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Thermochemical plume models can reconcile upper-mantle seismic velocity structure beneath Hawaii

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Volcanism far from plate boundaries, in Hawaii and elsewhere, has traditionally been explained by "classical" plume theory [1]. Classical plumes are typically described as purely thermal, narrow upwellings that rise through the entire mantle and are deflected into a thin (<100 km) bilaterally symmetric "pancake" beneath the overriding lithosphere [2-3]. New high-resolution seismic velocity images obtained from the Plume Lithosphere Undersea Melt Experiment (PLUME) indeed support the concept of a plume-like upwelling originating from the lower mantle to feed Hawaiian volcanism [4-6]. However, in detail those images challenge classical plume theory inasmuch as they indicate a low-velocity body in the upper mantle that is too thick (400 km) and non-symmetric to be interpreted as a classical plume pancake [4]. Classical thermal plumes are, moreover, inconsistent with aspects of the geochemistry of Hawaiian volcanism, which point to a heterogeneous mantle source involving mafic lithologies such as eclogite [7]. To explore the behavior of eclogite-rich plumes, we performed thermochemical, three-dimensional numerical experiments with strongly temperature-dependent rheology. Whereas the mantle is assumed to be peridotite, the plume is taken to be a fine-scale mixture involving 10-15% eclogite, which is denser than peridotite. The net buoyancy of an eclogite-rich plume is therefore markedly smaller than that of a purely thermal plume. This net buoyancy is minimal at depths 410-300 km [8], but grows at depths 250-190 km, where eclogite is removed by partial melting. For models with an eclogite content >12%, these effects cause the plume to form a broad and thick pool at depths of 480-300 km (deep eclogite pool, DEP). Near the leading edge of the DEP, a plumelet rises to feed a buoyant "pancake" that ponds beneath the lithosphere. Decompression melting at the deflection point of the plumelet supplies hotspot volcanism. Near the trailing edge of the DEP, a separate smaller plumelet rises to spawn widespread secondary volcanism. These two instabilities rising from the top of the DEP are transient in vigor, something that reconciles observations of temporal variability of Hawaiian shield volcanism [9-10]. The DEP, the plumelets and the pancake together form a bilaterally asymmetric feature. Thus, our model predictions can account for some of the prominent structures imaged by PLUME, including the thick and non-symmetric low-velocity body [4]. Whereas thermochemical convection has already been shown to play an important role in the lower mantle, our results indicate that it may be relevant to the upper mantle in terms of understanding seismic heterogeneity, the overall dynamics of mantle plumes, the generation of intraplate volcanism, and ocean island geochemistry.

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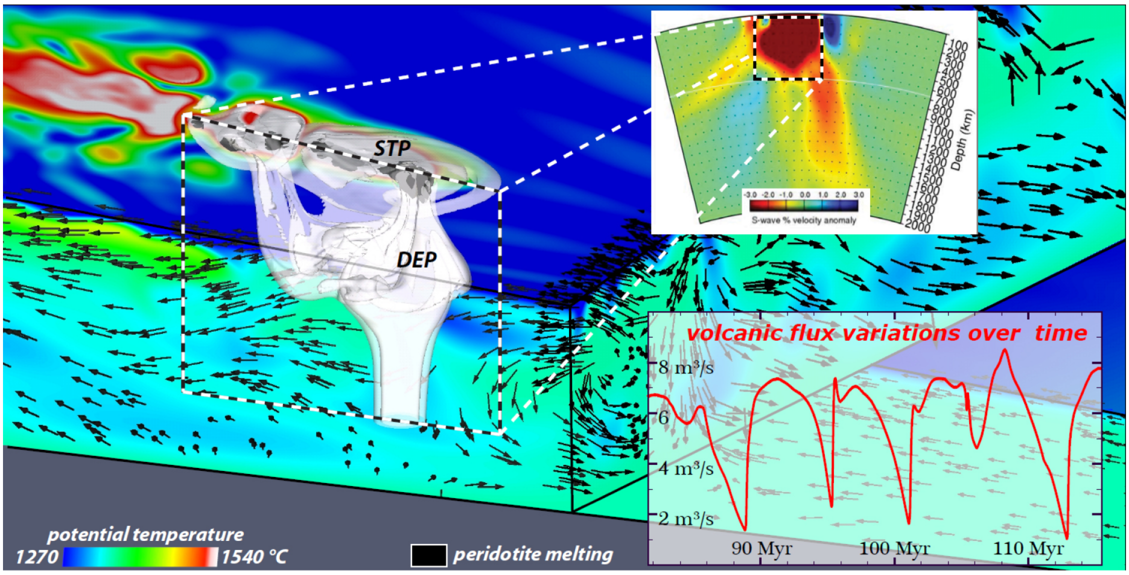

Figure 1: Numerical simulation of a thermochemical plume with 15% eclogite in the upper mantle. White isosurfaces of temperature reveal complex structure with a deep pooling of eclogitic material (DEP), secondary upwellings and a shallow thermal pancake (STP) below the lithosphere, which together could reconcile the body wave inversions from PLUME (cf. inset top right [4]). Predictions for such a thermochemical plume also include time variability of volcanic flux (cf. inset bottom right).