Geophysical Research Abstracts
Vol. 14, EGU2012-3262-2, 2012
EGU General Assembly 2012

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

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Volcanism far from plate boundaries has traditionally been explained by "classical" plume theory. Classical plumes are typically described as narrow thermal upwellings that rise through the entire mantle to be deflected into a thin (<100 km) "pancake" beneath the overriding lithosphere. The pancake is thought to be deflected by the drag of the overriding plate and hence to support a hotspot swell that is parabolic in map view and symmetric about the direction of plate motion. Many hotspots and their swells, such as Cape Verde and Iceland, are indeed well explained by near-classical thermal plumes.

High-resolution seismic velocity images obtained from the PLUME project support the concept of a deep-rooted mantle plume beneath the Hawaiian hotspot. However, in detail these images challenge traditional concepts inasmuch as they indicate a low-velocity body in the upper mantle that is too thick ($\sim$400 km) and asymmetric to be interpreted as a classical pancake. Classical plume theory is, moreover, inconsistent with several geochemical characteristics of Hawaiian magmas, which point to a heterogeneous mantle source involving mafic lithologies such as eclogite and not an exclusively thermal (i.e. isochemical) origin[1].

To explore the dynamical and melting behavior of plumes containing a substantial fraction ($\sim$15%) of eclogite, we performed three-dimensional numerical simulations of thermochemical convection. Relative to ambient-mantle peridotite, eclogite is intrinsically dense. This density contrast is sensitive to phase changes in the upper mantle; the contrast peaks at 410-300 km and lessens at about 250-190 km depth, where eclogite is subsequently removed by melting. For a plume core with an eclogite content >12%, these effects locally increase the density beyond that of the ambient mantle. Therefore, the upwelling column forms a broad and thick pool at depths of 450-300 km (which we term the deep eclogite pool, or DEP). As the DEP is well supported by the deeper stem of the plume and its non-eclogitic outskirts, it inflates to release a shallow thermal plume. This latter plume sustains hotspot volcanism and feeds a hot shallow pancake that compensates the seafloor swell.

Our model predictions reconcile a range of characteristics for Hawaiian volcanism. We find that the small-scale convection that develops within the hot pancake[2] is sufficient to support rejuvenated and arch volcanism, as well as to account for the apparent decrease of the geoid-to-topography ratio (GTR) along the Hawaiian Swell. The double layering of hot plume material (DEP and shallow pancake) forms a thick and asymmetric feature. Seismic resolution tests indicate that this double layering can account for the thick and asymmetric low-velocity body as imaged by PLUME. We also show that thermochemical plumes with slightly larger volumes of eclogitic material display pulsations from the DEP upwards, a behavior that can explain temporal variability of Hawaiian hotspot volcanism[3]. Finally, models with a diffuse distribution of eclogite in the plume give rise to bilateral asymmetry in the predicted contribution of mafic material to partial melting. Such lateral variability in the source of volcanism has been proposed to account for the prominent Loa-versus-Kea geochemical trends in Hawaiian lavas[1].

Building on previous work for the lower mantle, our results reveal the relevance of thermochemical convection for the upper mantle, specifically for the overall dynamics of mantle plumes, the genesis of intraplate volcanism, and ocean-island geochemistry.

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