nature geoscience

LETTERS

PUBLISHED ONLINE: 26 JUNE 2011 | DOI: 10.1038/NGEO1187

Spatial and temporal variability in Hawaiian hotspot volcanism induced by small-scale convection

Maxim D. Ballmer[1,2]*, Garrett Ito[1], Jeroen van Hunen[3] and Paul J. Tackley[2]

Volcanism far from plate boundaries is often attributed to an underlying mantle plume[1–6]. However, enigmatic observations of Hawaiian volcanism, such as variations in the volume of erupted volcanic material through time[7,8], a geographical asymmetry in the geochemistry of the lavas[9–18] and secondary volcanism that occurs far away from the hotspot[15–20], cannot be explained by the classical mantle plume concept. Here we present a numerical model of mantle plume upwelling beneath Hawaii. We find that small-scale convection in the ambient mantle can erode the base of the lithosphere, creating a washboard topography on the underside of the plate. As the plate migrates over the upwelling plume, the plume interacts with alternating thicker and thinner sections of lithosphere to generate temporal variations in the flux of erupted volcanic material. The pre-existing washboard topography also causes the plume to spread and melt asymmetrically. In our simulations, this asymmetry in mantle flow generates an asymmetry in the chemistry of the erupted lavas. Finally, a more vigorous type of small-scale convection develops within the spreading plume, generating localized zones of upwelling well away from the hotspot. The associated magmatism is fed by chemically distinct material originating from the edges of the plume conduit. Our results show that shallow processes have an important influence on the character of volcanism fed by deep-rooted mantle plumes.

Classical plumes are typically described as purely thermally driven, narrow upwellings rising through the entire mantle and being deflected into a thin ‘pancake’ beneath the overriding plate[1]. Such an upwelling dynamically generates an elongated, parabolically shaped swelling of seafloor topography[2–4]. Associated ‘hotspot’ volcanism is localized and stationary, therefore entailing an age-progressive island chain. This classical theory has indeed successfully predicted first-order observations at many hotspot chains, Hawaii being among the most prominent and best studied examples.

A set of enigmatic observations of Hawaiian volcanism, however, are not explained by the above idealized description. First, average volcanic flux as documented along the Hawaii–Emperor chain has varied by a factor of >2 over typical timescales of ~15 Myr (refs 7,8). Mechanisms involving intrinsic variations in buoyancy flux or tilt of the rising plume stem have been proposed as an explanation[5–8], but not yet tested. Second, the origin of the bilateral asymmetry in lava geochemistry, as documented by compositional distinctions between the southern (‘Loa’) and northern (‘Kea’) volcano sub-chains (Fig. 1a), is not well understood. One set

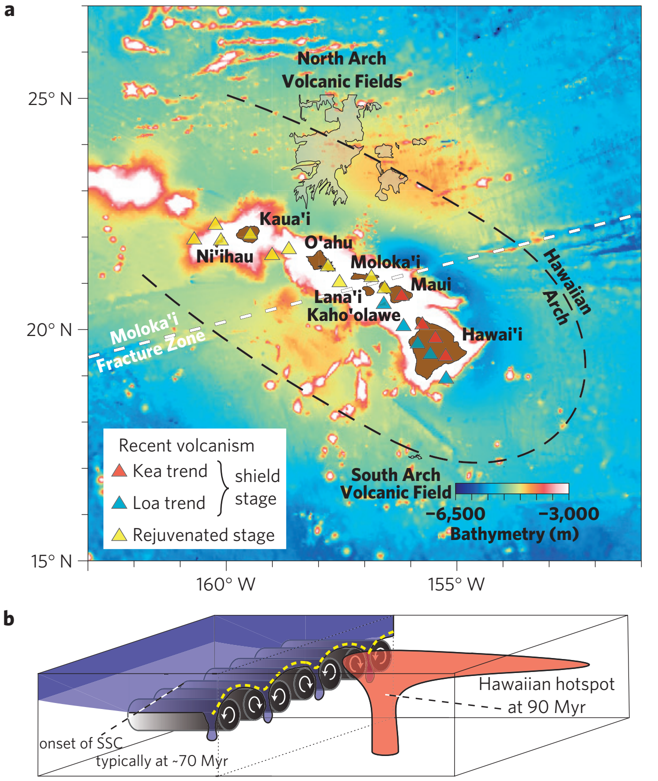

Figure 1 | Overview and concept. a, Geographic overview and bathymetry of the Hawaiian Islands. Shield volcanoes are marked with triangles and arch volcanic fields with strong acoustic reflectivity[19,20] are shaded. The shallow seafloor surrounding the islands is referred to as the Hawaiian arch (black dashed). **b**, Conceptual illustration of small-scale convection (SSC) interacting with the Hawaiian plume. Undulations on the base of the lithosphere (washboard pattern; dashed yellow line) were created by SSC in the ambient mantle.

of interpretations invokes some form of compositional zoning in the upwelling plume stem[9–11]. Other studies emphasize that if the mantle is a fine-scale mixture of different lithological components, spatial variations in pressure and temperature over the hotspot melting zone can create geographical patterns of magma composition that differ from those for an isochemical source[12]. Finally, widespread secondary volcanism[17–20] occurring

[1]School of Ocean and Earth Sciences and Technology, University of Hawaii, Honolulu, Hawaii 96822, USA, [2]Institute of Geophysics, ETH Zürich, 8092 Zürich, Switzerland, [3]Department of Earth Sciences, Durham University, Durham, DH1 3LE, UK. *e-mail: ballmer@hawaii.edu.

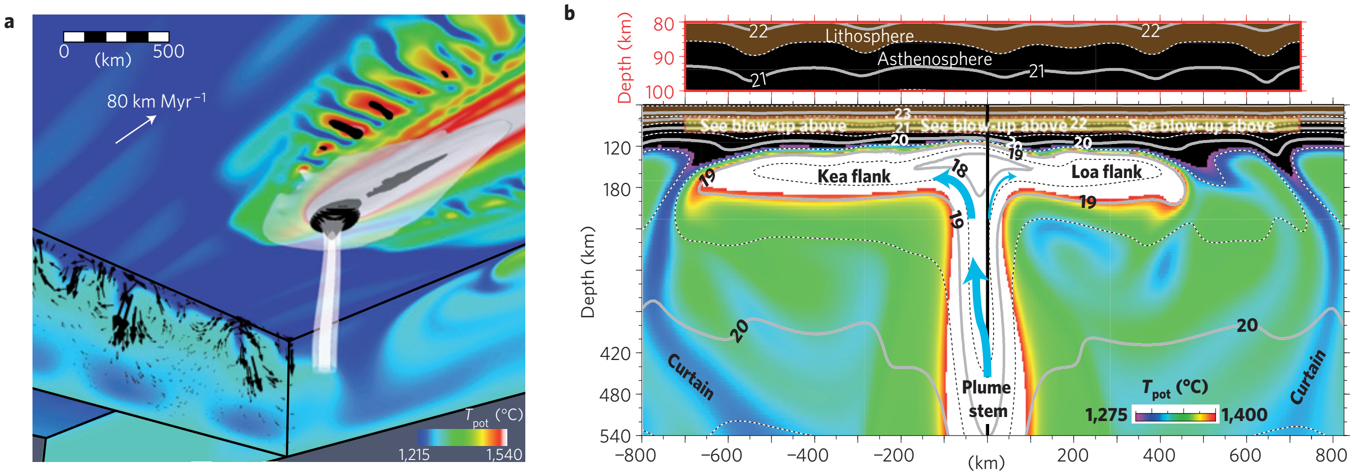

Figure 2 | Visualization of the central part of the reference model. a, Horizontal (at 130 km depth) and vertical cross-sections are coloured by potential temperature T_{pot}. The hotspot and secondary melting zones are in black. Isotherms of 1,550 and 1,620 °C are white. Black arrows show the direction and strength of ambient-mantle SSC 800 km upstream of the plume. See also Supplementary Movie. **b**, Vertical cross-section of T_{pot} and viscosity η through the upwelling plume oriented perpendicular to plate-motion with contours denoting $\log_{10}(\eta)$. Upper panel shows a blow-up of the yellow-shaded area. Light blue arrows show the schematic flow field indicating that the plume pancake spreads asymmetrically as guided by undulations in lithospheric thickness.

well away from the Hawaiian hotspot (Fig. 1a) has so far been attributed to lateral spreading of the pancake[3] or flexural uplift[18], but even a combination of both mechanisms cannot account for the large volumes of secondary volcanism as observed on the north arch[19], and Kauai[17] (cf. Supplementary Information SC). We use three-dimensional numerical simulations to show that the interaction of small-scale sublithospheric convection (SSC) with the Hawaiian plume (Fig. 1b)—a combination of two well-studied geodynamic phenomena[2–5,21–23]—can explain many key aspects of these three observations together.

Compared to previous geodynamic modelling studies[3–5,24] of mantle plumes, this study involves numerical simulations of significantly larger model boxes and a strongly temperature-dependent mantle rheology, advances that for the first time enable simulations of vigorous SSC both inside and outside the plume pancake. The effective ambient mantle viscosity, excess temperature and radius of the plume are fixed at 1.8×10^{19} Pa s, 300 K and 68 km, respectively (Supplementary Table S1; for methods see Supplementary Information SA). These parameters result in a flux of upwelling buoyant plume material of ~4,000 kg s^{-1} and a predicted seafloor swell of width ~1,300 and height ~1.2 km. A volcanic flux of ~150,000 km^3 Myr^{-1} predominantly (>99%) occurs at the hotspot centre of width ~110 km and length ~125 km. Thus, the island-building shield stage volcanism lasts ~1.5 Myr on the plate overriding the hotspot. We assume the mantle source to be a fine-scale mixture of 80% dry peridotite, 15% hydrous peridotite, and 5% pyroxenite. Each of these lithologies has a distinct melting behaviour with hydrous peridotite and pyroxenite having the deepest solidi, and pyroxenite melting much more extensively than peridotite. Thus, pyroxenite melting contributes >50% to shield stage volcanism, whereas the much more voluminous dry-peridotite matrix contributes only ~38%. These predictions are robust and fall close to the uncertainty of constraints for Hawaii as based on published data and/or models[7,8,25–27].

The numerical models predict two types of SSC to occur (Fig. 2a). In the ambient mantle, SSC self-organizes beneath mature oceanic lithosphere as convection rolls aligned with plate motion and spaced ~300 km. This form of SSC is thought to be the primary mechanism for limiting the maximum thickness of mature oceanic lithosphere globally, thus slowing the subsidence of seafloor of ages ≥70 Myr (ref. 22). SSC is therefore likely to be already well established beneath the ~90 Myr-old Hawaiian lithosphere. A different form of SSC develops inside the pancake of hot plume material ponding beneath the lithosphere (cf. ref. 24). This 'plume-pancake SSC' is more vigorous, of smaller scale, and forms a more variable pattern owing to lower viscosities in the hot pancake (Supplementary Fig. S1). Its occurrence does not require ambient-mantle SSC, but its pattern and strength in detail are sensitive to the style of the latter (Supplementary Information SB, Figs S2 and S3).

SSC in the ambient mantle upstream of the plume creates sublithospheric topography and hence affects plume-lithosphere interaction. It shapes a 'washboard' pattern into the base of the lithosphere (of wavelength ~300 km), which is thinned above SSC upwellings and thickened above downwellings (Fig. 2b). The Hawaiian plume impacts this pre-shaped lithosphere, and in all cases with the impact site not precisely beneath a minimum in lithospheric thickness, the pancake spreads asymmetrically: the buoyant and hot core of the ponding plume is deflected towards the nearest minimum in lithospheric thickness, resulting in slightly higher temperatures within one flank of the pancake—hereinafter referred to as the 'Kea' flank—compared with the opposite 'Loa' flank (Fig. 2b).

With the compositionally heterogeneous mantle source modelled, such asymmetry in mantle flow gives rise to asymmetry in the type of material that melts, with important implications for magma geochemistry. The hotter Kea half of the main hotspot melting zone experiences higher maximum and mean extents[12,28] of peridotite melting than the less hot Loa half, whereas pyroxenite melts 100% on both halves. Such a situation implies higher volcanic flux and a lower fractional contribution of pyroxenite-derived melts X_{PX} on the Kea side than on the Loa side. Figure 3 shows for our reference model that shield stage volcanic flux totals 86,800 km^3 Myr^{-1} with $X_{PX} \approx 49\%$ on the Kea side, whereas it totals 65,700 km^3 Myr^{-1} with $X_{PX} \approx 53\%$ on the Loa side. These predictions are consistent with the geological record of average volcanic flux along the Hawaiian Kea and Loa trends (94,400 and 75,400 km^3 Myr^{-1}, respectively[26]), as well as with evidence for mafic materials being an important source component of Hawaiian hotspot volcanism, and even more so in the Kea than in the Loa volcanoes[17,27]. In our models, the difference in X_{PX} between the Kea and Loa sides arises purely from interaction

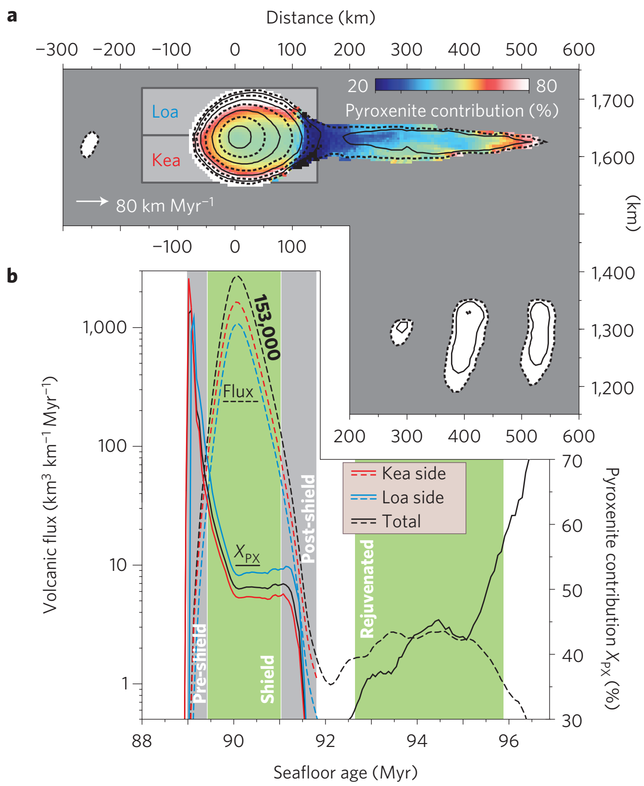

Figure 3 | Source and volume flux of surface volcanism. a, Colours give the pyroxenite contribution to volcanism (grey is no volcanism), and contours denote the rate of volcanism per area of seafloor. From outside to inside, dashed contours are at 0.01, 0.1, 1, and 10 $km^3\ km^{-2}\ Myr^{-1}$. The solid contours follow the same log scale shifted by $10^{0.5}$. Pyroxenite contribution X_{PX} in the centre of the hotspot is ~50%, but is slightly higher and lower along the Kea and Loa trends, respectively. This distinction persists through the postshield stage, as does the geochemical distinction between the two trends[10]. Rejuvenated and arch volcanism shows relatively low (~40%) and high (>97%, not shown) X_{PX}, respectively. **b**, Dashed lines denote volcanic fluxes ($km^3\ Myr^{-1}$ per km of distance along the chain) for the Kea trend (red), the Loa trend (blue), and the total of both trends (black). The assumed feeding zones for the two trends are denoted light grey in **a**. Solid lines show the pyroxenite contribution for the same colour code, and elucidate the asymmetry of shield and postshield volcanism arising from the distribution shown in the map view in **a**. The bold black number indicates the total flux of hotspot volcanism in ($km^3\ Myr^{-1}$). Green and grey shadings denote the predicted durations of the major phases of Hawaiian volcanism (as defined by volume flux).

of the plume with SSC, and a source with fine-scale compositional heterogeneity; it is independent of any large-scale compositional zoning in the plume conduit, as has been previously implied[9–11].

Moreover, the total volcanic flux at Hawaii is sensitive to the pattern and strength of ambient-mantle SSC. Model calculations show that modest (~100 km) changes in the relative position of SSC and the plume alone can alter volcanic flux by >25% (numbers in Fig. 3b, Supplementary Information S4 and SB). The main reason is that the spreading of and convection within the pancake are sensitive to lithospheric thickness undulations (washboard) created by ambient-mantle SSC. In nature, fracture zones, other sources of mantle density heterogeneity, and changes in plate motion can alter the position as well as the amplitude of the lithospheric thickness undulations[23], and hence influence magma production. Plume interaction with these undulations is a mechanism within the shallow, rather than deep mantle for creating some of the large variations in Hawaiian volcanic flux seen in the geologic record[7,8].

SSC in the plume-pancake gives rise to decompression melting well awayfrom the hotspot centre, thus explaining the occurrence of widespread secondary volcanism (Fig. 3a). At the distal flanks of the pancake, SSC occurs as short rolls perpendicular to plate motion (Supplementary Information SB and Fig. S1); associated melting can explain the expansive North Arch Volcanic Fields[19] (cf. Fig. 1a). Directly upstream of the hotspot melting zone, a localized SSC upwelling is predicted to support arch volcanism south of the islands[20]. Moreover, downstream of the main melting zone, a prominent upwelling erodes the lithosphere (by 10–15 km) and induces decompression melting, which would appear as the rejuvenated volcanic stage[13,17,18]. The most productive part of this secondary melting zone spans an along-chain distance of ~300 km, and is preceded by a pronounced minimum in melting, thereby producing a near 'gap' in magmatism spanning ~80 km. These length-scales agree well with observations[17,18]. The fluxes of the predicted arch and rejuvenated volcanism total 0.36–0.6% and 0.08–0.4% of the hotspot volcanic flux, respectively (i.e. ~0.5–1% combined); therefore our model has no difficulty in explaining voluminous secondary volcanism on the north arch[19] and Kauai[17] (details in Supplementary Information SB and SC). The precise fluxes of secondary volcanism, however, are sensitive to the rheological and melt extraction parameters applied (Supplementary Fig. S7). Finally, those of arch volcanism critically depend on the action of ambient-mantle SSC to thin the lithosphere. A separate calculation identical to the reference case, but without ambient-mantle SSC, predicts no arch volcanism at all (Supplementary Fig. S3).

Two distinct sources are predicted to feed secondary volcanism. The first involves relatively shallow melting (125–135 km) of harzburgitic peridotite; it accounts for ~60% of the rejuvenated volcanism but a negligible amount to arch volcanism (cf. Fig. 3a) and therefore should influence the major-element signature of rejuvenated lavas only (cf. ref. 17). The second source is pyroxenite: a deeper melting (135–150 km) fertile lithology, which can be traced back to the periphery of the plume stem. In contrast to the harzburgitic peridotite, this peripheral fertile source bypassed the main hotspot melting zone to avoid depletion and retain incompatible elements. Therefore, it is expected to control incompatible-element ratios and many isotope systems of both arch and rejuvenated lavas.

To satisfy isotopic evidence for distinct source materials in shield and secondary volcanism[13–16], the centre (which feeds the shields) and periphery of the plume stem would have to differ compositionally. As previously suggested, the peripheral source may be isotopically depleted ambient-mantle material as entrained by the mantle plume[9,15]. Trace-element signatures of secondary volcanism require that such peripheral material was metasomatized by incipient melts from the plume centre[14,16], whereas Os-isotope signatures point to pyroxenitic ambient-mantle heterogeneity[13]. Both these scenarios emphasize the importance of peripheral fertile material that starts melting deeper than dry peridotite (perhaps but not necessarily pyroxenite), and such behaviour is key to our model predictions of secondary volcanism.

Geophysical evidence lends additional credibility to our models. Recent high-resolution seismic tomography reveals a broad low-velocity body in the upper mantle beneath the Hawaiian swell with pronounced small-scale variability[29,30]. These variations are asymmetric about the islands[29,30], an observation that—in combination with asymmetric swell topography[25] (Fig. 1a)—is consistent with higher densities in the mantle northeast than southwest of Hawaii. Such constraints are well explained by the predicted effects of SSC on the Hawaiian plume—particularly by asymmetric plume-pancake spreading, and SSC in the pancake.

This study elucidates that shallow processes such as SSC affect plume-lithosphere interaction to induce temporal, spatial and geochemical variability in hotspot volcanism. SSC may not just affect the Hawaiian plume and associated volcanism, but also other plumes impacting mature lithosphere or spreading within low-viscosity asthenosphere (for example, in the South Pacific), where SSC is thought to develop beneath younger seafloor than elsewhere[21,23]. Future efforts are therefore needed to distinguish between shallow versus deep controls on hotspot magmatism, which is important for understanding patterns of heterogeneity and convection in the mantle.

Received 4 December 2010; accepted 20 May 2011; published online 26 June 2011

References

1. Morgan, W. J. Convection plumes in the lower mantle. *Nature* **230,** 42–43 (1971).
2. Sleep, N. H. Hotspots and mantle plumes—some phenomenology. *J. Geophys. Res.* **95,** 6715–6736 (1990).
3. Ribe, N. M. & Christensen, U. R. The dynamical origin of Hawaiian volcanism. *Earth Planet. Sci. Lett.* **171,** 517–531 (1999).
4. Zhong, S. J. & Watts, A. B. Constraints on the dynamics of mantle plumes from uplift of the Hawaiian Islands. *Earth Planet. Sci. Lett.* **203,** 105–116 (2002).
5. van Hunen, J., Huang, J. & Zhong, S. The effect of shearing on the onset and vigor of small-scale convection in a Newtonian rheology. *Geophys. Res. Lett.* **30,** 1991 (2003).
6. Steinberger, B. Plumes in a convecting mantle: Models and observations for individual hotspots. *J. Geophys. Res.* **105,** 11127–11152 (2000).
7. van Ark, E. & Lin, J. Time variation in igneous volume flux of the Hawaii–Emperor hot spot seamount chain. *J. Geophys. Res.* **109,** B11401 (2004).
8. Vidal, V. & Bonneville, A. Variations of the Hawaiian hot spot activity revealed by variations in the magma production rate. *J. Geophys. Res.* **109,** B03104 (2004).
9. Lassiter, J. C., DePaolo, D. J. & Tatsumoto, M. Isotopic evolution of Mauna Kea volcano: Results from the initial phase of the Hawaii Scientific Drilling Project. *J. Geophys. Res.* **101,** 11769–11780 (1996).
10. Hanano, D., Weis, D., Scoates, J. S., Aciego, S. & DePaolo, D. J. Horizontal and vertical zoning of heterogeneities in the Hawaiian mantle plume from the geochemistry of consecutive postshield volcano pairs: Kohala-Mahukona and Mauna Kea-Hualalai. *Geochem. Geophys. Geosyst.* **11,** Q01004 (2010).
11. Abouchami, W. *et al*. Lead isotopes reveal bilateral asymmetry and vertical continuity in the Hawaiian mantle plume. *Nature* **434,** 851–856 (2005).
12. Bianco, T. A., Ito, G., van Hunen, J., Ballmer, M. D. & Mahoney, J. J. Geochemical variation at the Hawaiian hot spot caused by upper mantle dynamics and melting of a heterogeneous plume. *Geochem. Geophys. Geosyst.* **9,** Q11003 (2008).
13. Lassiter, J. C., Hauri, E. H., Reiners, P. W. & Garcia, M. O. Generation of Hawaiian post-erosional lavas by melting of a mixed lherzolite/pyroxenite source. *Earth Planet. Sci. Lett.* **178,** 269–284 (2000).
14. Yang, H. J., Frey, F. A. & Clague, D. A. Constraints on the source components of lavas forming the Hawaiian North Arch and Honolulu volcanics. *J. Petrol.* **44,** 603–627 (2003).
15. Fekiacova, Z., Abouchami, W., Galer, S. J. G., Garcia, M. O. & Hofmann, A. W. Origin and temporal evolution of Ko'olau Volcano, Hawai'i: Inferences from isotope data on the Ko'olau Scientific Drilling Project (KSDP), the Honolulu Volcanics and ODP Site 843. *Earth Planet. Sci. Lett.* **261,** 65–83 (2007).
16. Dixon, J., Clague, D. A., Cousens, B., Monsalve, M. L. & Uhl, J. Carbonatite and silicate melt metasomatism of the mantle surrounding the Hawaiian plume: Evidence from volatiles, trace elements, and radiogenic isotopes in rejuvenated-stage lavas from Niihau, Hawaii. *Geochem. Geophys. Geosyst.* **9,** Q09005 (2008).
17. Garcia, M. O. *et al.* Petrology, Geochemistry and Geochronology of Kaua'i Lavas over 4 center dot 5 Myr: Implications for the Origin of Rejuvenated volcanism and the evolution of the Hawaiian plume. *J. Petrol.* **51,** 1507–1540 (2010).
18. Bianco, T. A., Ito, G., Becker, J. M. & Garcia, M. O. Secondary Hawaiian volcanism formed by flexural arch decompression. *Geochem. Geophys. Geosyst.* **6,** Q08009 (2005).
19. Clague, D. A., Uto, K., Satake, K., Davis, A. S. & Eruption, in *Hawaiian Volcanoes: Deep Underwater Perspective* Vol. 128 (ed. Takahashi, E.) 65–84 (Geophys. Monogr. Series, AGU, 2002).
20. Lipman, P. W., Clague, D. A., Moore, J. G. & Holcomb, R. T. South Arch Volcanic Field—newly identified young lava flows on the sea-floor south of the Hawaiian Ridge. *Geology* **17,** 611–614 (1989).
21. Ballmer, M. D., Ito, G., van Hunen, J. & Tackley, P. J. Small-scale sublithospheric convection reconciles geochemistry and geochronology of 'Superplume' volcanism in the western and south Pacific. *Earth Planet. Sci. Lett.* **290,** 224–232 (2010).
22. van Hunen, J., Zhong, S. J., Shapiro, N. M. & Ritzwoller, M. H. New evidence for dislocation creep from 3-D geodynamic modeling of the Pacific upper mantle structure. *Earth Planet. Sci. Lett.* **238,** 146–155 (2005).
23. Huang, J. S., Zhong, S. J. & van Hunen, J. Controls on sublithospheric small-scale convection. *J. Geophys. Res.* **108,** 2405–2417 (2003).
24. Moore, W. B., Schubert, G. & Tackley, P. J. Three-dimensional simulations of plume–lithosphere interaction at the Hawaiian swell. *Science* **279,** 1008–1011 (1998).
25. Wessel, P. Observational constraints on models of the Hawaiian hot-spot swell. *J. Geophys. Res.* **98,** 16095–16104 (1993).
26. Robinson, J. E. & Eakins, B. W. Calculated volumes of individual shield volcanoes at the young end of the Hawaiian Ridge. *J. Volcanol. Geotherm. Res.* **151,** 309–317 (2006).
27. Sobolev, A. V., Hofmann, A. W., Sobolev, S. V. & Nikogosian, I. K. An olivine-free mantle source of Hawaiian shield basalts. *Nature* **434,** 590–597 (2005).
28. Ito, G. & Mahoney, J. J. Flow and melting of a heterogeneous mantle: 1. Method and importance to the geochemistry of ocean island and mid-ocean ridge basalts. *Earth Planet. Sci. Lett.* **230,** 29–46 (2005).
29. Wolfe, C. J. *et al.* Mantle shear-wave velocity structure beneath the Hawaiian hot spot. *Science* **326,** 1388–1390 (2009).
30. Wolfe, C. J. *et al.* Mantle P-wave velocity structure beneath the Hawaiian hotspot. *Earth Planet. Sci. Lett.* **303,** 267–280 (2011).

Acknowledgements

M.D.B. has been supported by SNF-grants PBEZP2-127810 and 20020-119922/1, and G.I by grants NSF-0510482 and NSF-0855814. We are grateful to C. J. Wolfe and M. O. Garcia for input on earlier versions of the manuscript. Calculations were done at the Hawaii Open Supercomputing Center (HOSC).

Author contributions

M.D.B. carried out the numerical experiments. M.D.B. and G.I. led the interpretation of model results and writing, followed by J.v.H. and P.J.T.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.D.B.