# Two-stage subduction history under North America inferred from multiple-frequency tomography

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Published online: 29 June 2008; doi:10.1038/ngeo231

**Eastward subduction of oceanic tectonic plates has shaped the geologic history of western North America over the past 150 million years[1–4]. The mountain-building and volcanism that brought forth the spectacular landscapes of the West are credited to the vast ancient Farallon plate, which interacted mechanically and chemically with the overlying continent as it plunged back into the mantle. Here, we use finite-frequency travel-time and amplitude measurements of teleseismic P-waves in seven frequency bands to obtain a high-resolution tomographic image to ∼1,800 km depth. We discover several large, previously unknown pieces of the plate which show that two distinct stages of whole-mantle subduction are present under North America. The currently active one descends from the Pacific northwest coast to 1,500 km depth beneath the Great Plains, whereas its stalled predecessor occupies the transition zone and lower mantle beneath the eastern half of the continent. We argue that the separation between them is linked to the Laramide era 70–50 Myr ago, a time of unusual volcanism and mountain-building far inland generally explained by an episode of extremely flat subduction[5].**

Complementary pieces of the Farallon plate have been illuminated by different seismic methods. Near the trench of its currently descending small remnant, the Juan de Fuca plate (Fig. 1), it has been imaged down to ∼400 km depth by regional array studies[6–9]. Surface-wave studies[10] observed extended high-velocity zones in the transition zone under western North America. In the lower mantle beneath the continent's east coast, global-scale body-wave tomography picked up on a robust band of fast Farallon material[11,12]. However, its connection to the shallower western pieces was ambiguous, because large volumes beneath the central and eastern United States remained unresolved. This gap is filled by the present study. Surprisingly, the newly discovered fragments in the transition zone and lower mantle do not follow the norm that deeper material is always older. We also resolve tears or fractures in the submerged plate that are thousands of kilometres long. These detailed new observations on the plate's current geometry call for a critical review of earlier ideas about its subduction history.

Our study is the first large-scale application of finite-frequency body-wave tomography using multiple frequency bands[13,14]. It includes teleseismic P-wave arrivals from all suitable earthquakes between 1999 and August 2007, and from many earlier events, for a total of 637 sources (see Supplementary Information, Fig. S1). Image resolution and coverage benefit greatly from the new, densely spaced USArray stations in the western United States. This broadband array data is put to optimal use with finite-frequency modelling[15–19]. Resolution at depth is increased significantly by exploiting the frequency dependence of sensitivities on both travel times and amplitudes, which we measure[13] in seven passbands from 0.046 to 0.4 Hz, and invert for P-velocity and attenuation. Such multiple-frequency measurements increase the number of constraints on the solution by almost an order of magnitude, for a total of 434,013 travel-time and 109,045 amplitude data.

Figure 1 shows cross-sections through our solution for P-wave velocity anomalies, at latitudes of the currently active Farallon plate margin; the background model is IASPEI91 (Supplementary Information, Fig. S3 shows resolution tests. The complete tomographic model is part of the Supplementary Information as well). In Fig. 2, subducted material beneath all of North America is visualized as a three-dimensional isosurface, extracted from the same volumetric data. The threshold of $dV/V = +0.4\%$ does justice to weaker lower-mantle anomalies without distorting upper-mantle features, which are delineated with much larger velocity gradients.

The section at 42° N assembles our most salient observations. From its trench, the sharply defined slab sinks into the transition zone (anomaly S1), apparently shortening and thickening. For the first time we can see that it then continues to at least 1,500 km depth (S2). East of 100° W, a massive block of fast material F1 fills the transition zone and connects downward to lower-mantle anomaly F2. Figure 2a shows F2 as a high-velocity band stretching from the Caribbean to eastern Canada, as previously imaged[11,12]. Farallon subduction is known to have been uninterrupted over the past 150 Myr. The trench has moved westward continuously[1], so we would expect one slab of monotonous, west-to-east dip. Yet our images reveal two whole-mantle systems dipping from west to east. S2 in the western lower mantle must be younger than F1, which is still foundering on the 670 km discontinuity. The western edge of F1 is clearly delineated in Supplementary Information, Fig. S5a—it runs from Alberta to Louisiana. A frontal, trench-parallel break along this line must have severed the original connection between F1 and S2, allowing the younger material to descend independently and more steeply from there on.

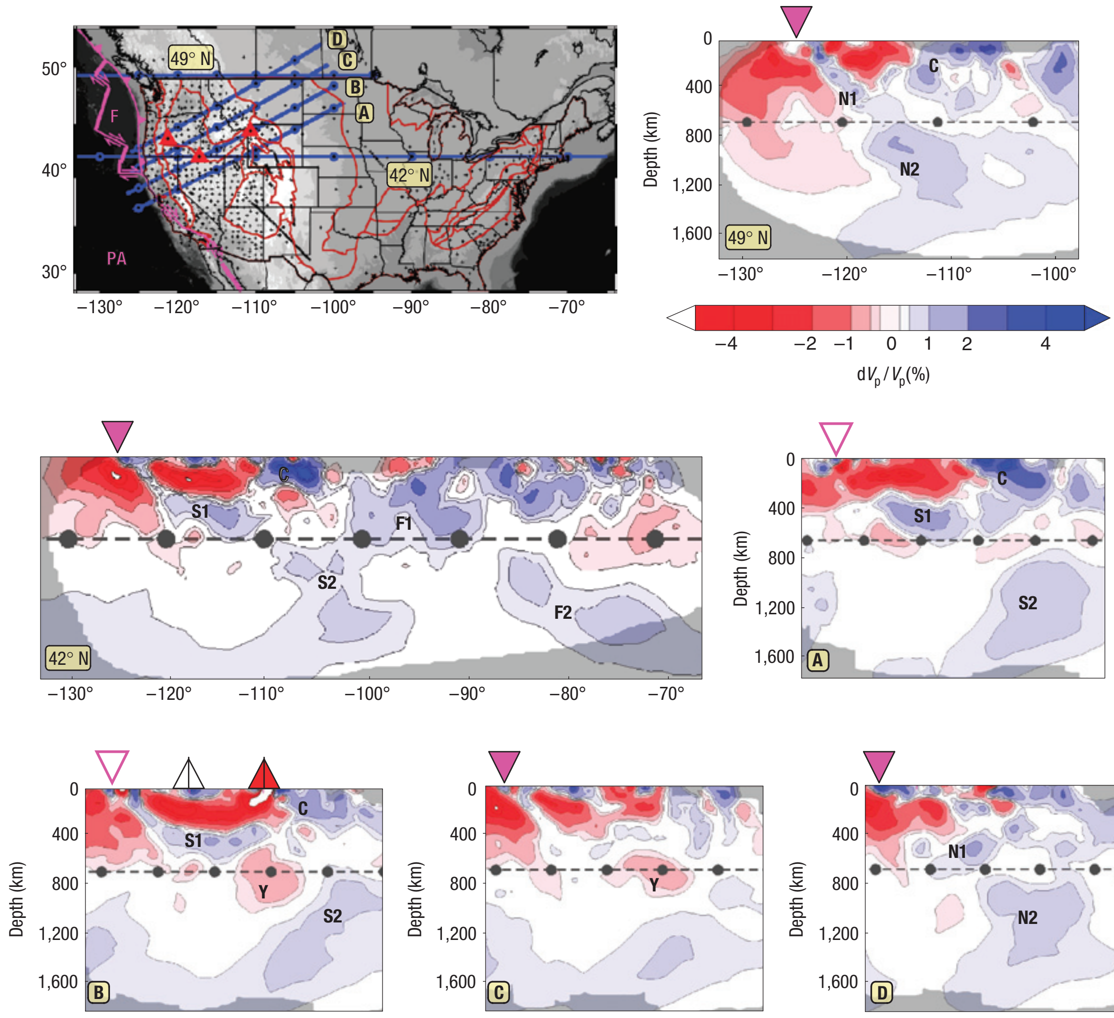


**Figure 1 P-wave velocity anomalies in the North American mantle down to 1,800 km depth.** The topographic map shows the locations of six cross-sections as blue lines and seismic stations as black dots. Boundaries: political (black), geological provinces (red), tectonic plates (magenta). F: Juan de Fuca plate, a Farallon remnant. PA: Pacific plate. Red triangles are volcanic fields, from west to east: Newberry, McDermitt, Yellowstone. Grey-shaded areas in cross-sections are not well resolved. Inverted triangles mark plate boundaries. The aspect ratio is approximately 1:1. The section at 42° N cuts through two whole-mantle subduction systems: the slab (fast anomalies S1 and S2) descends from the Cascadian trench to ∼1, 500 km depth, bounded by very slow material to the west (spreading ridge) and above (Great Basin). F1 and F2 represent an older episode of Farallon subduction. Younger material S2 sank, whereas F1 is still foundering above the 670 km discontinuity. Sections A to D strike along the direction of relative motion between the Farallon and North American plates over the past 70 Myr. In A, the connection between S1 and S2 is severed by a lateral tear; S1 abuts the craton C. Section B cuts through the hotspot track from McDermitt to Yellowstone. Up to 7% slow asthenosphere is underlain by slab S1. Slow anomaly Y fills a tear between S1 and S2 and has no plume-like connection to the surface. Section C strikes along the slab gap, where a fast slab signature is almost absent above 1,200 km. The slab picks up again in section D (anomalies N1, N2) but south of the Canadian border it remains fragmented in the upper mantle. At 49° N, subduction is once again continuous from the trench to ∼1,400 km depth.

We propose that this break ended the Laramide period (70–50 Myr) of flat-slab subduction by re-initiating a steeper angle of descent between 50–40 Myr, as illustrated in Fig. 3. The break was caused by collision along the edge of the craton ∼1,000 km inland, where stress was focused as the flat slab was deflected downward. This is deduced from the observed geometry: the slab length along the direction of relative plate motion, from the trench to S2 beneath eastern Montana, is ∼3,500 km, corresponding to 45 Myr of subduction[2]. The true age could be older because we see the (modern-day) slab thicken and shorten at the 670 km discontinuity. Yet even an effective length of 6,000 km would translate to an age of only 70 Myr owing to rapid plate convergence at the time. In summary, the lower tip of S2 entered the trench an estimated 60–50 Myr ago. It collided with the craton keel at 50–40 Myr, where its steepening explains the onset of westward migrating volcanism around that time (at 35 Myr, the volcanic arc along the west coast had been re-established[5,20,21]). Today, the craton keel is located ∼800 km southwest of F1's western margin (Fig. 2 and Supplementary Information, Fig. S5a), as would be expected[1] from ∼40 Myr of North American plate movement at ∼2 cm yr$^{-1}$.

Why has the 670 km discontinuity prevented F1 but not S2 from sinking into the lower mantle? A likely explanation lies in the rate of retrograde trench migration (North America's absolute velocity), which was ∼5 cm yr$^{-1}$ before 40 Myr and ∼2 cm yr$^{-1}$ after[1]. In convection simulations[22,23], rates above 2–4 cm yr$^{-1}$ are observed to

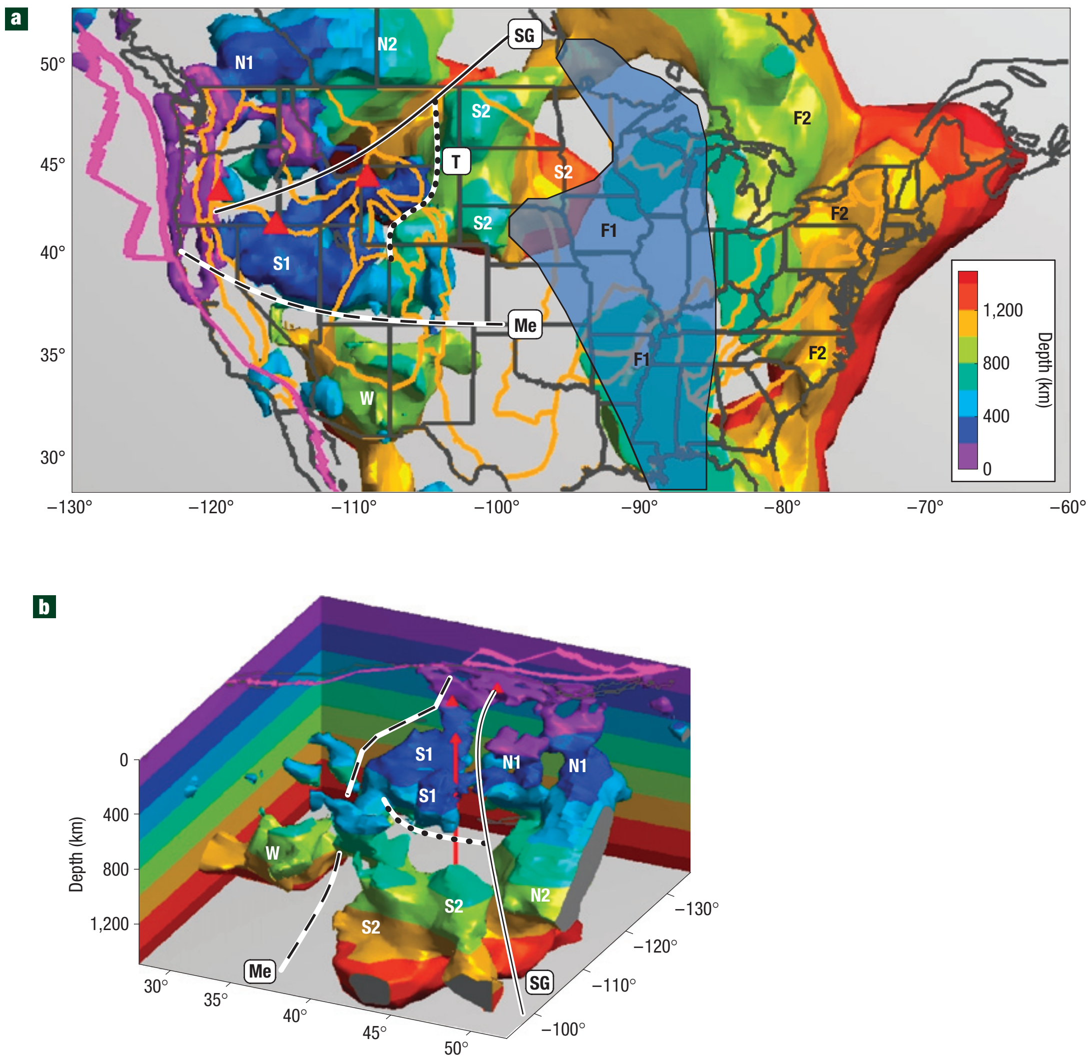


**Figure 2 Three-dimensional views of the subducted Farallon plate under North America.** Isosurface is rendered where P-velocity is 0.4% faster than expected; colour indicates depth. **a**, Map view of the Cascadia subduction system (S1, S2, N1, N2, W), and its predecessor (F1, F2) to the east. Shallow fast structure that would obstruct the view (for example, the craton) is not rendered. East of 100° W, only structure below 800 km depth is rendered; extent of slab material F1 in the transition zone is shaded blue. (All omitted features are shown in Supplementary Information, Fig. S5.) 'Me' (dashed line) is the continuation of the Mendocino fracture zone underground. 'SG' (solid line) marks the slab gap, a 2,500-km-long tear that subdivides the currently subducting plate. A lateral tear 'T' between upper and lower mantle (dotted line) is best appreciated in **b**. **b**, A bird's eye view of the Cascadia system from the northeast.

prevent passage through the endothermic phase transition as the slab hits the discontinuity at a flatter angle; flat-slab subduction probably enhanced this effect. As trench migration slowed, the slab had to steepen and pushed its way through the phase transition.

Sinking of a slab necessitates convective, viscous inflow of ambient mantle but a large flat slab prevents vertical mass exchange. To solve this geodynamical problem, various scenarios of tearing, followed by buckling or folding, have been suggested for the Farallon plate[24]. For the first time we actually resolve several large-scale tears or fractures. The Mendocino fracture zone, a long-lived transform fault, defines the southern limit of the Juan de Fuca plate at the surface. Its continuation in the mantle ('Me') is delineated by the southern edge of anomaly S1. South of it, no slab material is imaged in the upper mantle—this is the predicted 'slab window' associated with the onset of transform motion on the San Andreas fault since 30 Myr (refs 2,25). Newly imaged anomaly W must represent the last piece of plate that subducted south of the Mendocino fracture. W is clearly disconnected from S1/S2 now, along the line of the Mendocino fault's predicted continuation (see also Supplementary Information, Fig. S4). The relatively westerly[2] and deep location of W supports plate reconstructions[4] that inferred mechanical decoupling across the Mendocino as early as 55 Myr, leaving W free to sink more steeply.

An even longer tear or break is the 'slab gap' imaged beneath a 2,500-km-long line that runs from near the trench in Oregon to southern Saskatchewan. It is characterized by the absence of fast slab anomalies above 1,200 km depth (Fig. 1, section C), in contrast to sections B and D, which parallel C at 190 km distance. Figure 2 illustrates how the slab gap splits the subducting plate into a southern (S1/S2) and a northern (N1/N2) segment. The gap strikes perpendicular to the trench and parallel to the direction of

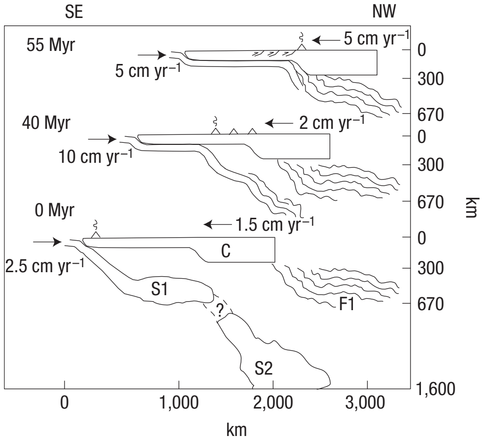


**Figure 3 Proposed explanation for the big break and the establishment of the current subduction system.** The *x* axis parallels the direction of relative plate motion. Plate velocities are given in the hotspot reference frame. 55 Myr ago: 'Flat-slab subduction' during the late Laramide era. Direct contact with the continental lithosphere causes basement thrust faulting hundreds of kilometres inland. The flat slab is forced downward at the cratonic keel, dehydrates and causes volcanism, but cannot penetrate the endothermic phase boundary at 670 km depth owing to its low subduction angle. Bending of the slab at the keel combined with the gradual westward motion of North America has caused the plate to repeatedly break off at the edge of the craton. 40 Myr ago: The 'big break.' As retrograde trench migration slows to 2 cm yr$^{-1}$, the subduction angle steepens. Material S2 disconnects from F1 and passes into the lower mantle. Surface volcanism migrates westward as the slab steepens; thrust faulting ceases. Today: Fully independent, steeply dipping subduction under Cascadia. Stalled material F1 is still foundering on the 670 km discontinuity.

relative plate convergence over the past 70 Myr. It must be very old because it separates the oldest parts of S2/N2 as well as even older F1 in the transition zone (see Supplementary Information, Fig. S5a). The slab gap may be a tear that has always operated close to the trench, probably self-perpetuating once N1 and S1 dipped at different angles. The Juan de Fuca sea floor features no obvious surface continuation of the slab gap.

Subduction dynamics change when a slab is subdivided by trench-perpendicular breaks and tears. Narrow segments can retreat more quickly, because material behind the slab is removed by flow around nearby edges[26,27]. Post-Laramide steepening of the Farallon slab is inferred from spatio-temporal propagation of several magmatic fronts; the general trend was westward but details are complex[21,24]. Such complications would be expected if different segments retreated independently and became warped by viscous flow through the slab gap and Mendocino fracture. The slab gap's predecessor on F1/F2 would have allowed flat subduction of the southern segment, independent of the northern segment. This could explain why the slab gap coincides with the northern margin of Laramide-aged basement uplifts[5,20]. More recently, the slab gap may have facilitated the break-up and re-orientation of the Juan de Fuca plate since 10 Myr (ref. 25), a process reflected in the fragmented geometry of N1.

A lateral tear ('T') at the 670 km discontinuity radiates south from the slab gap at around 105° W (Fig. 2). This tear accounts for the increasing disconnection between S1 and S2 in the sequence of sections '42° N–A–B'; slow anomaly Y (barely visible in A but fully developed in B) fills the space between the wings of the broken slab. If S1 and S2 were flattened in depth direction, the tear's ragged edges would fit together like puzzle pieces (Fig. 2a,b), confirming the former continuity of the plate and indicating the level of detail resolved. In the corner formed by T and the slab gap, a sliver of S1 protrudes far east and lies so shallow that it abuts the craton keel beneath Wyoming (Fig. 1, section A). Presumably this free northern edge rises because slab pull is concentrated south of 40° N, where the connection between S1 and S2 is intact. At the edge of this warped, shallowing sliver lies Yellowstone. Surprisingly, its hotspot track (the eastern Snake River Plain) is underlain by S1 at 350–600 km depth (Fig. 1, section B), and paralleled by the slab gap to the north. Asthenosphere is thus sandwiched between the antiparallel conveyor belts of lithosphere and slab. The shape of this very slow anomaly suggests flow driven east towards the craton keel and up beneath Yellowstone. The hotspot seems to be fuelled by shallow heat.

Hence the quest remains for a source of the massive sudden volcanism that erupted the Columbia River flood basalts 17 Myr ago[9,28] and heated the asthenosphere to its present level. We suggest that slow anomaly Y, located 500–1,000 km beneath Yellowstone, was the source region of a mid-mantle plume[29] that caused these events. Y is the most pronounced slow anomaly in this depth range, but we do not observe a clear connection to the surface nor to deeper depths. Just north of Yellowstone, the slab gap widens beneath Montana (Fig. 2a) and Y fills this widened gap segment. At 17 Myr, this segment and Y were underlying the basalt eruption area around the Oregon/Washington/Idaho border[28]. With no slab overhead, buoyant material would have made an unimpeded ascent to the surface. Ponding of mid-mantle plumes has recently been observed[30] and is predicted[29] if the endothermic phase transition at 670 km depth acts as a strong but incomplete barrier to vertical flow. We know this to be the case from the coexistence[22] of foundering slab F1 and descending slab S2. In convection models[29], mid-mantle plumes are brief, localized upward leakages with wider and hotter plume heads than classical lower-mantle plumes; this fits observations for the Columbia basalts[28]. The cause of the plume would have been an episodic exchange of material across the 670 km discontinuity. As tear T evolved, S1 shallowed and S2 dropped into the lower mantle. Hot low-viscosity material shot up in response to fill the opening gap but also ascended to the surface; the remnant of this heat source is Y. This scenario implies that subduction and plume dynamics were closely intertwined under North America, and were modulated by slab tears. F1, the part of the flatly subducted slab that never crossed the 670 km discontinuity, is not as pervasively segmented as the western system. Clearly, the strong phase boundary set the stage for the variety of subduction styles observed; large-scale tears and fractures determined the details of the subduction dynamics.

Received 9 February 2008; accepted 28 May 2008; published 29 June 2008.

## References

1. Engebretson, D. C., Cox, A. & Gordon, R. G. Relative motions between oceanic and continental plates in the Pacific Basin. *Geol. Soc. Am. Spec. Pap.* **206**, 1–58 (1985).
2. Schmid, C., Goes, S., van der Lee, S. & Giardini, D. Fate of the Cenozoic Farallon slab from a comparison of kinematic thermal modeling with tomographic images. *Earth Planet. Sci. Lett.* **204**, 17–32 (2002).
3. Bunge, H.-P. & Grand, S. Mesozoic plate-motion history below the northeast Pacific Ocean from seismic images of the subducted Farallon slab. *Nature* **405**, 337–340 (2000).
4. Atwater, T. *The Geology of North America* Vol. N, 21–72 (Geological Society of North America, Boulder, Colorado, 1989).
5. Dickinson, W. R. & Snyder, W. S. in *Laramide Folding Associated with Basement Block Faulting in the Western United States* Vol. 151 (ed. Matthews, V.) 355–366 (Geological Society of America Memoir, Boulder, Colorado, 1978).
6. Rasmussen, J. & Humphreys, E. D. Tomographic image of the Juan de Fuca plate beneath Washington and western Oregon using teleseismic P-wave travel-times. *Geophys. Res. Lett.* **15**, 1417–1420 (1988).
7. Harris, R. A., Iyer, H. M. & Dawson, P. B. Imaging the Juan de Fuca Plate beneath southern Oregon using teleseismic P-wave residuals. *J. Geophys. Res.* **96**, 19879–19889 (1991).
8. Bostock, M. G. & VanDecar, J. C. Upper-mantle structure of the northern Cascadia subduction zone. *Can. J. Earth Sci.* **32**, 1–12 (1995).
9. Xue, M. & Allen, R. M. The fate of the Juan de Fuca plate: Implications for a Yellowstone plume head. *Earth Planet. Sci. Lett.* **264**, 266–276 (2007).

10. van der Lee, S. & Nolet, G. Seismic image of the subducted trailing fragments of the Farallon plate. *Nature* **386**, 266–269 (1997).
11. Grand, S. P. Mantle shear structure beneath the Americas and surrounding oceans. *J. Geophys. Res.* **99**, 11591–11621 (1994).
12. van der Hilst, R. D., Widiyantoro, S. & Engdahl, E. R. Evidence for deep mantle circulation from global tomography. *Nature* **386**, 578–584 (1997).
13. Sigloch, K. & Nolet, G. Measuring finite-frequency body wave amplitudes and travel times. *Geophys. J. Int.* **167**, 271–287 (2006).
14. Hung, S.-H., Shen, Y. & Chiao, L.-Y. Imaging seismic velocity beneath the Iceland hot spot: A finite-frequency approach. *J. Geophys. Res.* **109**, B08305 (2004).
15. Dahlen, F. A., Hung, S.-H. & Nolet, G. Fréchet kernels for finite-frequency traveltimes—I. Theory. *Geophys. J. Int.* **141**, 157–174 (2000).
16. Dahlen, F. A. & Baig, A. M. Fréchet kernels for body wave amplitudes. *Geophys. J. Int.* **150**, 440–466 (2002).
17. Nolet, G. *A Breviary of Seismic Tomography* (Cambridge Univ. Press, Cambridge, 2008, in the press).
18. Tromp, J., Tape, C. & Liu, Q. Seismic tomography, adjoint methods, time reversal and banana-doughnut kernels. *Geophys. J. Int.* **160**, 195–216 (2005).
19. Tian, Y., Montelli, R., Nolet, G. & Dahlen, F. A. Computing traveltime and amplitude sensitivity kernels in finite-frequency tomography. *J. Comput. Phys.* **226**, 2271–2288 (2007).
20. Miller, D. M., Nilsen, T. H. & Bilodeau, W. L. in *The Cordilleran Orogen: Conterminous US Geological Society of America* (eds Burchfiel, B. C. *et al.*) (Boulder, Colorado, 1992).
21. The North American Volcanic and Intrusive Rock Database Movie: Magmatism in the Western United States over the past 65 Myr. <http://navdat.kgs.ku.edu/Navweb/WUS.mov> created/maintained by Allen F. Glazner and the NAVDAT team (2008).
22. Christensen, U. R. The influence of trench migration on slab penetration into the lower mantle. *Earth Planet. Sci. Lett.* **140**, 27–39 (1996).
23. Olbertz, D., Wortel, M. J. R. & Hansen, U. Trench migration and subduction zone geometry. *Geophys. Res. Lett.* **24**, 221–224 (1997).
24. Humphreys, E. D. Post-Laramide removal of the Farallon slab, western United States. *Geology* **23**, 987–990 (1995).
25. Severinghaus, J. & Atwater, T. in *Basin and Range extensional tectonics near the Latitude of Las Vegas, Nevada* (ed. Wernicke, B. P.) 1–22 (Geological Society of America Memoir 176, Boulder, Colorado, 1990).
26. Schellart, W. P., Freeman, J., Stegman, D.R, Moresi, L. & May, D. Evolution and diversity of subduction zones controlled by slab width. *Nature* **446**, 308–311 (2007).
27. Wortel, M. J. R. & Spakman, W. Subduction and slab detachment in the Mediterranean-Carpathian region. *Science* **290**, 1910–1917 (2000).
28. Pierce, K. L., Morgan, L. A. & Saltus, R. W. in *Tectonic and Magmatic Evolution of the Snake River Plain Volcanic Province* (eds Bonnichsen, B. *et al.*) 5–34 (Idaho Geological Survey Bulletin 30, 2002).
29. Cserepes, L. & Yuen, D. A. On the possibility of a second kind of mantle plume. *Earth Planet. Sci. Lett.* **183**, 61–71 (2000).
30. Nolet, G., Karato, S.-I. & Montelli, R. Plume fluxes from seismic tomography. *Earth Planet. Sci. Lett.* **248**, 685–699 (2006).

Supplementary Information accompanies this paper on www.nature.com/naturegeoscience.

## Acknowledgements

We thank the IRIS Data Management Center for timely and easy access to the seismic data. This work was supported by NSF grants EAR0345996 and EAR0309298, and by Princeton University.

## Author contributions

K.S. and G.N. designed the tomographic experiment. K.S. carried out the experiment and analysed the data. K.S. and N.M. worked out the tectonic interpretation. All authors participated in preparing the paper.

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