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Subcontinental-scale crustal velocity changes along the Pacific–North America plate boundary

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Transient tectonic deformation has long been noted within ∼100 km of plate boundary fault zones and within active volcanic regions, but it is unknown whether transient motions also occur at larger scales within plates. Relatively localized transients are known to occur as both seismic and episodic aseismic events[1], and are generally ascribed to motions of magma bodies, aseismic creep on faults, or elastic or viscoelastic effects associated with earthquakes. However, triggering phenomena[2,3] and systematic patterns of seismic strain release at subcontinental (∼1,000 km) scale along diffuse plate boundaries[4,5] have long suggested that energy transfer occurs at larger scale. Such transfer appears to occur by the interaction of stresses induced by surface wave propagation and magma or groundwater in the crust[6], or from large-scale stress diffusion within the oceanic mantle in the decades following clusters of great earthquakes[7]. Here we report geodetic evidence for a coherent, subcontinental-scale change in tectonic velocity along a diffuse ∼1,000-km-wide deformation zone. Our observations are derived from continuous GPS (Global Positioning System) data collected over the past decade across the Basin and Range province, which absorbs approximately 25 per cent of Pacific–North America relative plate motion. The observed changes in site velocity define a sharp boundary near the centre of the province oriented roughly parallel to the north-northwest relative plate motion vector. We show that sites to the west of this boundary slowed relative to sites east of it by ∼1 mm yr^{-1} starting in late 1999.

The Basin and Range Geodetic Network (BARGEN) is the first 1,000-km-aperture continuous GPS network to be deployed across a diffuse actively deforming plate boundary zone. Eighteen sites, comprising an east–west transect between latitudes 39° N and 41° N (Fig. 1), began recording in 1996–7. The time series are now long enough to obtain statistically reliable estimates of any changes in velocity that might occur on a regional scale. Dual-frequency GPS phase data from 1996.5–2005.7 were first analysed using the GAMIT/GLOBK GPS processing software, resulting in estimated average velocities and time series in a North American reference frame, as described in the Methods section. The average horizontal velocities of the sites (Fig. 1a) rise from near zero in the east to ∼3 mm yr^{-1} due west across western Utah, remain relatively constant across eastern Nevada, and then rotate northwestward and progressively increase up to ∼12 mm yr^{-1} in the Sierra Nevada.

Analysis of the position time series involves fitting for, and removal

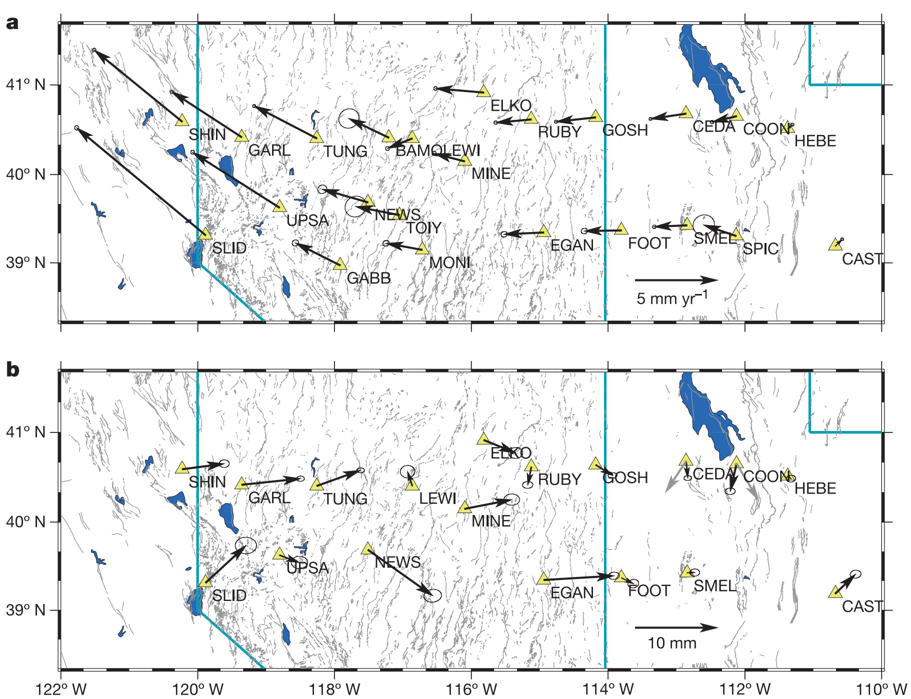

Figure 1 | Sites of the northern BARGEN GPS network. a, Positions (triangles) and average horizontal velocities (arrows). Error ellipses are 95% confidence (formal). Sites TOIY, BAMO, SPIC, GABB and MONI are shown, but their time series are too short to enable reliable determinations of velocity changes. Solid blue lines indicate US state boundaries. **b**, Deviations from linear motion, defined as the difference between the average position for the last year and the position predicted from a linear fit through the first 2.5 years of acquisition. Error ellipses are 95% confidence based on formal uncertainties scaled by the weighted root-mean-square residual to the linear fit and assuming the same north-east correlation as for the velocity estimates. The grey arrows for CEDA and COON represent a prediction based on a model for Great Salt Lake loading[8].

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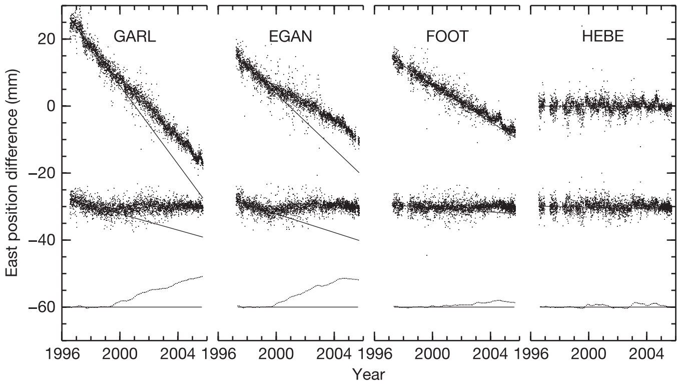

Figure 2 | Illustration of the post-analysis procedure, using time series of east position for four BARGEN sites. Top, 'raw' time series, in a North America-fixed geodetic reference frame (see Methods). Error bars are omitted for clarity, but are generally ~1 mm. The straight line is the best-fit straight line using position estimates from the first 2.5 years. Middle, residuals of the raw time series from a best-fit model consisting of a straight line and seasonal (annual and semi-annual sinusoids) terms. A statistical approach that allowed these terms to change with time in a constrained manner was used (see Methods). Bottom, residuals smoothed with a gaussian filter with a full-width at half-maximum (FWHM) of ~8 months. A model based on a linear fit to the first 2.5 years of data has been removed. The evolution of these final time series thus indicates deviation from temporally linear motion.

of, annual variations (see Methods) and smoothing, as illustrated in Fig. 2. Using smoothed horizontal position time series, we then calculate the deviation of position from temporally linear motion based on data acquired in the first 2.5 years (hereafter referred to as 'position deviations'). This analysis indicates that the velocities in this region have not been constant. Relative to their initial trajectories the western sites have slowed, resulting in a significant eastward position deviation (Fig. 1b). These velocity changes define two coherent domains, with an abrupt north-northwest-trending boundary in eastern Nevada (Fig. 1b). Sites west of the boundary deviate from the predicted linear motion by up to 10 mm, whereas those in easternmost Nevada and Utah have small deviations. Sites CEDA and COON, located near Great Salt Lake, exhibit large deviations due primarily to changes in lake level[8] and possibly to hydrological loading. The estimated deviation for site SLID includes rapid deformation from 2003–4, interpreted to be the result of magma injection into the lowermost crust beneath Lake Tahoe[9]. Observed changes in velocity for the western sites are ~5–10% of the respective average values.

The velocity changes are small, but they are evident in the position-deviation time series. Nearly all sites west-southwest of a boundary drawn between sites RUBY and ELKO to the north and sites FOOT and EGAN to the south have significant position deviations (Fig. 3a). With the exception of SLID, the onset of the deviation (that is, the velocity change) occurs between 1999.5 and 2001.0. The abruptness of the boundary in eastern Nevada is demonstrated by the fact that the relative position deviations across the boundary calculated by differencing sites adjacent to it are about the same as those derived by differencing sites at opposite ends of the network (Fig. 3b). If average position deviations for the western and eastern parts of the network are calculated by 'stacking' all of the position-deviation plots (Fig. 3c), the average position deviation for the west at the beginning of 2005 is ~5 mm, whereas that for the east is <1 mm.

We can test this interpretation further by fitting the east components with a model consisting of two straight lines, one before 1 January 2000 and one after it. Significant nonlinearity is indicated

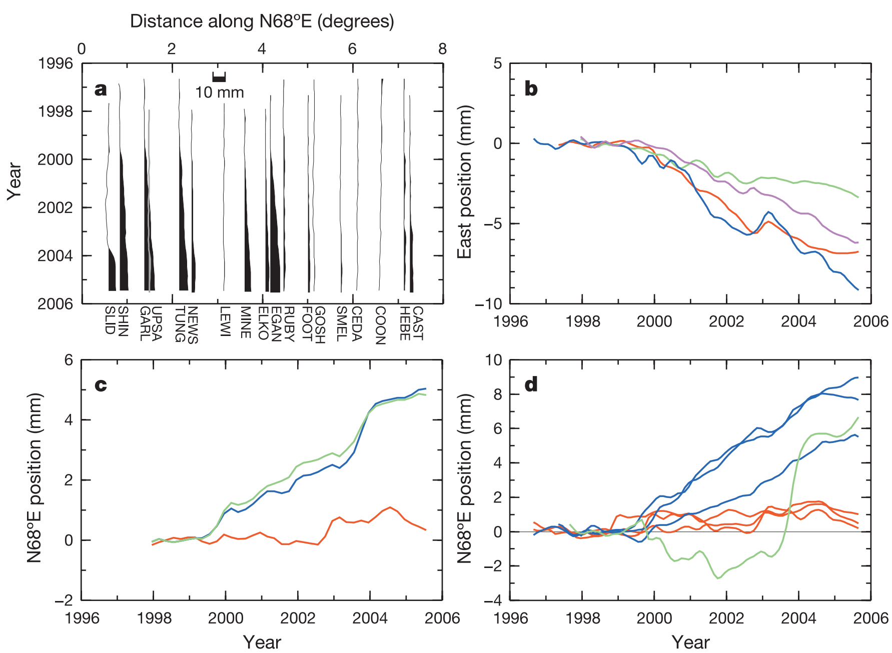

Figure 3 | Analysis of spatial variation of nonlinear deviations. a, Smoothed time series of position deviations from linear motion (see Fig. 2) in the direction N68°E, projected along a great circle with azimuth N68°E near the centre of the network. Where these deviations are positive, the space between the trace and zero has been shaded black (or grey, for site UPSA, whose line lies atop that for GARL). The significant deviations occur in the western part of the network. **b**, East components of intersite vectors for EGAN–FOOT (red), ELKO–GOSH (green), GARL–HEBE (blue) and MINE-SMEL (purple). GARL–HEBE, which spans the entire network east–west, and EGAN–FOOT, which spans a short distance in the centre of the network (Fig. 1), show nearly identical deviations, indicating an abrupt boundary for velocity changes in eastern Nevada. **c**, Regionally averaged nonlinear deviations of N68°E position. Red, eastern BARGEN (HEBE, FOOT, COON, CAST, CEDA, SMEL, GOSH and RUBY). Green, central/western BARGEN (MINE, TUNG, ELKO, EGAN, LEWI, NEWS, GARL, UPSA and SHIN). Blue, same as green plus SLID. Only data from a common epoch range (1997.86–2005.18) were used. The figure demonstrates that the velocity change has moved the western part of the network, on average, 3–4 mm eastward or northeastward compared to the eastern part of the network. **d**, N68°E position time series for three groups of sites. Red, eastern sites RUBY, FOOT and HEBE. Blue, western sites EGAN, MINE and GARL. Green, site SLID.

if the F-statistic[10] exceeds a limit. All sites except CEDA, COON, FOOT, HEBE and LEWI pass this test for nonlinearity with 99.9% confidence. However, this test is sensitive to the degrees of freedom in the solution, which can be fewer than the assumed value if the noise in the data is temporally correlated. If we assume a correlation time of ~1 week, then sites CAST, ELKO, GOSH, SMEL and UPSA also fail the nonlinearity test. This larger list of 'linear' sites includes all those east of the RUBY–FOOT–ELKO line. Among sites west of this line, only UPSA and LEWI fail the F-test for nonlinearity.

There may be non-tectonic contributions to the observed deviations. Shortcomings in models used to analyse the GPS data could induce correlated systematic errors in the position estimates. The most obvious candidates are probably insignificant compared to the observed effects. Simulations of satellite antenna phase-offset and phase-pattern[11] effects indicate that in this region these errors are ≤0.2 mm. Second-order ionospheric effects may be at the millimetre level. This error depends on magnetic latitude[12], which varies by only ~2° over this network, and is therefore very nearly homogeneous for the network. Reference-frame errors can also be significant, but it is unlikely that they would yield significant intra-network deformations for a network of this size.

Another possibility is that the deviations are real but do not reflect a tectonic process. For example, the crust deforms owing to hydrological and atmospheric pressure loading and movement of the local soil. However, local effects are inconsistent with the coherence of the patterns, and numerical predictions of regional pressure loading yield deviations one order of magnitude smaller than those observed.

Site velocities in central Nevada may reflect postseismic deformation of strong (magnitude $M > 6.5$) twentieth-century earthquakes (Pleasant Valley, 1915; Dixie Valley, 1954; Fairview Peak, 1954). Investigators have used GPS[13,14] and InSAR[15] to determine models for viscoelastic relaxation of the crust and upper mantle. During the short time period of this study relative to reasonable viscoelastic relaxation times, viscoelastic relaxation will not affect the position deviations.

Supporting evidence for a tectonic origin, which may also provide a clue to its depth of generation in the lithosphere, comes from the apparent lower crustal source of SLID's previously reported[9] rapid transient in late 2003. Unlike the other Nevada sites, SLID (although noisier) did not systematically accelerate eastward through most of the observation period, being 'left behind' by the accelerating sites. Then, by virtue of the transient, it 'caught up' with the eastward deviations of the other sites (Fig. 3d). We speculate that an episodically creeping detachment horizon ~500 km wide at or near the base of the crust may provide a general explanation for the velocity changes. In one scenario, the mantle would either translate or stretch smoothly below the horizon, imparting a westward component of shear traction on the base of the crust (before 1997 to about 2000). Top-to-the-east plastic yielding along the horizon translates the crust eastward *en bloc*, as internal stretching and shear of the crust continues. Yielding thus relaxes stress on the eastern margin of the accelerating domain (where baselines ELKO–GOSH and EGAN–FOOT were contracting at ~0.5 mm yr^{-1} and 1 mm yr^{-1}, respectively), and focuses strain accumulation (2000–3), and subsequently strain release (2003–4) along the western margin of the domain.

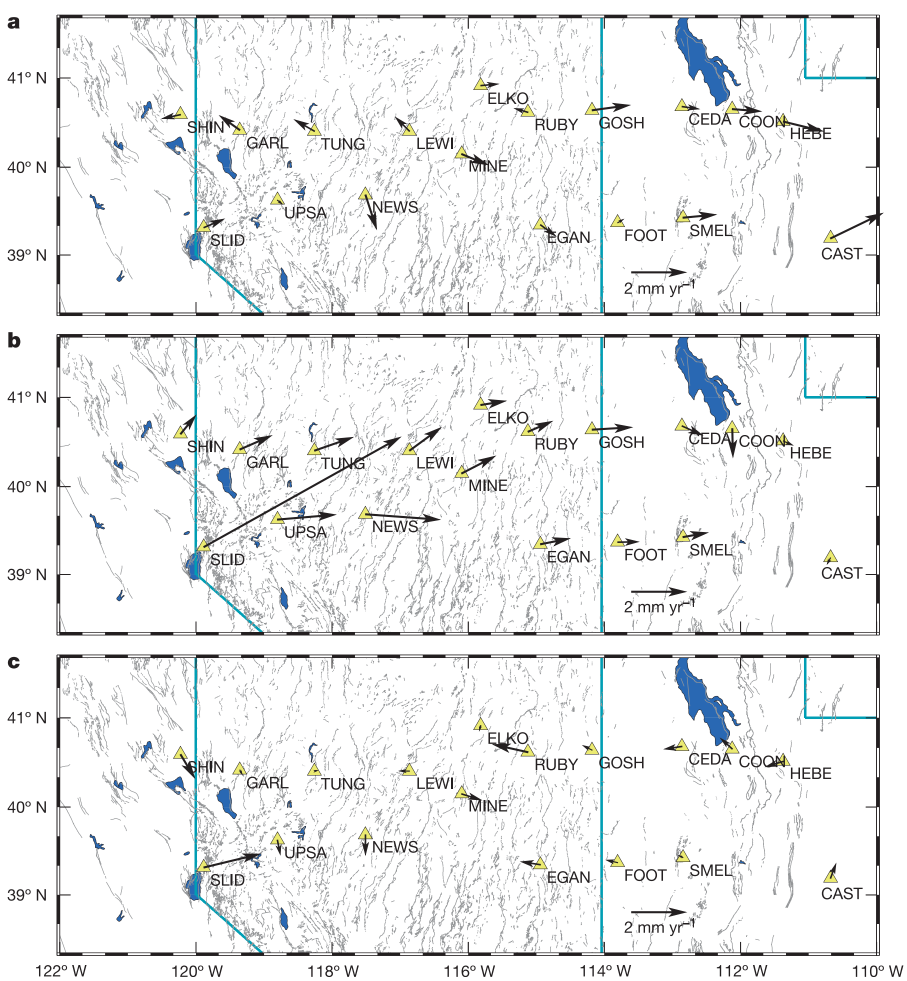

Figure 4 | Differences of horizontal velocity for one-year periods relative to the average velocities for the period 1997.0–2002.0. a, Differences for the calendar year 2002. **b**, 2003. **c**, 2004. 1σ errors for each component are ~0.4 mm yr^{-1}.

Several independent lines of evidence support a contrast in lithospheric properties between the western and eastern parts of the network. On the basis of S-wave tomography and petrologic data, Dixon *et al.*[16] have proposed that the upper mantle beneath the western part of the network contains a higher concentration of partial melt. An active decoupling zone at the base of the crust under the Nevada Basin and Range, accompanied by magmatic injection, has long been suspected on the basis of nearly continuous, bright seismic reflections along the Moho[17–19]. Like the GPS velocity change, these reflections also die out near the Nevada–Utah border, suggesting that the reflection Moho may be an active, coherent structure that episodically yields, thereby transferring strain energy hundreds of kilometres across the province.

Within the overall pattern of velocity changes that begin in about 1999.5, spatially coherent velocity changes associated with the onset of the anomalous SLID motion can be observed. Figure 4 shows the site velocity differences averaged over one-year intervals relative to the average velocities for 1997.0–2002.0 for one-year slices of the time series. The relative velocities for the year 2002.0–2003.0 (that is, calendar year 2002; Fig. 4a) are mostly $<1\ \mathrm{mm\,yr^{-1}}$ and exhibit little regional coherence, except for an eastward trend for GOSH, SMEL and sites eastward. During 2003 (Fig. 4b), most of the anomalous SLID motion occurred, resulting in an apparent northeast velocity change of $\sim 9\ \mathrm{mm\,yr^{-1}}$. During this year, most of the sites exhibited a smaller, easterly or northeasterly velocity change, the amplitude of which decreases to the east (Fig. 4a; see also Fig. 3c). During 2004 (Fig. 4c), all the sites returned to within $\sim 1\ \mathrm{mm\,yr^{-1}}$ of their average 1997–2002 average velocities, except for SLID, which exhibited a small amount of residual motion associated with the 2003 event. For the eastern sites, a coherent westward increase in velocity of $\sim 1\ \mathrm{mm\,yr^{-1}}$, relative to that of 2003, is observed. (This increase is clearly reflected in the averaged time series of Fig. 3c.) These motions are further evidence for large-scale strain transfer, with anomalous motions occurring first in the east and later propagating west on a timescale of ~ 1 year.

METHODS

Geodetic solutions for position and velocity were generated using the GAMIT/GLOBK software package, following methods previously detailed[20]. Briefly, the dual-frequency GPS phase data were analysed on a daily basis using GAMIT. Data from some non-BARGEN GPS sites were included for frame determination. The resulting site-position parameters were combined using the Kalman-filter-based GLOBK software to provide estimates of (average) velocity vectors. We also incorporated into our solution data products from other continuous GPS networks, including the International GNSS Service (IGS) and Bay Area Regional Deformation (BARD) networks, obtained from the Scripps Orbit and Permanent Array Center (SOPAC). Minimization of velocity parameters for sites on 'stable' North America provided an approximation to a North America-fixed reference frame.

Time series were generated using the GLRED software, which minimized site position deviations on a day-by-day basis in a realization of the North America reference frame. In analysing time series of horizontal position estimates, we used a statistical approach that allowed for estimation of nuisance parameters (mainly seasonal variations) when arbitrary changes in velocity occur over the length of the time series. We first removed all apparent 'jumps' that occur owing to changes in antennas and radomes. (Only three such jumps are required for all the data presented here.) We used a technique that 'sutures' the time series together using data only from the time around the jump (± 1 month), thereby minimizing the effect of possible mismodelling of the temporal behaviour of the time series.

We then modelled the time series over one-year segments using parameters that make up the two components of the model: linear terms plus seasonal terms. The seasonal component consists of annual and semi-annual sinusoids with amplitude (sine and cosine terms) parameters. The two components of the model (linear and seasonal) were individually constrained to be piecewise continuous at the segment boundaries. The first time derivative of the seasonal component at the segment boundaries was likewise constrained. Typical formal uncertainties are $\sim 0.3\ \mathrm{mm\,yr^{-1}}$ for the rates, and ~ 0.1 mm for the seasonal amplitudes. For each site, the north and east components of position were analysed independently. We did not apply spatial filtering[21], as this technique removes spatially correlated nonlinear signals.

This approach provides two useful products that can be used for further analysis. We obtain clean time series of site position that have the (variable) seasonal terms removed. We also obtain time series of site velocities that can be used to investigate the spatial coherence of velocity changes. These time series have been derived with no assumptions regarding the spatial variations of site position changes.

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1. Rogers, G. & Dragert, H. Episodic tremor and slip on the Cascadia Subduction Zone: The chatter of silent slip. *Science* **300,** 1942–1943 (2003).
2. Hill, D. P. *et al.* Seismicity remotely triggered by the M 7.3 Landers, California, earthquake. *Science* **260,** 1617–1623 (1993).
3. Prejean, S. G. *et al.* Remotely triggered seismicity on the United States west coast following the M_w 7.9 Denali Fault earthquake. *Bull. Seimol. Soc. Am.* **94,** S348–S359 (2004).
4. Press, F. & Allen, C. Patterns of seismic release in the Southern California region. *J. Geophys. Res.* **100,** 6421–6430 (1995).
5. Le Pichon, X., Chamot-Rooke, N., Rangin, C. & Sengör, A. M. C. The North Anatolian fault in the Sea of Marmara. *J. Geophys. Res.* **108,** 2179, doi:10.1029/2002JB001862 (2003).
6. Brodsky, E. E., Roeloffs, E., Woodcock, D., Gall, I. & Manga, M. A mechanism for sustained groundwater pressure changes induced by distant earthquakes. *J. Geophys. Res.* **108,** 2390, doi:10.1029/2002JB002321 (2003).
7. Pollitz, F. F., Bürgmann, R. & Romanowicz, B. Viscosity of oceanic asthenosphere inferred from remote triggering from earthquakes. *Science* **280,** 1245–1249 (1998).
8. Elósegui, P., Davis, J. L., Mitrovica, J. X., Bennett, R. A. & Wernicke, B. P. Measurement of crustal loading using GPS near Great Salt Lake, Utah. *Geophys. Res. Lett.* **30,** 1111–1114 (2003).
9. Smith, K. D. *et al.* Evidence for deep magma injection beneath Lake Tahoe, Nevada-California. *Science* **305,** 1277–1280 (2004).
10. Bevington, P. R. & Robinson, D. K. *Data Reduction and Error Analysis for the Physical Sciences* 3rd edn (McGraw-Hill, Boston, 2003).
11. Ge, M., Gendt, G., Dick, G., Zhang, F. P. & Reigber, C. Impact of GPS satellite antenna offsets on scale changes in global network solutions. *Geophys. Res. Lett.* **32,** L06310, doi:10.1029/2004GL022224 (2005).
12. Kedar, S., Hajj, G. A., Wilson, B. D. & Heflin, M. B. The effect of the second order GPS ionospheric correction on receiver positions. *Geophys. Res. Lett.* **30,** 1829, doi:10.1029/2003GL017639 (2003).
13. Wernicke, B., Friedrich, A. M., Niemi, N. A., Bennett, R. A. & Davis, J. L. Dynamics of plate boundary fault systems from Basin and Range Geodetic Network (BARGEN) and geologic data. *GSA Today* **10,** 1–7 (2000).
14. Hetland, E. A. & Hager, B. H. Postseismic relaxation across the Central Nevada Seismic Belt. *J. Geophys. Res.* **108,** 2394, doi:10.1029/2002JB002257 (2003).
15. Gourmelen, N. & Amelung, F. Postseismic mantle relaxation in the Central Nevada Seismic Belt. *Science* **310,** 1473–1476 (2005).
16. Dixon, J. E., Dixon, T. H., Bell, D. R. & Malservisi, R. Lateral variation in upper mantle viscosity: role of water. *Earth Planet. Sci. Lett.* **222,** 451–467 (2004).
17. Hauser, E. *et al.* Crustal structure of eastern Nevada from COCORP deep seismic-reflection data. *Geol. Soc. Am. Bull.* **99,** 833–844 (1987).
18. Allmendinger, R. W. *et al.* Overview of the COCORP 40°N transect, western United States: The fabric of an orogenic belt. *Geol. Soc. Am. Bull.* **98,** 308–319 (1987).
19. Jarchow, C. M., Thompson, G. A., Catchings, R. D. & Mooney, W. D. Seismic evidence for active magmatic underplating beneath the Basin and Range Province, western United States. *J. Geophys. Res.* **98,** 22095–22108 (1993).
20. Bennett, R. A., Davis, J. L., Normandeau, J. E. & Wernicke, B. P. in *Plate Boundary Zones* (eds Stein, S. A. & Freymuller, J. T.) 27–55 (AGU Geodyn. Ser. 30, Washington DC, 2002).
21. Wdowinski, S., Bock, Y., Zhang, J., Fang, P. & Genrich, J. Southern California permanent GPS geodetic array: Spatial filtering of daily positions for estimating coseismic and postseismic displacements induced by the 1992 Landers earthquake. *J. Geophys. Res.* **102,** 18057–18070 (1997).

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