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 years1–4. 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 transition zone and lower mantle beneath the eastern half of the continent.

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 studies5–9. Surface-wave studies10 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 material11,12. 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 bands13,14. 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 modelling15–19. Resolution at depth is increased significantly by exploiting the frequency dependence of sensitivities on both travel times and amplitudes, which we measure11 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 IASP91 (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 imaged11,12. Farallon subduction is known to have been unimpeded over the past 150 Myr. The trench has moved westward continuously1, 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 founding 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.
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. 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-established2,21). Today, the craton keel is located ∼800 km southwest of F1’s western margin (Fig. 2 and Supplementary Information, Fig. S5a), as would be expected1 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$^{-1}$ after1. In convection simulations22,23, 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**, 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 plate44. 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 (ref 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 westerly2 and deep location of W supports plate reconstructions4 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
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\textsuperscript{13,27}. 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\textsuperscript{14,24}. 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\textsuperscript{26,29}. 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\(^\circ\)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 eastward to 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\textsuperscript{26,27} 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\textsuperscript{28} that caused these events. Y is the most pronounced slow anomaly in this depth range. We do not observe a clear connection to the surface nor 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\textsuperscript{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\textsuperscript{29} and is predicted\textsuperscript{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\textsuperscript{22} of foundering slab F1 and descending slab S2. In convection models\textsuperscript{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\textsuperscript{29}. 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


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 EAR0343996 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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Supplementary Figure 1 shows the 637 earthquake sources (left) and 1125 receiving seismic broadband stations (right) used in this study. Each earthquake lies at 30-85 degrees distance from at least five broadband stations with good measurements. Measurement quality is determined by the cross-correlation of measured and predicted broadband P-wave seismograms. We use all suitable events (usually larger than magnitude 5.8) from the IRIS DMC database that happened between Jan. 1999 and August 2007, and many earlier events back to 1990. Traveltimes are measured in the broadband and seven frequency passbands (center periods; 21 s, 15 s, 11 s, 7.5 s, 5.3 s, 3.75 s, 2.7 s); amplitude anomalies are measured in the lower three frequency bands. We obtain a total of 434,013 travelt ime and 109,045 amplitude measurements.
Supplementary Figure 2. Global-scale tetrahedral mesh used for the tomography. Cell size adapts to station density. Since we used receivers in North America, the grid is denser below this region. Facet length of the smallest tetrahedra is ~60 km. Meshing software by Persson & Strang, SIAM Review, Volume 46 (2), pp. 329-345, (2004).
**Supplementary Figure 3.** Resolution tests. Top panel shows the input, bottom panel the recovered structure for a cross-section at latitude 42°N under North America. We use Gaussian-shaped spherical anomalies as input (peak anomaly $dV_p/V_p = \pm 3\%$). Each panel is a graphical superposition of two resolution tests, one using Gaussians of 200 km diameter, the other of 400 km diameter over the entire volume. We use the smaller anomalies to assess resolution for the upper mantle, and the larger ones for the lower mantle. White Gaussian noise of standard deviation 1 is added to the synthetic data generated.

We do four different tests with the smaller Gaussians, and four tests with the larger kind. The tests differ in that each time the anomalies are translated by a fraction of their width in x, y, and z direction. For each test, we manually contour resolved areas in slices of constant latitude that are spaced by 0.5 degrees. The gray shaded area marks the region that is not resolved by any of the tests. For oblique cross-sections A-D, we estimate the non-resolved area by cutting through the volume obtained from the procedure described above.
Supplementary Figure 3 (continued). Resolution tests at 46°N and 49°N.
Supplementary Figure 3 (continued). Resolution tests at 38°N and 34°N.

INPUT

longitude (at latitude 38.0 N)

RECOVERED

longitude (at latitude 38.0 N)

INPUT

longitude (at latitude 34.0 N)

RECOVERED

longitude (at latitude 34.0 N)
Supplementary Figure 4. The subterranean continuation of Mendocino Fracture Zone expresses itself as a narrow, linear gap in fast plate material that separates the subducting slab S1/S2 north of ~38°N from fragment W to the south. The section at 37.5°N strikes along this fracture and shows that essentially no fast material is present in the upper and lower mantle. This is predicted for the uppermost mantle (the so-called Slab Window). However, a fast anomaly would be expected at some deeper depth if material south of the fracture zone were still connected to S1/S2. Further south at 34°N, fast anomaly W is indeed well delineated in the lower mantle. The origin of anomaly X (see also supplementary figure 5c) is mysterious due its deep location west of the former Farallon trench. It must be very old material unrelated to Farallon subduction over the past 150 Myr. Its true westward and downward extent is not resolved by our data set.
Supplementary Figure 5a shows all fast structure (dVp/Vp>0.4%) under North America except the current western subduction system (which is shown in fig. 5b), and an unrelated deep anomaly (5c). In contrast to all other 3-D renderings of this type, deeper structure is shown in the foreground in order to be visible (i.e. the depth axis is inverted). The pink line maps out the front along which we think the Farallon plate broke in the transition zone ~40 million years ago. Northeast of it, the transition zone is filled with stalled older slab material F1, that is still foundering on the 670-km discontinuity. It connects east and down to older slab material F2 (orange/red). The present-day Slab Gap (b&w solid line) seems to have had a (slightly more southerly) predecessor on plate F1, supporting the notion that the Slab Gap is a very old zone of weakness. The rectangular "hook" in the pink outline might seem questionable in light of the otherwise simple, trench-parallel strike of the front. We think it is real because the transition zone material "missing" here shows up instead as a protruding piece of S2, the oldest part of the younger western subduction system (c.f. figure 5b). Southwest of the pink line, fast material is essentially limited to the upper 400 km; the deepest pieces (dark blue) represent the deep keel of the North American craton. The green line marks the keel’s western edge (where present). Today this edge lies 700-900 km southwest of the frontal break line, in accordance with predicted North American plate translation of 800 km (~20 mm/yr over 40 Myr). This supports the idea that the flatly subducting slab south of the Slab Gap broke where it encountered the craton keel 40 Myr ago.
Supplementary Figure 5b. The more recent subduction system under western North America, rendered at the same threshold as fig. 5a; z-axis runs into the plane. Outline of frontal break (pink) line, present-day Slab Gap (black&white), and craton keel (green) as in figure 5a. The hook in the frontal break corresponds to the area where the oldest material S2 of the current subduction system extends farthest to the northeast. This is an example how spatially separate parts of slab material complement each other like pieces of a 3-D puzzle, underscoring that the original geometry must have been continuous and sheet-like. It gives us confidence that we really are resolving structure to this level of detail. (Another example is the lateral tear T discussed in the text.)
Supplementary Figure 5c. This figure shows all fast material not rendered in figs. 5a and 5b. It consists of a lower-mantle anomaly X offshore California. The anomaly’s exact depth and western extent are badly constrained due to its location west of our seismic stations (in fact even its western half in this figure is poorly resolved due to smearing and damping). We think this anomaly must be unrelated to subduction over the past 150 Myr because it lies west of the Farallon/Pacific trenches’ westernmost location ever (i.e., the present-day one). Hence Farallon/Pacific plate reconstructions do not suggest a straightforward explanation.