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Double layering of a thermochemical plume in the upper mantle beneath Hawaii

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ABSTRACT

According to classical plume theory, purely thermal upwellings rise through the mantle, pond in a thin layer beneath the lithosphere, and generate hotspot volcanism. Neglected by this theory, however, are the dynamical effects of compositional heterogeneity carried by mantle plumes even though this heterogeneity has been commonly identified in sources of hotspot magmas. Numerical models predict that a hot, compositionally heterogeneous mantle plume containing a denser eclogite component tends to pool at ∼300–410 km depth before rising to feed a shallower sublithospheric layer. This double-layered structure of a thermochemical plume is more consistent with seismic tomographic images at Hawaii than the classical plume model. The thermochemical structure as well as time dependence of plume material rising from the deeper into the shallower layer can further account for long-term fluctuations in volcanic activity and asymmetry in bathymetry, seismic structure, and magma chemistry across the hotspot track, as are observed.

1. Introduction

Hotspots dominate volcanism interior to Earth's tectonic plates and are related to convective processes and chemical heterogeneity in the underlying mantle. The characteristics of the Hawaiian hotspot, in particular, have been key to the development of classical plume theory, a well-established paradigm for understanding the hotspot phenomenon (Morgan, 1972). According to this theory, a high-temperature, buoyant plume rises vertically from the base of the mantle to pond beneath the lithosphere in a ∼100-km-thick "pancake." The ascending plume supports a broad area of uplifted seafloor, known as the hotspot swell, and sustains localized decompression melting that feeds age-progressive volcanism on the overriding plate (Morgan, 1972; Sleep, 1990; Ribe and Christensen, 1994, 1999).

Regional seismic tomographic studies of the Hawaiian hotspot (Wolfe et al., 2009, 2011; Laske et al., 2011) have called aspects of this model into question. Whereas anomalously low seismic velocities found in the lower and upper mantle confirm the presence of a high-temperature mantle plume, the upper-mantle low-velocity anomaly appears to have a greater vertical extent and is laterally more asymmetric about the island chain than predicted by the classical plume theory (Figs. 1–2). In particular, the station-averaged, body-wave travel-time residuals across the Hawaiian swell are larger than would be expected from a ∼100-km-thick pancake on the basis of independent surface-wave constraints (Wolfe et al., 2009, 2011; Laske et al., 2011). Moreover, episodic, high-amplitude variations in volcanic flux along the chain are evident in the geologic record for the past ∼85 Myr (van Ark and Lin, 2004; Vidal and Bonneville, 2004). These characteristics of the Hawaiian hotspot suggest that plume upwelling is more complex in space and time than portrayed by the classical model.

The classical plume theory emphasizes thermal buoyancy of typical mantle material, or peridotite, to drive upwelling. However, there is growing petrologic and geochemical evidence, especially at Hawaii, for the presence of eclogite in the magma source region (Hauri, 1996; Farnetani and Samuel, 2005; Sobolev et al., 2005, 2007; Herzberg, 2011; Jackson et al., 2012; Pietruszka et al., 2013), thought to originate from subducted oceanic crust and to be entrained by upwelling flow in the lower mantle (e.g., Deschamps et al., 2011). Because eclogite is denser than peridotite throughout the upper mantle and most of the lower mantle (Hirose, 2002; Aoki and Takahashi, 2004), the ascent of plumes containing both peridotite and eclogite will be influenced by a competition between non-diffusive, negative chemical buoyancy and diffusive, positive thermal buoyancy (e.g., Davaille, 1999). Compared with classical thermal plumes, such thermochemical plumes therefore display much more complex dynamics. For example, dense materials carried by the plume can induce large fluctuations in ascent

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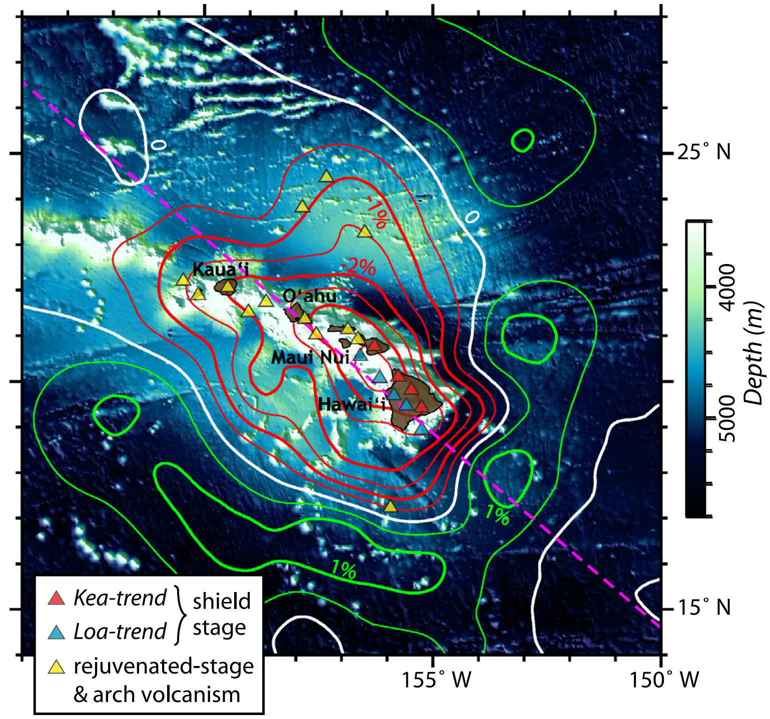

Fig. 1. Overview of bathymetry, volcanism, and seismic tomography of the Hawaiian hotspot. Bathymetry (colors) and contours of shear-wave velocity anomaly (Wolfe et al., 2009) at 200 km depth (1% contour interval for thick contours), two independent datasets, display consistent asymmetry about the island chain and indicate more buoyant asthenosphere southwest than northeast of the island of Hawaii. Triangles show sites of recent (<1 Ma) volcanic activity (Hanyu et al., 2005; Robinson and Eakins, 2006; Dixon et al., 2008). The pink dashed line denotes the location of the cross-section in Fig. 2. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

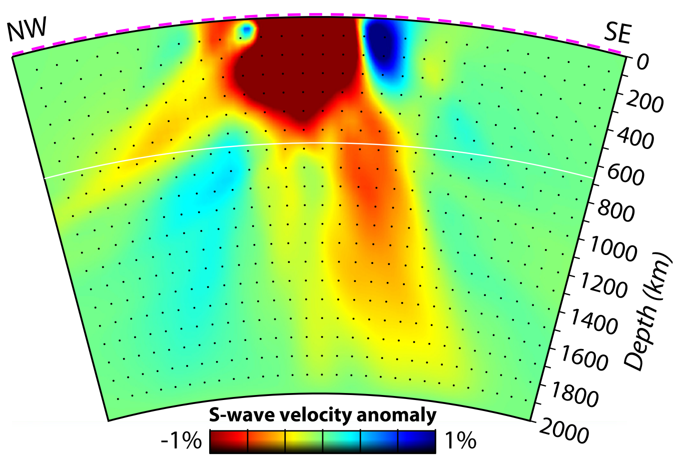

Fig. 2. Vertical cross-section of shear-wave velocity beneath Hawaii (Wolfe et al., 2009) along a northwest–southeast-trending profile (denoted by the pink dashed line in Fig. 1). (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

rate and volume flux as well as asymmetric behavior (Farnetani and Samuel, 2005; Lin and van Keken, 2005; Samuel and Bercovici, 2006; Kumagai et al., 2008; Sobolev et al., 2011). The effects of phase changes can further modify this behavior, for example, by affecting the rise of plumes through the boundary between the lower and upper mantle at 660 km depth (Farnetani and Samuel, 2005; Tosi and Yuen, 2011). Moreover, phase changes in the depth range of about 300–410 km can further increase the compositional density excess of eclogitic material (Aoki and Takahashi, 2004), an effect that is should strongly influence the dynamics of thermochemical plumes, but one that has yet to be explored.

In order to study the dynamics and melting behavior of a thermochemical plume in the upper mantle beneath the Hawaiian hotspot and to address the enigmatic seismic structure imaged, we have conducted three-dimensional numerical simulations. We show that the interaction of a thermochemical plume with phase changes can give rise to pooling of plume material in the mid upper mantle. Strong pulsations of plume flow out of this layer can lead to temporal and spatial variations in the volume flux and composition of hotspot magmatism, respectively. The behavior of this double-layered, thermochemical plume indeed permits a range of geophysical, geochemical, and geological observations to be addressed.

2. Methods and model description

The numerical simulations were produced using an extended version (see Section 2.1) of the finite element code Citcom (Moresi et al., 1996). The model domain of the numerical experiment was 5280 km long, 3300 km wide, and 660 km deep. It was divided into $768 \times 512 \times 96$ finite elements with rectangular faces and with the smallest elements (i.e., highest resolution) about $4.5 \times 4.5 \times 4.5$ km in dimensions and located in the asthenosphere near the hotspot. A velocity condition of 80 km/Myr was applied at the top boundary to simulate Pacific plate motion. Accordingly, the boundaries at the front and back were open to inflow and outflow, respectively. The other boundaries were closed except for a small circular area of radius 360 km around the base of the plume (which is centered 3135 km from the front boundary and 1650 km from the sides) to allow influx of plume material. At the bottom boundary, the plume's thermal anomaly was specified to decrease as a Gaussian function of radial distance from the center, with a peak amplitude of 300 K and a half width of 75 km.

The modeled plume contains eclogite within a radial distance r_P of its center, and the eclogite makes up 15% of the mass of this portion of the plume (cf. Sobolev et al., 2005). Outside of r_P, the ambient mantle was taken to contain no eclogite, but instead 15%