BRP's eastern margin suggest that deformation there may be controlled by lithospheric weakness, a lithological contrast, and/or a regional gradient in gravitational potential energy. Our result indicating net zero dilatation in subregion *b* does not support the notion that the North America margin east of the San Andreas fault collapses toward the southwest (e.g., Dokka and Ross, 1995). Rather, the presence of large compressional stresses normal to the entire plate boundary except along the southern Cascadia subduction zone may indicate a relative weakness of the plate boundary (i.e., a "window of escape") at the southern Cascadia subduction zone that acts as a stress guide for material flowing from areas of high gravitational potential energy in the BRP.

Our areal-change estimates reflect changes occurring essentially in the present day, because they are constrained by geodetic measurements made in the last 10–20 yr. Thus, uncertainty in our analysis and inferences arises from the difference between our model and the long-term (averaged over many seismic cycles) crustal deformation pattern. For example, all or most of the contraction geodetically observed onshore on the Cascade forearc will be accommodated offshore at the trench in the long term. In addition to this seismic cycle issue, significant permanent strain appears to have occurred in northern Cascadia, associated with Cascade forearc rotation/translation (McCaffrey et al., 2000; McCrory, 1996; Wells et al., 1998). Regardless of the time frame considered, the total strain around moving rigid blocks inside the plate boundary zone should integrate to zero net dilatation (Fig. 2C). However, this equivalence relies on the containment of the strain associated with Cascade forearc motion inside subregion *a*. If Cascade forearc migration does affect the strain in subregion *c*, then shortening in northern Washington may need to be considered while evaluating the dilatational strain rate budget in the BRP and northern California. The latter hypothesis would require more geodetic data in northern California and southern Oregon, and, if true, it would confirm some suggestions that shortening in Washington State may partly offset extension in the BRP (McCaffrey et al., 2000). That idea would then also be consistent with the fact that only part of the observed geodetic shortening in northern California is permanent, and would otherwise not necessarily undermine the "window of escape" hypothesis.

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