nature geoscience

LETTERS

PUBLISHED ONLINE: 28 MARCH 2010 | DOI: 10.1038/NGEO829

The role of oceanic plateau subduction in the Laramide orogeny

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The cause of the Laramide phase of mountain building remains uncertain[1]. Conceptual models implicate the subduction of either ocean ridges[2] or conjugates of the buoyant Hess[3] or Shatsky[4] oceanic plateaux. Independent verification of these models has remained elusive, because the putative ridges or plateaux are no longer at the Earth's surface. Inverse convection models[5] have identified two prominent seismic anomalies on the recovered Farallon plate. Here we combine inverse convection models with reconstructions of plate motions, to show that these seismic anomalies coincide palaeogeographically with the restored positions of the Shatsky and Hess conjugate plateaux as they subducted beneath North America. Specifically, the distribution of Laramide crustal shortening events[6] tracked the passage of the Shatsky conjugate beneath North America, whereas the effects of the Hess conjugate subduction were restricted to the northern Mexico foreland belt[7]. We propose that continued subduction caused the oceanic crust to undergo the basalt–eclogite phase transformation, during which the Shatsky conjugate lost its extra buoyancy and was effectively removed. Increases in slab density and coupling between the overriding and subducting plates initially dragged the surface downward, followed by regional-scale surface rebound. We conclude that Laramide uplift resulted from the removal, rather than emplacement, of the Shatsky conjugate.

Previously, the plateau subduction model has been investigated using the reconstruction of synthetic conjugates to the Pacific plate plateaux[3,4], but these models differ substantially from each other depending on the underlying plate kinematic models, and the role of plateau subduction in driving Laramide deformation remains unclear. Recent development of inverse models of mantle convection based on seismic tomography allows reconstruction of the history of subduction, providing a link between present-day mantle structures and geological observations[8]. This approach has the potential of recovering the now subducted former oceanic plateaux back to the surface directly from the observed present-day mantle seismic structures. The inverse calculation, therefore, offers a complementary approach to inferring the position of the oceanic plateau back in time. Here, we combine both forward (kinematic) and inverse (dynamic) approaches with geological observations from the overriding plate to test the hypothesis of plateau subduction.

Using a recent plate reconstruction[9], we predict positions of the Shatsky and Hess conjugates on the Farallon plate during the Late Cretaceous period (Supplementary Information). The reconstructed Shatsky conjugate intersects the North American continent at ~90 million years (Myr) BP in Southern California, and the Hess conjugate intersects the northern part of Mexico at ~70 Myr BP (Fig. 1a). Alternatively, we carry out an inverse calculation of mantle convection starting with a shear-wave seismic tomography model[10]. The model that best fits stratigraphy over the western United States reveals an epoch of flat-slab subduction characterized by a thicker-than-ambient oceanic lithosphere on the Farallon plate during the Late Cretaceous[5]. We highlight the thickest part of this segment of lithosphere with passive tracers to illustrate its location, and run the model forward from 100 Myr BP to the present. At 90 Myr BP, the thickened lithosphere is located largely to the west of the Farallon subduction zone, whereas its northeast flank is subducted beneath North America, initiating a segment of shallow flat subduction (Fig. 1b). The thickened lithosphere denoted by tracers falls in almost the same area as the kinematically predicted Shatsky conjugate, with both its orientation and geometry in the two models reasonably correlative (Fig. 1). At 70 Myr BP, the entire area of this thickened lithosphere shifts below the western United States and a second flat-slab segment forms to the south correlative with the predicted position of the Hess conjugate (Fig. 1a,b).

As the plate reconstruction approach starts with positions of the extant Shatsky and Hess plateaux whereas the inverse-convection approach uses the seismic structures of the present-day mantle, the two approaches are independent, although they share the same plate reconstruction from 90 Myr BP to the present. Both temporal and spatial consistencies of these now-subducted plateaux from the two approaches suggest that these features existed on the Farallon plate during the Cretaceous. Identification of these oceanic plateaux allows a quantitative assessment of their relation to the sequence of geological events over the western United States, especially those of the Laramide orogeny.

Traditionally, plateau subduction is thought to cause synchronous crustal uplift. Therefore, earlier models attributed the Laramide orogeny to subduction of conjugates of either the Hess[3] or Shatsky rise[4] between roughly 70 and 60 Myr BP, the time of classic Laramide exhumation[11]. We find that this relationship is true only along the continental margin where the plateaux initially entered the subduction zone. Initial subduction of the Shatsky conjugate beneath Southern California in both up-to-date plate reconstructions and inverse convection models (Fig. 1) corresponds to forearc destruction, intra-arc ductile thrusting and rapid exhumation of the southern Sierra Nevada batholith (SNB) during 96–86 Myr BP (ref. 12; Supplementary S1, Fig. 2). Continuing subduction of the Shatsky conjugate progressively disrupted the Southern California active margin, producing the distinctive South-

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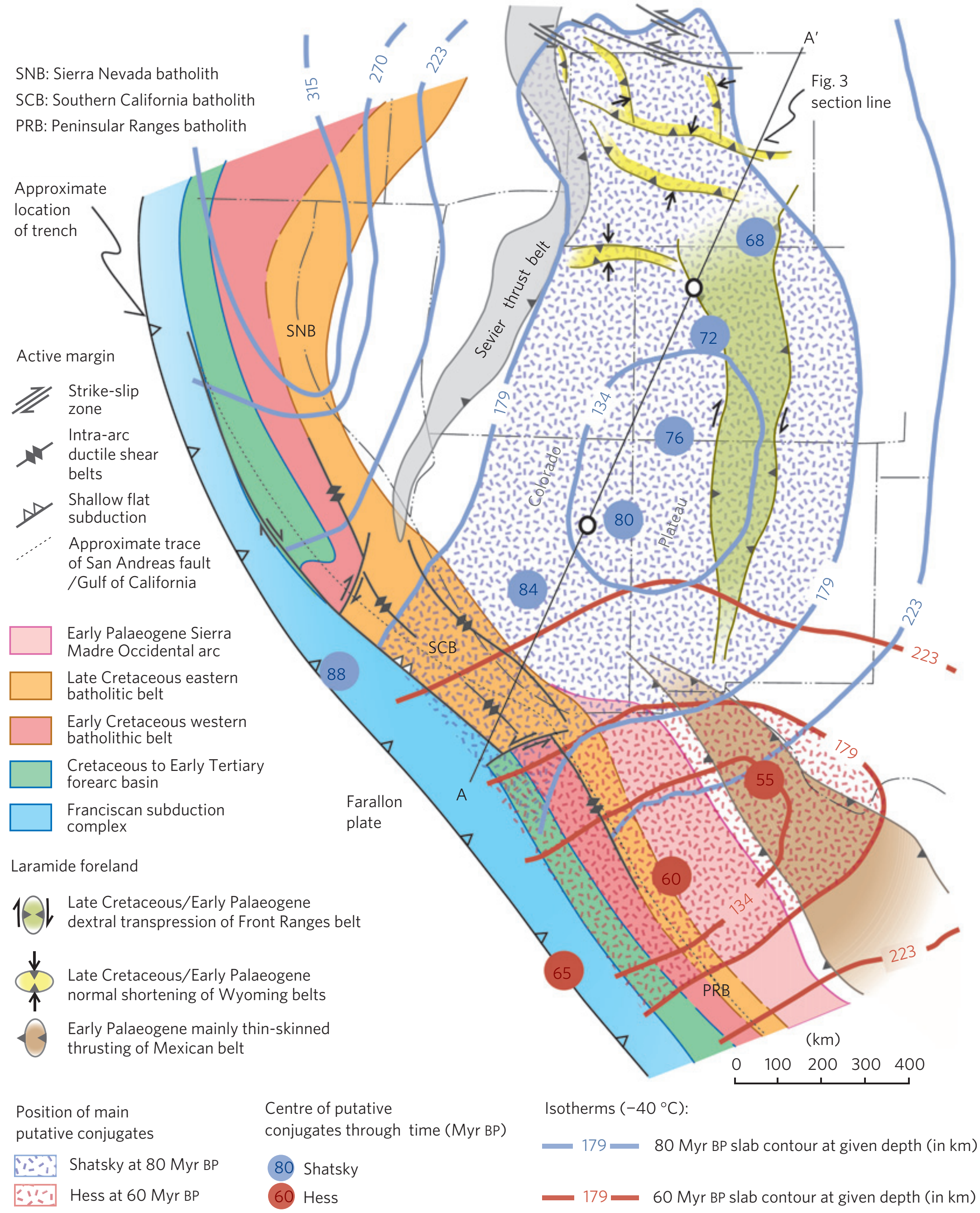

Figure 2 | Palinspastic map showing the southwest Cordilleran active margin and the Laramide foreland for the end of Cretaceous time[3] with the temperature field overlain. Contours (same as Fig. 1; light blue for 80 Myr BP, red for 60 Myr BP) and predicted positions of the putative Shatsky and Hess conjugate plateaux (inside the 179 km contour) are from the inverse model. Filled circles represent the volumetric centre of the putative Shatsky (light blue) and Hess (red) conjugate plateaux at given age during their subduction beneath North America. Line AA′ indicates the surface trace of the cross-sections shown in Fig. 3.

these areas (Fig. 3a,b). Collectively, our study suggests that initial subduction of the plateau should have caused the slab to flatten because of the extra buoyancy associated with its thick crust, but continuing flattening would mostly result from the increased plate coupling with a possibly weakened mantle wedge[21]. As the Shatsky conjugate translated beneath the Colorado Plateau region (Fig. 2), the oceanic crust is deep enough to undergo the basalt–eclogite phase transformation, during which the plateau loses its positive buoyancy[22]. Both the overall negative slab density anomaly and enhanced plate coupling during shallow subduction drag the surface downward (Fig. 3a). A present-day analogy is the subducting Inca plateau in Peru[23], where broad surface subsidence is observed above the flat slab (Supplementary S2).

Laramide uplifts, at local scales, initiated along thrust faults during flat-slab underplating[11] (Fig. 2). Subsequent regional-scale uplifts, however, are associated with removal of the plateau from beneath the Laramide province. The flat-slab associated with the Shatsky conjugate gradually sank deeper into the mantle as it migrated to the northeast. Both horizontal removal of flat slab from beneath the Colorado Plateau region after 80 Myr BP and the overall diminishing negative dynamic topography associated with cold slabs (Fig. 3b,c) led the surface to rebound in a

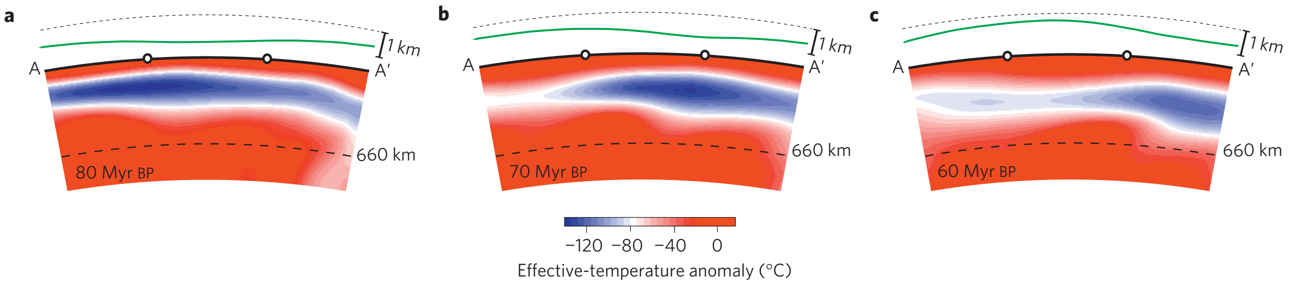

Figure 3 | Configuration of the subducting Farallon slab and the corresponding surface dynamic topography along profile AA′ (shown in Fig. 2). Three representative times (**a**–**c**) during the Late Cretaceous to Early Palaeocene are chosen. The dynamic topography is shown with green lines.

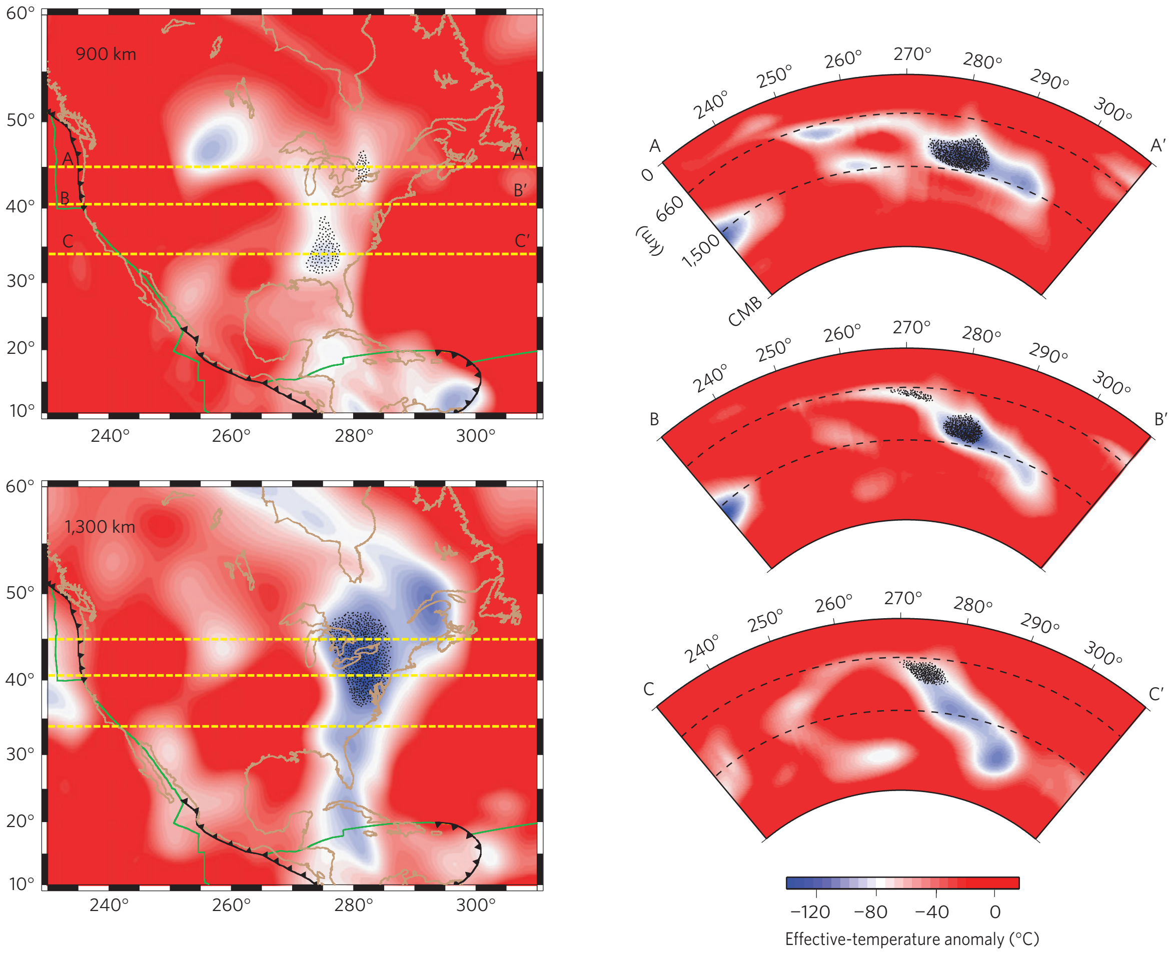

Figure 4 | Location and geometry of the Shatsky and Hess conjugate plateaux inside the present-day mantle. Map view at two different depths (900 and 1,300 km) and cross-sectional view at three latitudes (45°, 41° and 33° N). Tracers highlight the predicted locations and distributions of these plateaux. The Shatsky conjugate is to the east of the Great Lakes and the Hess conjugate is to the south. CMB, core–mantle boundary.

southwest–northeast trend with a maximum of ∼600 m uplift occurring during the Late Cretaceous over the Colorado Plateau (Fig. 3). This corresponds to regional uplifts starting as early as 80 Myr BP and peaking at 70–60 Myr BP across the Laramide province, and the overall eastward migration of marine conditions from the Sevier foredeep region to regions further into the continental interior[11]. The amount of predicted uplift by the Eocene epoch agrees with the inferred kilometre-scale rock uplift over the southern Colorado Plateau[20]. Removal of the Shatsky conjugate, by its sinking northeastward into the mantle, may have further facilitated fault reactivation, causing distributed basement uplifts intervened by the Laramide foredeep basins[11,14], although we do not yet understand the details of the process. Our study, therefore, may explain the 20 Myr lag-time between the Late Cretaceous (∼80 Myr BP) shortening deformations and early Palaeocene (∼60 Myr BP) cooling events of the Laramide orogeny[11].

Our geodynamic model also predicts the locations and geometries of the deeply subducted rise conjugates in the present-day mantle using tracers (Fig. 4). Both conjugates are now situated under the east coast of the United States, with the Shatsky conjugate to the east of the Great Lakes and the Hess conjugate to the south. The Shatsky conjugate is predicted to extend from 900 to 1,400 km in depth, covering ∼1,000 km in the north–south direction and ∼500 km east–west; the Hess conjugate essentially stays above 1,000 km depth with ∼500 km cross-sectional dimensions (Fig. 4). A recent high-resolution P-wave seismic inversion[24] reveals similar configurations of the Farallon remnants to those in the S-wave tomography[10] (Supplementary S3), reinforcing the interpreted positions of these oceanic plateau conjugates.

Stishovite-structured silica, one of the main proposed constituents of deeply subducted mid-ocean-ridge basalt (MORB) material[25], has seismic velocities ∼20% higher than the ambient mantle after the post-stishovite phase transition[26] (P_{tr}). In MORB, incorporation of a few wt% Al_2O_3 and H_2O into silica is favourable[25,27] and decreases the depth of post-stishovite P_{tr} to ∼800 km (ref. 27). Although effects of temperature on the wave speeds of post-stishovite are unknown, an estimated decrease by <4% in the lower mantle is reasonable[28]. Therefore, ∼25% of hydrous aluminious post-stishovite in the deep MORB crust would cause seismic velocity anomalies >4%, where current tomography models are blurry. As a result of the substantially thicker-than-ambient crust accreted during formation of an oceanic plateau and expected slab thickening on its entrance into the lower mantle, present remnants of the Shatsky and Hess conjugates could have an accumulated crustal pile thickness of >50 km. The predicted strong seismic anomalies, in conjunction with the large volumes, should make these foundered crustal blocks detectable as sharp seismic features, in which travel-time anomalies and waveform multipathing are expected[29]. The ongoing seismic experiment with the USArray shifting to the east coast of the United States should provide the opportunity to detect these subducted oceanic plateau conjugates.

Received 25 August 2009; accepted 26 February 2010;

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Acknowledgements

We thank D. Helmberger, D. Anderson, P. DeCelles and K. Karlstrom for helpful discussions and P. DeCelles for a helpful review. This represents Contribution number 10026 of the Division of Geological and Planetary Sciences and 102 of the Tectonics Observatory, Caltech. At Caltech this work has been supported by the National Science Foundation (EAR-0739071 and EAR-0810303) and through the Tectonics Observatory by the Gordon and Betty Moore Foundation.

Author contributions

L.L. and M.G. designed the whole workflow and carried out the inverse convection model, M.S. and R.D.M. carried out the plate reconstruction, J.S. worked on the geological interpretation and J.M.J. provided mineral physics analysis. All authors participated in preparing the paper.

Additional information

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