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Plume fluxes from seismic tomography

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Abstract

We use mantle plume images from finite frequency tomography and the Stokes equation to obtain a quantitative estimate of the heat and volume flux across several well resolved plume sections in mid-mantle. Although not a perfect barrier, widening of plumes just below 670 km depth indicates that the phase transition from ringwoodite to perovskite plus magnesowüstite and possibly iron enrichment of the lower mantle resists plume passage into the upper mantle. Estimated heat- and volume flux for individual plumes at mid-mantle depths is greater than predicted by surface observations of buoyancy flux, even for very high viscosity. Although uncertainties are large, the high flux observed in plumes at mid-mantle depth is compatible with the view that plumes are responsible for all upward advective heat transport in the lower mantle that eventually breaks through into the upper mantle.

Keywords: Mantle heat flux; Plumes; Lower mantle heterogeneity

1. Introduction

The Earth radiates about 44 TW (teraWatt or 10^{12} J/s) into space. Part of this energy is generated by radioactive decay of long-lived isotopes, mostly U, Th and K, part is due to secular cooling of the planet. The ratio between the two, the Urey number, is subject of intense debate [1,2]. But whatever the value of the Urey number, a substantial fraction of the heat flux must come from the lower mantle or core.

The lack of topography associated with buoyant upwellings generated at a possible thermal boundary layer precludes that heat moves from lower to upper mantle by conduction [3]. Both slabs and plumes are obvious candidates for heat transport by advection. In this paper we investigate if new tomographic results support the widely accepted view that only a small fraction (3 TW) of heat transport from lower to upper mantle is effected through plumes located beneath known, strong hotspots [3–5]. This view is based on the estimated values of the buoyancy flux for a number of plumes. The buoyancy flux B relates to the heat flux $Q_c^{\rm surf}$ near the surface through the thermal expansivity α and the heat capacity c_P: $B=\alpha c_P^{-1}\, Q_c^{\rm surf}$. For reasonable values of α and c_P near the surface of the Earth, this translates to a surface heat flux of

$$Q_c^{\rm surf} = 4.2\times10^7 B \qquad (1)$$

if B is in kg/s and Q_c in Watt. Sleep [4] gives a total buoyancy flux of 5.49×10^4 kg/s which translates to

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2.3 TW, or only 5% of the total heat flux of the Earth. Adding the contribution of flood basalts averaged over time this could be raised to 3.3 TW [6].

Seismic evidence for the existence of plumes in the lower mantle was until recently indirect (see Nataf [7] for a review). Broad lower mantle upwellings or 'superplumes' appeared in global tomographic studies in the past decade (see Romanowicz [8] for references). Plume-like features in the lower mantle were first imaged seismologically under Iceland [9], Central Europe [10], Africa [11], and a number of hotspots in the Pacific and Indo-Antlantic region [12,13]. The introduction of finite frequency tomography [14] greatly improved the imaging by correcting for 'wavefront healing', and the first study using this new technique resulted in tomographic images of the mantle with some twenty plumes that reach clearly below the 670 km discontinuity and that were shown to have diameters of 500 km or more [15]. Recently, Montelli et al. [16] improved this model (PRI-P05) and presented confirming evidence for lower mantle plumes from independent data (long-period S waves). The large width of the plumes suggests that they play a much more substantial role in heat transport than is implied by the 3 TW estimate. Simply put: plumes are difficult to resolve, if they were not big we wouldn't be able to see them, and assuming they have the heat capacity that befits them, they are important in the Earth's heat budget. Estimates from topographic swells are so far the only direct quantitative observations we have for plume fluxes. The first direct tomographic images of plumes seem to contradict these estimates at least in a qualitative sense. This paper is a first attempt to make this statement a little more quantitative. Though we realize that the uncertainties are very large, it is important to investigate if at least an agreement within an order of magnitude can be obtained for plume fluxes obtained from tomography and from surface observations.

The progress in plume imaging is such that we can make reasonably accurate estimates of the plume temperature anomaly for several well-resolved plume sections. This enables us to estimate the heat capacity of the plume. However, to calculate the *flux*, we also need to know the rise velocity v_z of the plume which makes additional demands on resolution quality and plume geometry. In this paper we use a simple model based on Poiseuille flow to derive approximate plume fluxes from the tomographic images. We assume a balance between frictional and buoyancy force at well-resolved cross-sections of several plumes. This assumption implies that the flow is predominantly vertical and that we are far away from the top or bottom of the plume where boundary forces operate. In fact, we shall see that the computations give nonphysical results at shallow levels, and we use this as a diagnostic that the assumption of vertical flow breaks down near the top of the plume. Surprisingly, the 'top' boundary is not necessarily the Earth's surface. In inspecting the plume images in model PRI-P05, it is remarkable how many plumes change character at the 670 km discontinuity. The role of this phase transition as a possible boundary for plumes is discussed in the next section.

2. The role of the 670 km discontinuity

Fig. 1 gives a good example of a plume meeting resistance upon entering the upper mantle. The large anomaly near the core–mantle boundary is linked to the African superplume. Temperatures are computed assuming a perovskite–magnesiowüstite composition, which may not be correct in the deepest part of the mantle, as exemplified in the blow-up of cold as well as hot anomalies. Canary rises up from the superplume. The Cape Verde plume further south is less well resolved and the merging of the plumes at mid-mantle depth may very well be a resolution artifact, as shown in the lower half of Fig. 1. At 670 the plume changes abruptly in character, and is very weak in the upper mantle. With broadband stations (TBT and SACV) on top of both plumes and several ISC-reporting stations on Cape Verde islands, the change in character cannot easily be attributed to lack of resolution, an observation that is confirmed by the resolution tests in [15]. Note also that even the upper mantle signal beneath the Azores shows up as an anomaly despite a relative lack of resolution.

Fig. 2 shows four more examples of plumes that broaden or deflect significantly when approaching the 670 km discontinuity. Resolution calculations for these plumes similar to those shown in Fig. 1 show that the spreading below the 670 is not a resolution artifact. In the case of Easter and Tahiti, the plume has broken through and reaches the surface.

The apparent hesitancy of several plumes to penetrate the phase transition resembles that of some slabs that reside in the transition zone before breaking through and sink into the lower mantle [17]. The spreading of plume material in the mesosphere which we observe here was hypothesized by Allègre [18] to explain the geochemical characteristics of basalts. However, the situation is not universal. In fact, several plumes seem to experience little resistance, as shown in Fig. 3, a situation also reminescent of that observed for slabs. Others such as Bouvet, Hainan, Hokkaido or Juan Fernandez appear as a blob just below 670 km, whereas Afar, Kerguelen, Bowie, Galapagos and Iceland seem to be stalling blobs that have broken through into the upper mantle (images not shown, but see [16]).