nature geoscience

ARTICLES

PUBLISHED ONLINE: 24 MAY 2009 | DOI: 10.1038/NGEO526

Vertical mantle flow associated with a lithospheric drip beneath the Great Basin

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Rapid surface uplift or subsidence and voluminous magmatic activity have often been ascribed to regional-scale downwelling of lithospheric mantle. However, because lithospheric drips—sinking plumes of cold and dense lithosphere—are relatively small and transient features, direct evidence of their existence has been difficult to obtain. Moreover, the significant vertical mantle flow that should be associated with such structures has not been detected. Here we integrate seismic anisotropy data with tomographic images to identify and describe a lithospheric drip beneath the Great Basin region of the western United States. The feature is characterized by a localized cylindrical core of cooler material with fast seismic velocities and mantle flow that rapidly shifts from horizontal to vertical. Our numerical experiments suggest that the drip can be generated by gravitational instability resulting from a density anomaly of as little as 1% and a localized temperature increase of 10%. The drip tilts to the northeast—opposite to the motion of the North American plate in the hotspot reference frame—and thereby indicates northeast-directed regional mantle flow.

Lithospheric downwellings in the form of drips (Rayleigh–Taylor instabilities) or delamination (mechanical removal of lithosphere)[1] are often invoked but have been rarely directly detected in the mantle. Substantial previous work examining the generation of lithospheric drips and delamination has focused on regions where removal of eclogitic roots may result in surface uplift[2–4], areas where an upwelling mantle plume head impacts and heats the base of the lithosphere[5], and margins of active rift zones[6]. In many cases, numerical modelling of these processes predicts massive volcanism due to the downwelling lithosphere and associated upwelling on the drip margins. However, drips in regions of young, thin lithosphere have generally not been considered, although such regions may be intrinsically gravitationally unstable[7]. Lithospheric drips in tectonic settings such as the Great Basin of the western United States may not provide overt surficial clues such as detectable elevation changes over time or significant volcanism[8], and therefore require geophysical means to probe for their existence.

The Great Basin province of western North America is a well-known region of widespread extension and magmatism. Its recent geologic history includes several major episodes of magmatism from ∼80 to ∼20 Myr ago, including the 'ignimbrite flareup' between 31 and 20 Myr ago[9,10]. Since 20 Myr ago, very limited volcanism has occurred across the whole of the Great Basin with the exception of Lunar Crater, a small (∼10 km by ∼40 km) monogenetic volcanic field with eruption ages of 4.2 Myr and younger[11]. Crustal extension across the Great Basin initiated at ∼45 Myr ago and has been generally in an east–west direction, continuing to the present at 10–15 mm yr^{-1} (refs 12, 13). At present, the Great Basin is characterized by high (1,500–1,700 m) average elevation, high (∼100 mW m^{-2}) average heat flow[14], moderate (∼35 km) average crustal thickness[15] and thin (60–75 km) lithosphere[16].

One of the more perplexing seismic observations of the Great Basin has been the apparent absence of a mantle fabric[17,18] consistent with lateral asthenospheric flow. As a result, a range of mantle flow models have been proposed for the region, including vertical upgoing flow from a mantle plume[17] and toroidal flow generated by the retreating Juan de Fuca slab[19]. Here, we present

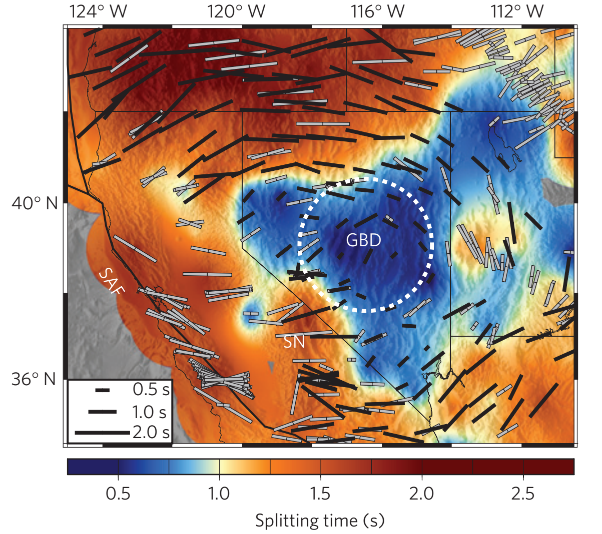

Figure 1 | Shear-wave splitting results for the Great Basin and surrounding provinces. The black bars are splitting results for 139 seismic stations across the region (see Supplementary Tables S1 and S2); the grey bars are results from other previously published studies[17,18,40–50] (see Supplementary Methods for the complete list). The bar orientation denotes the fast polarization direction; the bar length is proportional to the splitting time. The background is the regionally contoured splitting time demonstrating a pronounced zone of small splitting times (blue areas) for the central Great Basin region surrounded by large splitting times in most other regions (red/orange regions). SAF: San Andreas fault, SN: Sierra Nevada. The circle labelled GBD denotes the area underlain by the Great Basin drip (Fig. 2).

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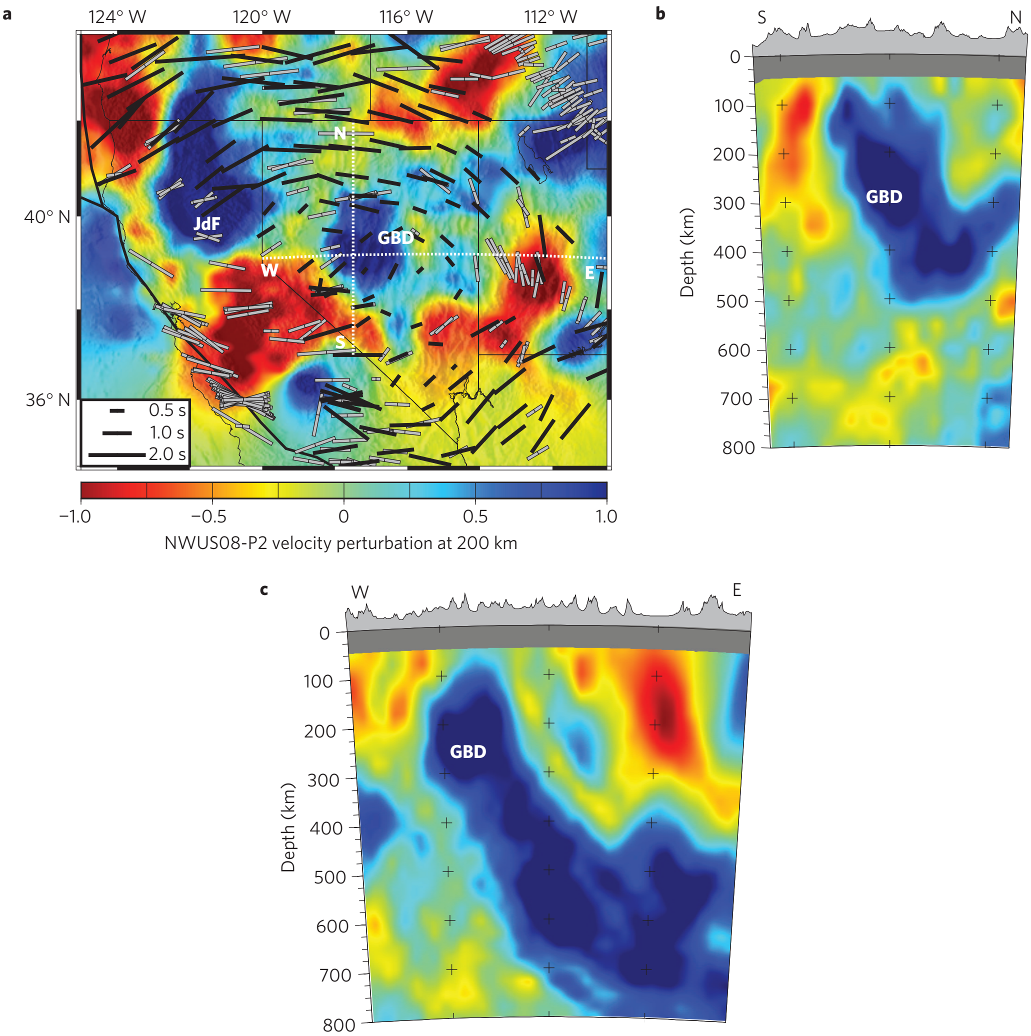

Figure 2 | Combined shear-wave splitting and tomography results. a, Map view of the shear-wave splitting results as in Fig. 1. The background is a 200 km depth slice of tomographic model NWUS08-P2 (see Supplementary Methods). GBD: Great Basin drip, a near-vertical cylinder of increased seismic velocities[20], is collocated with the region of smallest splitting times. JdF: southern edge of the subducting Juan de Fuca slab. The line marked N–S is the location of the cross-section in **b**; the line marked E–W is the location of the cross-section in **c**. **b**, North–south vertical cross-section of model NWUS08-P2. **c**, East–west vertical cross-section of model NWUS08-P2. The GBD is clearly evident as a cylinder of increased seismic velocities extending to 500 km depth and perhaps deeper, and bottom-tilted to the northeast.

new seismic evidence that, when considered in concert with a host of geological and geochemical data, instead suggests the presence of a well-developed lithospheric drip beneath the Great Basin.

Shear-wave splitting and seismic tomography

Our results are primarily derived from analyses of new seismic data recorded by EarthScope's USArray Transportable Array and other regional broadband seismic stations. We determined SKS-phase shear-wave splitting results at 139 broadband seismic stations, revealing marked variations in seismic azimuthal anisotropy across the western US (Fig. 1). SKS phases are seismic waves that propagate through the Earth's crust and mantle as shear waves and through the fluid outer core as compressional waves. Splitting times drop to near-zero values across the central Great Basin, the only region in the western US exhibiting such observations. Outside the central Great Basin, splitting times range from $\sim$1.25 to $\geq$2.25 s and fast polarization directions are predominantly oriented northeast–southwest south of the region and generally east–west north of the region. We also constructed a new high-resolution P-wave delay time tomographic model using 526 broadband stations across the northwestern US to provide a three-dimensional (3D) image of mantle thermal and compositional heterogeneity. The results of this seismic imaging reveal a near-vertical cylindrical zone of increased P-wave velocities in the upper mantle beneath the central Great Basin, coincident with the region of smallest splitting times (Fig. 2a). This feature, originally termed the 'Nevada Cylinder'[20], is approximately 100 km in diameter (Fig. 2a), extends near-vertically from $\sim$75 km depth to at least 500 km, and is bottom-tilted to the northeast (Fig. 2b, c). Near 500 km depth, the cylinder merges with a separate zone of high-velocity material, making resolution of a distinct cylinder difficult below this depth. Resolution tests indicate that the Great Basin drip is well resolved, and the tilt is not an artefact of the tomography process (see Supplementary Methods and Fig. S2). Furthermore, its existence is confirmed by a complementary regional seismic analysis using surface waves[21]. We note that the initial estimate of the base depth of the cylinder was $\sim$300 km from the preliminary tomographic image[20]; however, the improved resolution of the new tomographic model presented here clarifies the depth extent of the cylinder. The increased seismic velocities delineating the cylinder are similar in magnitude to those of the subducting Juan de Fuca slab to the west[20], suggesting a lithospheric origin. We estimate that the volume of

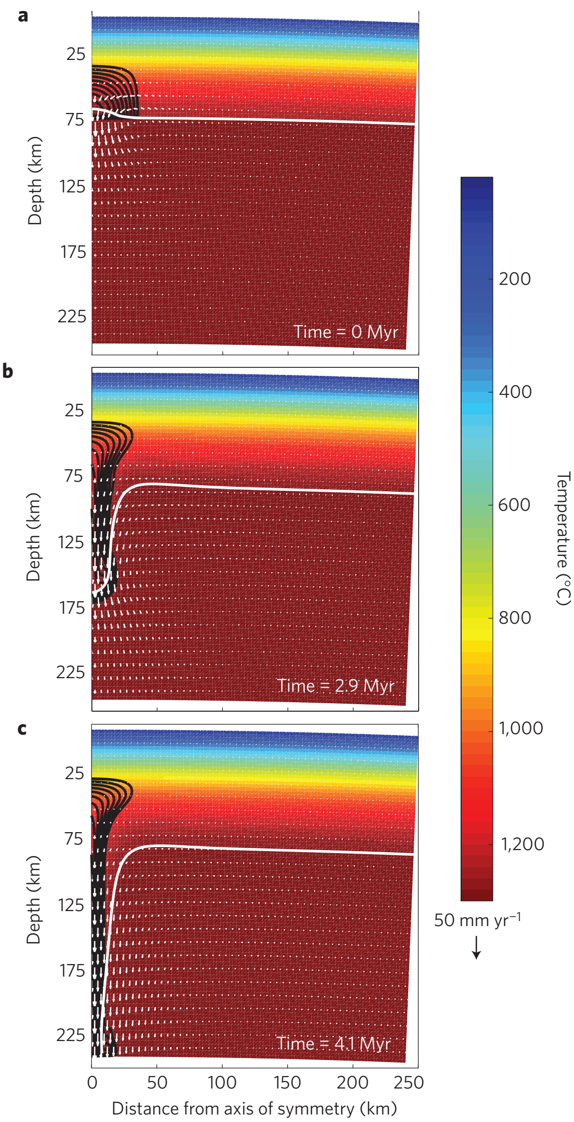

Figure 3 | Geodynamic model of a lithospheric drip. The colours denote temperature; the 1,300 °C contour is marked with a white line; the colour steps are in 20° increments; the temperature scale shown at the right. The black contours denote the distribution of the seed density anomaly in 0.1% increments. The white vectors denote flow direction; 50 mm yr^{-1} reference shown at the right. **a**, The initial geometry of the density anomaly and temperature distribution. **b**, By 2.9 Myr, the density anomaly has dropped into the asthenosphere, drawing cooler lithosphere with it in an organized downwelling flow. **c**, By 4.1 Myr, the sinking material narrows and widespread downward lithospheric flow is well established.

the cylinder is approximately 1–4 million km^3 (see Supplementary Methods and Fig. S8).

Shear-wave splitting of seismic waves travelling through the mantle is generally considered to be due to flow-induced strain and resulting lattice-preferred orientation (LPO) of mantle minerals such as olivine[22]; thus, splitting fast directions are assumed to be a good proxy for the direction of horizontal upper mantle flow. Combined with the constraint of thin (∼60–75 km) lithosphere across the western United States[16], the similarity in fast directions over broad length scales strongly suggests that the bulk of the shear-wave splitting signal is due to sublithospheric mantle flow. Furthermore, the large (≥2.25 s) splitting times observed across much of the region are some of the largest in North America, which we interpret as due to a predominantly lateral mantle flow field creating a well-developed sublithospheric mantle fabric due to horizontal strains. The large splitting times and fast direction pattern therefore are consistent with simple plate-driven mantle flow across the region[23] with a locally modified flow field due to Juan de Fuca slab rollback in the northwestern US. The localized region of small splitting times in the central Great Basin could be due to isotropy resulting from small strains in the area, or to complex anisotropy that produces minimal shear-wave splitting. However, given the large splitting values in nearly all other parts of western North America, the marked reduction in splitting times is most likely due to a rapid, localized shift to vertical flow and thus a reorientation of the anisotropic geometry. Such a shift is consistent with a host of numerical and laboratory experiments[24] that demonstrate that the response to changes in a flow field is through LPO rotation rather than broad-scale LPO reduction. We note that the vertical fast directions inferred in this region probably contribute to the strength of the cylindrical seismic anomaly (see Supplementary Methods). The region of small splitting times collocated with the conduit of higher seismic velocities therefore implies the presence of a lithospheric drip beneath the Great Basin.

Numerical modelling of a lithospheric drip

To investigate the nature of the Great Basin drip and its effects on the local mantle flow and thermal fields, we conducted a series of numerical experiments for gravitationally driven convective instabilities using parameters appropriate for the Great Basin region following the approach of ref. 8 (Fig. 3; Supplementary Figs S3–S7 and Table S3). These models predict that as little as a 1% density anomaly with a localized initial 10% temperature increase will produce a gravitational instability resulting in downwelling of lithosphere into the sublithospheric mantle. Sources of higher-density material in the Great Basin lithosphere include localized compositional or structural variations due to accretionary processes in the early geologic development of the region, or perhaps more likely, localized depleted residue zones (that is, eclogite or dense mafic cumulates) following widespread regional volcanism[10,25]. The source of heat necessary to initiate the instability may be asthenospheric warming due to opening of the Farallon plate 'slab window' and the subsequent northward-migrating southern edge of the Juan de Fuca/Gorda slab[26], or from mechanical lithospheric thinning due to extension. High lithospheric strain rates from late-stage Great Basin extension may also serve as a trigger mechanism for downwelling[25].

Our numerical models are consistent with the interpretation that the seismic results presented here can be explained by a lithospheric drip beneath the Great Basin. The range of models explored in this study (see Supplementary Figs S3–S7 and Table S3) all demonstrate that a strong and focused lithospheric drip can develop over time periods of <1–∼25 Myr, and large downward mantle flow velocities are quickly established. In several of the models presented, downwelling velocities are greater than the regional North American absolute plate velocity of 27 mm yr^{-1} (ref. 27), and lateral flow that feeds the drip is at least 50–100 times smaller than flow in the core of the downwelling. These lateral flow rates are small compared with the rates of extension in the region (10–15 mm yr^{-1}; refs 12, 13) and are therefore compatible with the overall extensional regime across the Great Basin. If the Great Basin crust–mantle system is indeed mechanically decoupled[28], then mantle processes such as the lithospheric drip would have a limited effect on upper crustal deformation. Alternatively, the lack of localized crustal extension in the central Great Basin[13] could be the result of weak contractional forces generated from the drip process, a mechanism not previously considered for this observation.

We note that the only volcanism recorded in the central Great Basin in the past 4.2 Myr is Lunar Crater[11], a small zone located just southeast of the edge of the high-velocity cylinder. Hot upwelling

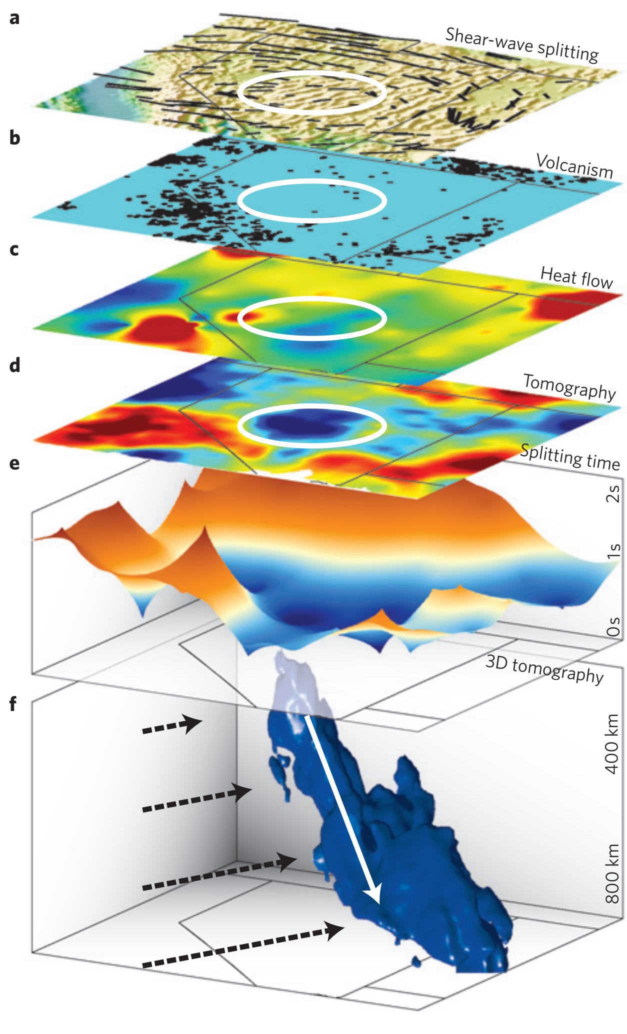

Figure 4 | Summary of geological and geophysical constraints for the central Great Basin. **a**, Shear-wave splitting with the topography background for reference. **b**, Post-10-Myr volcanism (black circles)[29] shows a regional dearth of volcanic activity. **c**, Heat flow[14] showing reduced values ($\sim$50 mW m^{-2}, blue) in the regional high ($>$100 mW m^{-2}; yellow and red). **d**, Seismic tomography horizontal slice at 200 km depth, as in Fig. 2a. **e**, Shear-wave splitting times surface showing the strong drop in the central Great Basin. The colour range is as in Fig. 1. **f**, Isosurface at $+0.95\%$ velocity perturbation for NWUS08-P2 showing the morphology of the drip, which merges with a larger structure at $\sim$500 km depth. The black arrows denote the inferred mantle flow direction; the white arrow denotes the flow direction of the Great Basin drip.

asthenosphere, as could be expected at the edge of the Great Basin drip[8], is therefore a viable explanation for the source of Lunar Crater volcanism. Furthermore, although lithospheric drips are often invoked to explain temporal variations in elevation, the models presented here predict insignificant surface topographic change, consistent with previous results for regions of thin lithosphere[8]. However, as presented in previous work[8], a broad range of factors can influence the pattern of uplift and subsidence, including localized asthenospheric upwelling around a drip, and the rheology of the crust and mantle. As with all geodynamical modelling, the models presented here are thus a guide to drip dynamics in a Great Basin-type tectonic setting, rather than a definitive set of parameters that may be used to predict all components of this complex system.

Lithospheric drips are a distinct process from lithospheric delamination, although the two terms are sometimes used interchangeably in the literature. Here we follow the convention used by Göğüş and Pysklywec[1] to clarify some differences in the structure and origin of these two processes on the basis of geodynamic modelling. Lithospheric drips, analogous to negative plumes, begin as a seed density anomaly, and fall from the lithosphere into the deeper mantle by means of Rayleigh–Taylor instabilities. A drip is expected to have a central, symmetrical core of downward flow with large vertical velocities relative to plate motion velocity, and is thus capable of generating a shift from azimuthal anisotropy due to lateral mantle flow to radial anisotropy due to vertical mantle flow. As lithospheric material feeds laterally into the drip from a much larger disc-shaped volume, it is only near the downwelling conduit that strains become sufficient to influence LPO-generated mantle fabric. Conversely, lithospheric delamination involves peeling away of a dense layered structure, often from the base of thickened crust[1]. The tabular nature of delamination and bending forces involved in peeling away from the upper lithosphere generally make delamination a slower, broader-acting process less likely to generate substantial modification of regional fabric due to mantle flow. It is not surprising, therefore, that regions of likely lithospheric delamination in the western US, including the Sierra Nevada[2,4] and the Wallowa Mountains[3], do not seem to show the same strong local variations in shear-wave splitting observed beneath the Great Basin.

Other models of Great Basin mantle dynamics

Constraints from regional geological and geophysical studies corroborate the interpretation of a lithospheric drip beneath the Great Basin (Fig. 4). The dearth of widespread recent volcanic activity[29], the observation that Basin and Range magmatism at the edges of the Great Basin was generated from a shallow asthenospheric source rather than from upwelling mantle[30], a zone of regionally reduced heat flow[14] and the cold mantle cylinder of the Nevada seismic anomaly are inconsistent with previous models suggesting a mantle plume upwelling for the region[17]. A more recent alternative model of toroidal flow around the southern edge of the present-day subducting Juan de Fuca slab has been proposed to explain the shear-wave splitting pattern in the region[19]. Although this model is consistent with present-day geological and geophysical observations, it requires that the central region of very low splitting times beneath the Great Basin be due to low strain rates in the centre of the toroid. Present-day low strain rates in the mantle beneath the Great Basin would not erase previously established mantle fabric generated by plate motion, slab subduction or the outer regions of the toroid as it moved into its proposed present position[24]. Although the observed splitting pattern might be due to an isotropic zone in the mantle beneath the Great Basin, the region of low splitting is coincident with the seismically fast and presumably cold cylinder, which would be denser than surrounding mantle. Such a cylinder would not be a stable mantle structure, as it would sink into the mantle owing to its negative buoyancy.

Constraints on upper mantle flow

The orientation of the Great Basin drip also provides constraints on the direction of the mantle flow field beneath the western US. The direction and magnitude of horizontal mantle flow beneath this region has been a subject of considerable debate, with proposed flow directions being east[23], south southwest[31] or a complex flow field varying significantly with depth[32]. The Great Basin drip is bottom-tilted approximately northeast (Figs 2b, c and 4), roughly opposite the direction of plate motion in the hotspot reference frame[27]. This result suggests that the overall direction of horizontal asthenospheric mantle flow is approximately northeast relative to the North American plate.

Our results reveal the presence of a 3D regional mantle flow field beneath the Great Basin and surrounding regions. Although mantle flow is frequently thought to be predominantly horizontal except in regions of plumes or subduction, drips probably contribute to more complex 3D flow in many regions of the upper, and perhaps lower, mantle. We note that drips are a typical component of many mantle convection models, but because of their transient and small-scale nature compared with larger-scale subduction-related downwellings, drips are often disregarded in these models. The origination of the Great Basin drip may be closely related to the rapid change in plate boundary geometry as the southern margin of the Juan de Fuca plate continues to progress northward; however, it may also simply be a natural component of mantle convection. We offer that continued regional investigations using the geophysical tools presented here, combined with geologic, geochemical and petrological constraints where available, will elucidate the existence and importance of lithospheric drips in the framework of global tectonics.

Methods

We determined 628 new, well-constrained SKS splitting measurements in this study (see Supplementary Tables S1 and S2). We used the method of ref. 33 as implemented in the SplitLab toolset[34] (see Supplementary Fig. S1) to carry out our splitting analysis, determining for each event/station pair the fast polarization axis (φ) and the splitting delay time (dt). For each event/station pair, we band-pass-filtered the waveforms over a frequency range of 0.02–0.2 Hz. We evaluated for SKS splitting over multiple windows and chose the window giving us the most robust results. Uncertainties in φ and dt were calculated at the 2σ bounds.

The tomographic model presented here is an update to the model presented in ref. 20, and provides significantly improved resolution in the Great Basin area compared with that model. We used the approach first developed by VanDecar[35] with several modifications presented in subsequent studies[36]. We used a multi-channel cross-correlation method to determine precise ($\sim$0.03 s) relative P-wave delay times. We quality-checked delay time data for timing errors, and visually inspected the delay time measurement on all records to eliminate cycle skipping. We corrected the relative delay time data for station elevation, and inverted the data for station terms, earthquake relocations and slowness perturbations. The resulting 3D model of seismic velocity perturbations is therefore the minimum structure necessary to satisfy the data after the effects of local structure beneath the stations and earthquake mislocations have been removed. We also carried out a host of resolution tests to confirm the geometry of the Nevada Cylinder, which are presented in Supplementary Methods.

The geodynamic numerical experiments were carried out using the approach of ref. 8, through a 2D axisymmetric finite-element fluid dynamic code called SSAXC (refs 37, 38). The model domain consists of 100 by 100 nodes and corresponds to 250 by 250 km, with the left-hand boundary as an axis of symmetry. The code solves non-dimensional equations for fluid flow[39]. The models use parameters appropriate for the Great Basin, and include a buoyant 35-km-thick crust underlain by 40 km mantle lithosphere with a flat lower boundary (no lithospheric root) in which a 'seed' region of higher-density material is present. The diameter of the denser region is 80 km, and is 1% denser than the laterally adjacent mantle lithosphere. Other models presented in Supplementary Methods and Figs S3–S7 include those with a seed density of 3% for comparison. The viscosity of the asthenosphere is 10^{19} Pa s and varies throughout the model box as a function of temperature and pressure. Topographic variations are calculated by computing surface stresses at each node at the top of the box and redimensionalizing them into topographic height assuming crustal density and gravity[8]. We present several models in Supplementary Methods to demonstrate the dependence of starting conditions, but note that details of all modelling methods used here, as well as a broader exploration of model space, are discussed extensively in refs 8 and 38.

Received 5 January 2009; accepted 23 April 2009; published online 24 May 2009

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Acknowledgements
We thank E. Garnero, A. McNamara and R. Rudnick for lively discussions of the possible causes of the Nevada anomaly, G. Zandt and G. Humphreys for discussions of Great Basin shear-wave splitting patterns and interpretation, and A. Sheehan and B. Holt for discussions of lithospheric dynamics. Thanks also to M. Savage for constructive and insightful comments on the manuscript. Partial support for this project came from US National Science Foundation grants EAR-0548288 (MJF EarthScope CAREER grant) and EAR-0507248 (MJF Continental Dynamics High Lava Plains grant).

Author contributions
J.D.W. and M.J.F. carried out shear-wave splitting measurements; J.B.R. and M.J.F. created the tomography models; L.T.E. created the geodynamical models; J.D.W. and M.J.F. prepared the manuscript with input, comments and review from all authors.

Additional information
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