Supplementary material

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SA. First-order plume characteristics

The size of the modeled plumes in cases A and B and their most robust surface expressions are comparable with those estimated for the Hawaiian plume. The excess temperature of 300 K for the modeled plumes is consistent with petrologic estimates for the excess temperature of the source of Hawaiian lavas (Herzberg et al., 2007). At the base of the model domain, the thermal buoyancy fluxes are 6850 kg/s in case A and 5300 kg/s in case B. The compositional buoyancy fluxes (i.e., the product of the volume flux of eclogitic material and its negative excess density) are -4350 kg/s in case A and -3800 kg/s in case B. In the shallowest part of the plume, the compositional buoyancy fluxes are greatly reduced because of the effects of eclogite melting, whereas the thermal buoyancy fluxes remain almost unchanged. Therefore, the total buoyancy fluxes in the shallowest plume are similar to the thermal buoyancy fluxes at the base of the model domain and are within the range of previous estimates for Hawaii, i.e., 2800–8700 kg/s (Sleep, 1990; Ribe and Christensen, 1994, 1999; Vidal and Bonneville, 2004; Crosby and McKenzie, 2009; Asaadi et al., 2011). The predicted hotspot swell dimensions (e.g., ~1 km in relief and ~1200 km in width for case A) are consistent with estimates for the Hawaiian swell (Wessel, 1993; Crosby and McKenzie, 2009). Both for the actual topography and for our models, the shape of the swell is asymmetric about its main axis. Age–distance relationships of volcanism predicted by cases A and B are linear and nearly linear, respectively, and correspond to the imposed speed of plate motion. In case B, the lateral hotspot motion due to plume wobble of 50 km or less is similar to the average spacing of the Hawaiian volcanoes (ten Brink, 1991) and hence too small to considerably disrupt this relationship. Finally, the predicted volcanic fluxes in cases A and B (Fig. 8) are comparable to those inferred for the Hawaiian hotspot (van Ark and Lin, 2004; Robinson and Eakins, 2006).

SB. Seismic resolution test

In order to test our results, we compared geodynamic model predictions with the seismic shear-wave velocity model obtained from the inversion of shear-wave travel-time delays measured during the Plume-Lithosphere Undersea Melt Experiment (PLUME) (Wolfe et al., 2009). We calculated a three-dimensional synthetic shear-wave velocity model from the temperature, density, and lithostatic pressure of the quasi steady-state case A. These fields were projected from our finite-element mesh to the grid of *Wolfe et al.* (2009) and extrapolated into the lower mantle. The synthetic model was computed (Faul and Jackson, 2005) with a grain size d = 1 mm, activation volume V^* = 12 cm^3/mol, and seismic frequency f = 0.07 Hz. In computing a first synthetic, we neglected the compositional effects of water, melt, and eclogite content, as well as the effect of depletion of peridotite on the synthetic seismic velocities (except for the effects of compositional density on lithostatic pressure). Although the high garnet content in dry eclogites acts to increase seismic velocities at depths <410 km and >780 km, the effect of volatiles in eclogites (both in nominally anhydrous and hydrous minerals) may trade off with and actually reverse this increase (Connolly and Kerrick, 2002; Zhang and Green, 2007; Abalos et al., 2011). To estimate this influence of eclogite conservatively, we computed a second synthetic including the effects of modal mineralogy and density of MORB-like eclogite on seismic velocity (Xu et al., 2008), but excluding the effects of volatile content in eclogite (Table S1, Fig. 9A). Finally, we computed synthetic shear-wave velocities for a classical thermal plume (Fig. 9B), derived from a numerical simulation [cf. reference case in *Ballmer et al.* (2011)] with a model set up and controlling parameters that are analogous to those of cases A and B except for the missing effects of eclogite on plume ascent and magmatism.

As a first step, we compared synthetic delay times with PLUME observations. Delay times for each event–station pair (Wolfe et al., 2009) were computed as travel-time residuals relative to a IASPEI one-dimensional reference model. Residuals from each station were averaged and interpolated to the profile from Fig. 1 by continuous-curvature surface gridding (insets in Figs. 9A-B). As a second step, we compared seismic shear-wave velocity models (Figs. 9C-D) obtained from inversions of these predicted delay times [after the addition of white noise (Wolfe et al., 2009)] with the velocity models from the inversion of actual observations (Fig. 2). Comparisons both of the level of delay times as well as of shear-wave velocity models argue against a simple thermal plume and in favor of a thermochemical plume beneath Hawaii (see main text and Figs. 2, 9), independent of whether or not the effects of eclogite on seismic velocity were taken into account. Since we estimated these effects conservatively, we conclude that they are insufficient to render the DEP seismically invisible.

Table S1. Effect of eclogite on seismic velocities.

Depth range [km]	Velocity increase [km/s]
100 to 300	0.17302
300 to 410	0.2378
410 to 660	-0.10619
660 to 780	-0.43255
780 to 2000	0.12628

Notes: These estimates were derived from the thermodynamics-based parameterizations of *Xu et al.* (2008) (cf. their Figure 5b), which neglects the potentially important effects of volatiles and hydrous minerals to reduce seismic velocities (Connolly and Kerrick, 2002) and thus yields conservative values. The velocity increases shown are valid for pure eclogite. To generate synthetic seismic velocities, these increases were scaled by the model eclogite fraction (e.g., by 15% in the deep plume stem). Note that even dry eclogite acts to reduce seismic velocities in the depth range 410 to 780 km.

Supplemental Movies

Movie S1. Animation of a perspective view of potential temperature and magmatism for case A. For a detailed description, see Fig. 3A.

Movie S2. Animation of a perspective view of potential temperature and magmatism for case B. For a detailed description, see Fig. 5A. Model time is annotated.

Movie S3. Animation of the geographical distribution of volcanism for case B. For the legend and a detailed description, see Fig. 6B. Model time is annotated.

References

Abalos, B., Fountain, D.M., Ibarguchi, J.I.G., Puelles, P., 2011. Eclogite as a seismic marker in subduction channels: seismic velocities, anisotropy, and petrofabric of Cabo Ortegal eclogite tectonites (Spain). Geol. Soc. Am. Bull. 123, 439-477.

Asaadi, N., Ribe, N.M., Sobouti, F., 2011. Inferring nonlinear mantle rheology from the shape of the Hawaiian swell. Nature 473, 501-504.

Ballmer, M.D., Ito, G., van Hunen, J., Tackley, P.J., 2011. Spatial and temporal variability in Hawaiian hotspot volcanism induced by small-scale convection. Nature Geoscience 4, 457-460.

Connolly, J.A.D., Kerrick, D.M., 2002. Metamorphic controls on seismic velocity of subducted oceanic crust at 100-250 km depth. Earth Planet. Sci. Lett. 204, 61-74.

Crosby, A.G., McKenzie, D., 2009. An analysis of young ocean depth, gravity and global residual topography. Geophys. J. Int. 178, 1198-1219.

Faul, U.H., Jackson, I., 2005. The seismological signature of temperature and grain size variations in the upper mantle Earth Planet. Sci. Lett. 234, 119-134.

Herzberg, C., Asimow, P.D., Arndt, N., Niu, Y.L., Lesher, C.M., Fitton, J.G., Cheadle, M.J., Saunders, A.D., 2007. Temperatures in ambient mantle and plumes: constraints from basalts, picrites, and komatiites. Geochem. Geophys. Geosyst. 8, 34, doi: 10.1029/2006gc001390.

Ribe, N.M., Christensen, U.R., 1994. Three-dimensional modeling of plume-lithosphere interaction. J. Geophys. Res. 99, 669-682.

Ribe, N.M., Christensen, U.R., 1999. The dynamical origin of Hawaiian volcanism. Earth Planet. Sci. Lett. 171, 517-531.

Robinson, J.E., Eakins, B.W., 2006. Calculated volumes of individual shield volcanoes at the young end of the Hawaiian Ridge. J. Volcanology Geothermal Res. 151, 309-317.

Sleep, N.H., 1990. Hotspots and mantle plumes - some phenomenology. J. Geophys. Res. 95, 6715-6736.

ten Brink, U., 1991. Volcano spacing and plate rigidity. Geology 19, 397-400.

van Ark, E., Lin, J., 2004. Time variation in igneous volume flux of the Hawaii-Emperor hot spot seamount chain. J. Geophys. Res. 109, B11401 doi: 10.1029/2003jb002949.

Vidal, V., Bonneville, A., 2004. Variations of the Hawaiian hot spot activity revealed by variations in the magma production rate. J. Geophys. Res. 109, B03104, doi: 10.1029/2003jb002559.

Wessel, P., 1993. Observational constraints on models of the Hawaiian hot-spot swell. J. Geophys. Res. 98, 16095-16104.

Wolfe, C.J., Solomon, S.C., Laske, G., Collins, J.A., Detrick, R.S., Orcutt, J.A., Bercovici, D., Hauri, E.H., 2009. Mantle shear-wave velocity structure beneath the Hawaiian hot spot. Science 326, 1388-1390.

Xu, W., Lithgow-Bertelloni, C., Stixrude, L., Ritsema, J., 2008. The effect of bulk composition and temperature on mantle seismic structure. Earth Planet. Sci. Lett. 275, 70-79.

Zhang, J., Green, H.W., 2007. Experimental investigation of eclogite rheology and its fabrics at high temperature and pressure. J. Metamorphic Geol. 25, 97-115.