Diffuse Pacific–North American plate boundary: 1000 km of dextral shear inferred from modeling geodetic data

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ABSTRACT

Geodetic measurements tell us that the eastern part of the Basin and Range Province expands in an east-west direction relative to stable North America, whereas the western part of the province moves to the northwest. We develop three-dimensional finite element representations of the western United States lithosphere in an effort to understand the global positioning system (GPS) signal. The models are constrained by known bounding-block velocities and topography, and Basin and Range Province deformation is represented by simple plastic (thermal creep) rheology. We show that active Basin and Range spreading by gravity collapse is expected to have a strong southward component that does not match the GPS signal. We can reconcile the gravitational component of displacement with observed velocity vectors if the Pacific plate applies northwest-directed shear stress to the Basin and Range via the Sierra Nevada block. This effect reaches at least 1000 km east of the San Andreas fault in our models.

INTRODUCTION

The Basin and Range Province of the western United States is Earth's widest active extensional province found above sea level (e.g., Olsen, 1995). Stretching of this enigmatic tectonic province has invited explanations that include thickening and gravity collapse (e.g., Rey et al., 2001, and references therein), interaction with the westward component of Pacific plate motion (e.g., Atwater, 1970), Cascadia rollback (Humphreys and Coblentz, 2007; Kreemer and Hammond, 2007), or some combination of these processes (e.g., Flesch et al., 2000; Klein et al., 2009; Yang and Liu, 2010). These explanations include models of active and passive spreading with and without tractions applied to the base of the lithosphere, indications that the fundamental causes of Basin and Range extension remain mysterious. In this paper we employ simple numerical models to understand the forces causing current Basin and Range Province displacements, which we assume represent long-term tectonically driven motions (Fig. 1). Physics-based tectonic models produce results that are contingent on boundary conditions and the instructions given to them. Our goal is to minimize complexity, details, and parameter choices so that we can isolate the broadest influences on Basin and Range deformation.

We examine two hypothesized drivers: (1) the topographic collapse of the Basin and Range Province, and (2) the Pacific–North American plate boundary. As such, we want to diminish the influence of specific fault structures, cyclical interseismic/postseismic strain variation, and crustal and mantle structural-rheological variations. Our strategy is to focus on what we know, and assume that over the very long term, the crust and mantle can uniformly accommodate deformation as a continuum. We therefore shape a three-dimensional (3-D) finite element model according to observed topography, and enforce gravity as well as observed uniform displacements of the Sierra Nevada and Colorado Plateau blocks. We then treat the intervening Basin and Range Province crust and mantle as a plastic solid; it creeps, endures permanent deformation, and stores no long-term differential stress. It is thus an approximation of brittle faulting in the elastic layers and aseismic flow or creep beneath. Finally, we experiment with the proportions of gravitational and plate-motion drivers to assess their relative importance, as constrained by geodesy.

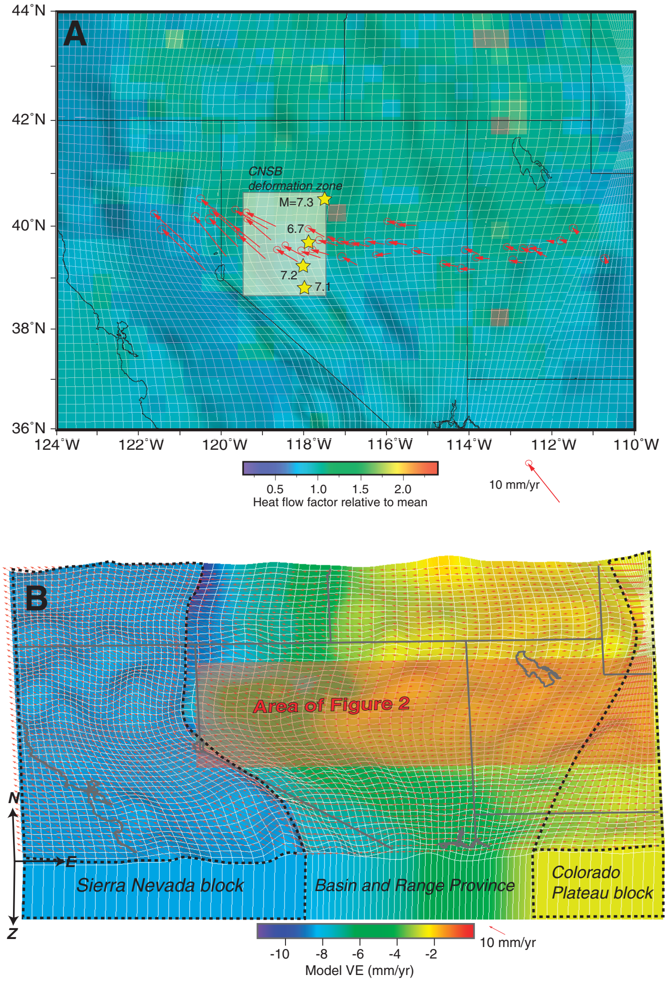

Figure 1. A: Study region and model boundaries showing global positioning system velocities along 39.5°N transect. Shading represents surface heat flow variations used in thermal creep approximation of long-term plastic deformation of Basin and Range Province. Boxed area shows Central Nevada seismic belt (CNSB) deformation zone, where twentieth century M ~ 7 earthquake occurred, and continues to influence geodetic signal. B: Finite element model, with smoothed topography and boundary conditions constraints, and example model velocity grid superposed. Arrows show east velocity (VE).

DATA

Here we use a present-day velocity field relative to stable North America derived from campaign and continuous global positioning system (GPS) data in the central Basin and Range Province analyzed by the U.S. Geological Survey (USGS). The campaign data from a 55 station, ~800 km aperture network were collected by the USGS during 1992–2002 and analyzed by Hammond and Thatcher (2004). Continuous GPS data from 82 stations of the Plate Boundary Observatory (PBO) established since 2005 in the central Basin and Range Province have been analyzed by the USGS. Details of processing are described, and time series and velocities are archived, at http://quake.usgs.gov/research/deformation/gps/auto/WesternBRPBO/.

The current velocity field in the central Basin and Range Province is perturbed by widespread, low-amplitude transient deformation due to aftereffects of several M ~ 7 twentieth century earthquakes in the Central Nevada seismic belt (CNSB; see epicenters in Fig. 1) (Hetland and Hager, 2003). To investigate the influence of these effects on our results, we have made first-order corrections to observed velocities using the modeling results of Hammond et al. (2009) following the methods of Pollitz (1997). Such corrections reach 2–3 mm/yr within ~100 km of the Central Nevada seismic belt, but are typically <1 mm/yr farther away. Nonuniqueness of the postseismic model introduces uncertainties in the corrections that are difficult to quantify precisely, including (1) uncertainty in layering of viscoelastic structure, (2) possible lateral heterogeneity, (3) and appropriateness of rheological models (W.C. Hammond, 2010, personal commun.), but the uncertainties may be as large as ~1 mm/yr. Although we have used these corrected velocities in our model-data comparisons, the perturbations are small and our major conclusions are not dependent on them.

MODELING

Our modeling strategy is intended to advance a simple, idealized representation of the lithosphere using the fewest parameters. We do not seek a realistic model of the lithosphere in close-up detail, but instead intend to represent the physics of long-term permanent deformation resulting from topographic loads and interaction with major tectonic blocks at the "view-from-space" scale. We concentrate on four constraints: (1) known motion of the contiguous Sierra Nevada block, which shows virtually no internal deformation (e.g., Dixon et al., 2000), (2) known motion of the Colorado Plateau block, which also has little current internal deformation (e.g., Bennett et al., 2003), (3) observed topography, and (4) measured heat flow variation. Knowledge of these boundary conditions coupled with geodetically observed internal strain of the Basin and Range are the inputs we use in an attempt to understand the broadest-scale components and causes of current deformation.

We generate a suite of 3-D finite element models of the western United States, all with smoothed topographic surfaces (50 × 50 km grid) (Fig. 1). The models all have two internal boundaries that demark the Basin and Range Province; a generalized boundary along the east edge of the Sierra Nevada block, which is taken from westernmost mapped normal faults in the Basin and Range (Barton et al., 2003), and similarly, a generalization of the Colorado Plateau and Wasatch Front boundaries along the eastern Basin and Range Province (Fig. 1). In the models, the Sierra Nevada move as a rigid block with uniform velocity of 13.8 mm/yr directed parallel to Pacific–North American relative plate motion (Dixon et al., 2000), and the Colorado Plateau is also treated as a rigid block moving 0.9 mm/yr at N51°W relative to fixed North America (Bennett et al., 2003). The model free surface has no displacements imposed on it. The model base is free to move laterally, but is restricted in the vertical direction. The northern and southern model boundaries of the Basin and Range Province are not free to move in the north-south direction in order to simulate confinement of the model by adjacent lithosphere. The other outer model boundaries move with the Sierra Nevada and Colorado Plateau block velocities. While the boundary areas have high topography like the Basin and Range Province, we do not model gravitational effects in the boundary blocks because they appear to move as rigid blocks (Dixon et al., 2000; Bennett et al., 2003).

We do not attempt to simulate faults in the Basin and Range Province; instead, we treat the province as a deforming plastic solid. This is equivalent to assuming that, over the long term, the fault network fully accommodates strain in the elastic crust and underlying layers deform by aseismic flow. This approach does not enable us to model detailed deformation such as behavior of individual faults or postseismic relaxation, but can accurately describe broad-scale effects on lithosphere subjected to external forces. For example, our simple model cannot replicate the localized GPS velocity gradients across either the Wasatch Front (~2.5 mm/yr) or the Central Nevada seismic belt (~1.5 mm/yr). We also neglect potential mantle drivers such as active upwelling, convection forces, or other imposed tractions. Such forces could readily be designed into a model to explain all western United States deformation, but are difficult to constrain or directly observe; our preference is to study effects of observed block motions and topography. We therefore set the model to an arbitrary uniform 100 km thickness, so that it is much greater than topographic variation, but otherwise has no impact on the results.

We want to allow the Basin and Range Province to respond to external forces as progressive deformation under constant loading. This is the definition of creep, and we thus simulate the province as a thermally creeping solid; this can be accomplished with a time-independent creep relation, $\dot{\varepsilon} = A\exp(-Q_c/RT)\sigma^n$ (e.g., Kirby and Kronenberg, 1987), where $A = 6.3 \times 10^{-2}$ MPa^{-n} s^{-1}, $Q_c = 276$ KJ/mol (activation energy), and n = 3.1 are experimentally derived constants, R is the universal gas constant, and T is temperature (parameters from Birch, 1966; Hansen and Carter, 1983; Christensen, 1996; Christensen and Mooney, 1995; Caristan, 1982; Carter and Tsenn, 1987). Viscosity is thus a function of stress, temperature, and material properties.

Combined uncertainty in physical parameters, layer geometries, and temperature can allow an all-encompassing spectrum of behavior. We therefore fix material constants and do not divide the lithosphere into compositional and rheological layers, but instead control deformation rate by varying only one parameter, an average base temperature. We opt to use material parameters of basalt; we could choose any rock because trading off material constants with temperature variation can produce the same rheological behavior. By trial and error we find the best fit to observed GPS velocities with base temperature, $T_b = 300$ °C. This is not a depiction of actual lithospheric temperature, but is instead an average value set to simulate plastic deformation of the entire lithosphere, which in actuality includes a cold elastic crust. The base temperature is further factored by surface heat flow variations that have a relative range from ~0.5 to ~1.5 between the coldest and warmest regions (Blackwell and Richards, 2004). This factor builds in regional strain rate variability and improves fits to geodetic velocity observations. This construct results in a model Basin and Range Province that focuses on the relative importance of applied tectonic forces and displacements on its rate and direction of deformation, while depending on only a single base-temperature parameter.

MODEL RESULTS

We want to understand geodetic observations from the Basin and Range Province, and thereby the underlying forces that cause them. We consider gravitational collapse and displacements caused by tectonic interactions. Consequently, we begin our analysis with models in which the Basin and Range Province was completely decoupled from adjacent terranes (Fig. 2).

Calculations that isolate the strain component of Basin and Range Province gravitational collapse (no imposed velocity boundary conditions on its edges) yield displacements that are directed southwest and southeast from the highest topography in the north-central part of the province (Fig. 2A). Of course the Basin and Range is not isolated from adjacent terranes, but the exercise is instructive because if active spreading were due to collapse, we would expect a southward component to the measured displacement field instead of the observed more northward trend. If Basin and Range Province collapse were strongly affecting motion of the Sierra Nevada block, our modeling suggests it would move southwest rather than northwest. We further note that a Sierra Nevada block that actively moves northwest, but that does not exert any stress onto the Basin and Range Province, leaves enough space behind it

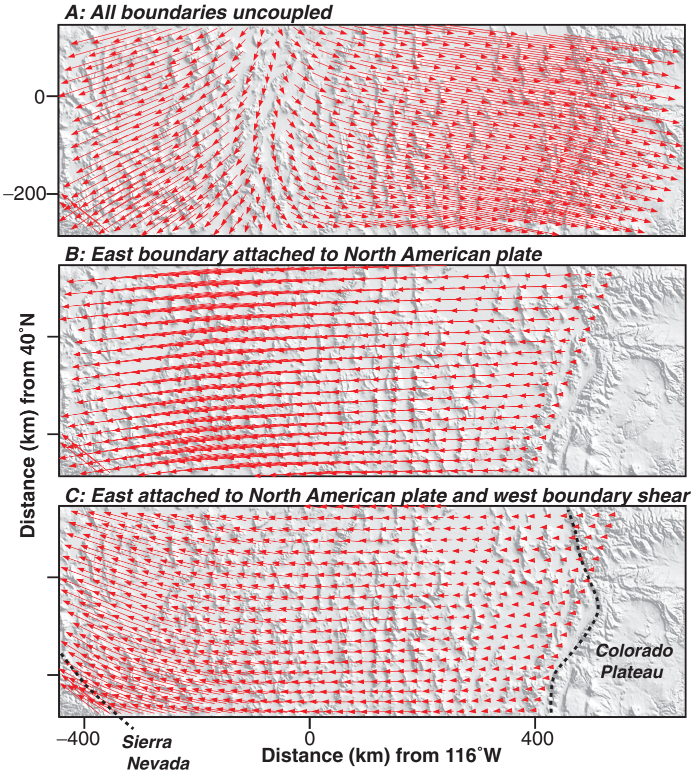

Figure 2. End-member velocity fields for different model boundary conditions; red arrows show displacement directions. Box boundaries are shown on larger model area in Figure 1. A: Basin and Range Province is allowed to collapse by gravity due to its topographic head. Without external forces acting, province would tend to spread outward from its center to lower lying regions southeast and southwest. B: Eastern Basin and Range is fixed to North American plate, leading to more uniform southwest displacement. C: Northwest Sierra Nevada block motion is imposed, which causes more east-west displacement in central Basin and Range that transitions into northwest-directed displacement along western part of province.

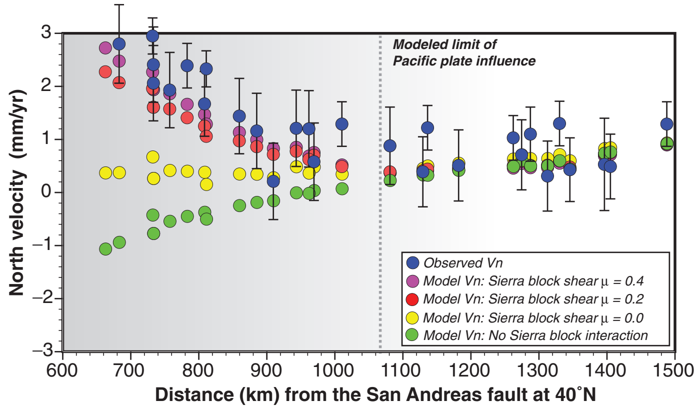

Figure 3. Observed and modeled velocities projected onto east-west profile along 39.5°N. North component velocities from variety of models are compared with observed that range from no interaction between Basin and Range Province and Sierra Nevada block to contact between provinces with increasing shear. Shear influence is expressed as friction coefficient along contact. North component of velocity (Vn) in Basin and Range Province cannot be explained by passive spreading due to gravitational collapse alone, but instead requires interaction with Sierra Nevada block. This implies that Pacific plate influences deformation at least 1000 km east of San Andreas fault. Dashed gray line shows eastward limit of Pacific plate influence inferred from our modeling.

that southwest displacement of the eastern Basin and Range still occurs (Fig. 2B).

In our modeling we thus find that, without some degree of interaction with the Sierra Nevada block, it is difficult to match the observed north component of the GPS signal, because the gravitational collapse of the Basin and Range is directed to the south (Fig. 3). We want to replicate progressive deformation under constant loading, so we simulate interaction between the Basin and Range and the Sierra Nevada block by treating their contact as a Coulomb surface with a friction coefficient. This applies a constant shear load that drives permanent deformation by creep. We find that the broad north component of the GPS signal could be reasonably matched with relatively low friction (friction coefficient $\mu = 0.2–0.4$) (Fig. 3). Use of the friction coefficient here can be interpreted as representing the continuity and efficiency of the fault network in transmitting shear stress into the Basin and Range. We require slightly higher friction than Humphreys and Coblentz (2007) and Klein et al. (2009), who estimated the shear coupling to be on the order of $\mu = 0.1–0.3$.

We note that for our models to explain the northward component in the GPS signal, the influence of the Sierra Nevada block shear boundary must reach to the central Basin and Range Province, ~500–600 km east of the block boundary (Fig. 3). If northwest motion of the Sierra Nevada block is driven by interaction with the Pacific plate (e.g., Flesch et al., 2000; Melbourne and Helmberger, 2001; Whitehouse et al., 2005), then plate boundary right-lateral motion extends at least 1000 km inland of the San Andreas fault (Fig. 3).

DISCUSSION AND CONCLUSIONS

Plate boundary right-lateral shear in the western Basin and Range Province is clearly observed. Gianella and Callaghan (1934) and Romney (1957) noted the seismological similarity between right-lateral slip components of large Nevada earthquakes and San Andreas events, and Nielsen (1965) recognized pervasive geological evidence for right-lateral faulting throughout the Walker Lane region of western Nevada. We estimated the eastward extent of plate boundary influence by using the lack of internal deformation in the Colorado Plateau (e.g., Bennett et al., 2003) and the Sierra Nevada (e.g., Dixon et al., 2000) to define appropriate boundary conditions at the margins of the province, including the effect of buoyant topography, and examining the internal deformation of the Basin and Range Province in more detail than has been attempted previously.

Our models lack any mantle-driven deformation (e.g., Sonder and Jones, 1999) because such processes are not necessary to explain present-day crustal velocities, and their addition would add considerable model complexity. However, we make implicit assumptions about the role of the mantle in our modeling because we assume that the high topography has upper mantle support (e.g., Lachenbruch and Morgan, 1990; Jones et al., 1998). Further, there are indications of a mantle lithosphere role in connecting the Pacific plate to the Sierra Nevada block (e.g., Melbourne and Helmberger, 2001) that may explain their similar motion directions (e.g., Whitehouse et al., 2005).

In conclusion, we find that the only way we can reproduce northward-oriented velocity vectors in the western Basin and Range Province, and the almost completely east-west–directed velocities deeper into the province, is to apply right-lateral shear along the western edge of the Sierra Nevada block. This is because Basin and Range spreading caused by collapse of the high plateau is directed generally southward, away from highest elevations. With this simple two-component model of the western United States lithosphere, we can fit the general trends of the west and north velocity components of the observed GPS velocity field (Fig. 4).

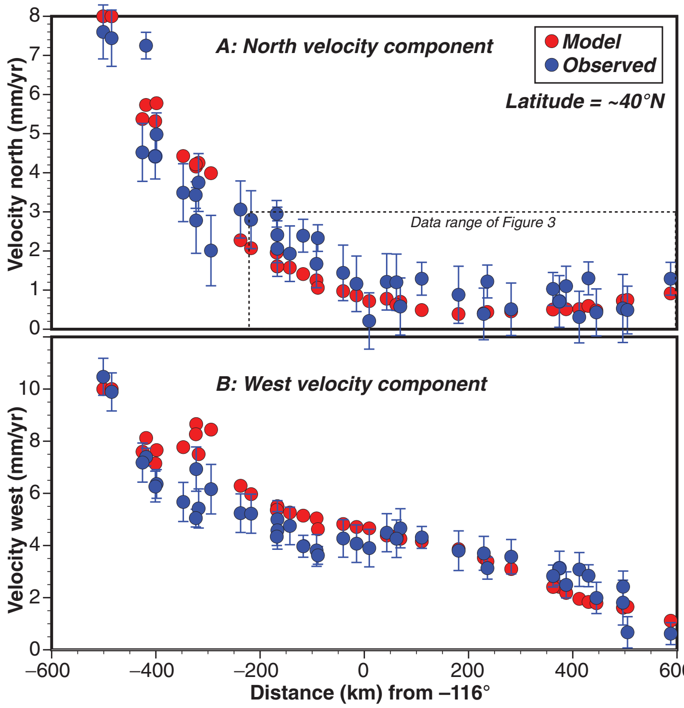

Figure 4. Observed and modeled velocities projected onto east-west profile along 39.5°N. A: North component fits. B: West-directed velocities. Observed velocities are plotted in blue with error bar uncertainties. Model velocities from nearest nodes are shown in red. Most points are fit within 1σ uncertainties, but some local variations would require more detailed submodels to explain.

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REFERENCES CITED

Atwater, T.M., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of North America: Geological Society of America Bulletin, v. 81, p. 3513–3536, doi:10.1130/0016-7606(1970)81[3513:IOPTFT]2.0.CO;2.

Barton, K.E., Howell, D.G., and Vigil, J.F., 2003, The North America tapestry of time and terrain: U.S. Geological Survey Geologic Investigations Series I-2781, scale 1:8,000,000.

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, 1008, doi:10.1029/2001TC001355.

Birch, F., 1966, Compressibility; elastic constants, *in* Clark, S.P., Jr., ed., Handbook of physical constants: Geological Society of America Memoir 97, p. 97–173.

Blackwell, D.D., and Richards, M., 2004, Geothermal map of North America: Tulsa, Oklahoma, American Association of Petroleum Geologists, scale 1:6,500,000.

Caristan, Y., 1982, The transition from high temperature creep to fracture in Maryland diabase: Journal of Geophysical Research, v. 87, p. 6781–6790, doi:10.1029/JB087iB08p06781.

Carter, N.L., and Tsenn, M.C., 1987, Flow properties of the lithosphere: Tectonophysics, v. 136, p. 27–63, doi:10.1016/0040-1951(87)90333-7.

Christensen, N.I., 1996, Poisson's ration and crustal seismology: Journal of Geophysical Research, v. 101, p. 3139–3156, doi:10.1029/95JB03446.

Christensen, N.I., and Mooney, W.D., 1995, Seismic velocity structure and composition of the continental crust: A global view: Journal of Geophysical Research, v. 100, no. B6, p. 9761–9788, doi:10.1029/95JB00259.

Dixon, T.H., Miller, M., Farina, F., Wang, H., and Johnson, D., 2000, Present-day motion of the Sierra Nevada block and some tectonic implications for the Basin and Range province, North American Cordillera: Tectonics, v. 19, p. 1–24, doi:10.1029/1998TC001088.

Flesch, L.M., Holt, W.E., Haines, A.J., and Shen-Tu, B., 2000, Dynamics of the Pacific–North American plate boundary in the western United States: Science, v. 287, p. 834–836, doi:10.1126/science.287.5454.834.

Gianella, V.P., and Callaghan, E., 1934, Cedar Mountain, Nevada, earthquake of December 20, 1932: Seismological Society of America Bulletin, v. 24, p. 345–377.

Hammond, W.C., and Thatcher, W., 2004, Contemporary tectonic deformation of the Basin and Range province, western United States: 10 years of observation with the global positioning system: Journal of Geophysical Research, v. 109, B08403, doi:10.1029/2003JB002746.

Hammond, W.C., Kreemer, C., and Blewitt, G., 2009, Geodetic constraints on contemporary deformation in the northern Walker Lane: 3. Central Nevada seismic belt postseismic relaxation, *in* Oldow, J.S., and Cashman, P.H., eds., Late Cenozoic structure and evolution of the Great Basin–Sierra Nevada transition: Geological Society of America Special Paper 447, p. 33–54, doi:10.1130/2009.2447(03).

Hansen, F.D., and Carter, N.L., 1983, Semibrittle creep of dry and wet Westerly granite at 1000 MPa: Proceedings, U.S. Symposium on Rock Mechanics, 24th: Denver, Colorado, Association of Engineering Geologists, p. 429–447.

Hetland, E.A., and Hager, B.H., 2003, Postseismic relaxation across the Central Nevada Seismic Belt: Journal of Geophysical Research, v. 108, 2394, doi:10.1029/2002JB002257.

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

Jones, C.H., Sonder, L.J., and Unruh, J.R., 1998, Lithospheric gravitational potential energy and past orogenesis: Implications for conditions of initial Basin and Range and Laramide deformation: Geology, v. 26, p. 639–642, doi:10.1130/0091-7613(1998)026<0639:LGPEAP>2.3.CO;2.

Kirby, S.H., and Kronenberg, A.K., 1987, Rheology of the lithosphere: Selected topics: Reviews of Geophysics, v. 25, p. 1219–1244, doi:10.1029/RG025i006p01219.

Klein, E.C., Flesch, L.M., Holt, W.E., and Haines, A.J., 2009, Evidence of long-term weakness on seismogenic faults in western North America from dynamic modeling: Journal of Geophysical Research, v. 114, B03402, doi:10.1029/2007JB005201.

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. 943–947, doi:10.1130/G23868A.1.

Lachenbruch, A.H., and Morgan, P., 1990, Continental extension, magmatism and elevation; formal relations and rules of thumb: Tectonophysics, v. 174, p. 39–62, doi:10.1016/0040-1951(90)90383-J.

Melbourne, T., and Helmberger, D., 2001, Mantle control of plate boundary deformation: Geophysical Research Letters, v. 28, p. 4003–4006, doi:10.1029/2001GL013167.

Nielsen, R.L., 1965, Right-lateral strike-slip faulting in the Walker Lane, west-central Nevada: Geological Society of America Bulletin, v. 76, p. 1301–1308, doi:10.1130/0016-7606(1965)76[1301:RSFITW]2.0.CO;2.

Olsen, K.H., 1995, Continental rifts: Evolution, structure, tectonics: Amsterdam, Elsevier, 466 p.

Pollitz, F.F., 1997, Gravitational viscoelastic postseismic relaxation on a layered spherical Earth: Journal of Geophysical Research, v. 102, p. 17921–17941, doi:10.1029/97JB01277.

Rey, P., Vanderhaeghe, O., and Teyssier, C., 2001, Gravitational collapse of the continental crust: Definitions, regimes and modes: Tectonophysics, v. 342, p. 435–449, doi:10.1016/S0040-1951(01)00174-3.

Romney, C., 1957, Seismic waves from the Dixie Valley–Fairview Peak earthquakes: Seismological Society of America Bulletin, v. 47, p. 301–319.

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. 417–462, doi:10.1146/annurev.earth.27.1.417.

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, doi:10.1016/j.epsl.2005.03.028.

Yang, Y., and Liu, M., 2010, What drives short- and long-term deformation in the southwestern United States?: Geophysical Research Letters, v. 37, L04306, doi:10.1029/2009GL041598.

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