Evidence for mantle plumes?

Arising from: B. Bourdon, N. M. Ribe, A. Stracke, A. E. Saal & S. P. Turner *Nature* **444,** 713–717 (2006)

Geophysical hotspots have been attributed to partially molten asthenosphere, fertile blobs, small-scale convection and upwellings driven by core heat[1–4]. Most are short-lived or too close together to be deeply seated, and do not have anomalous heat flow[5,6] or temperature[7,8]; many are related to tectonic features[9–11]. Bourdon *et al.*[12] investigate the dynamics of mantle plumes from uranium-series geochemistry and interpret their results as evidence for thermal plumes. Here we show why alternative mechanisms of upwelling and melting should be considered.

Revised estimates of temperature, heat flow and buoyancy at ridges and hotspots, and developments in plume[3,13] and plate theory[2,9,10] are relevant to the conclusions of Bourdon *et al.*[12]. No near-ridge hotspot has anomalous temperature[7] and no hotspot has a significant heat flow anomaly[5,6]. The only active hotspot with a petrology-based temperature higher than mid-ocean-ridge basalt is, arguably, Hawaii[14]. Hawaiian lithosphere, however, is 140 °C colder than predicted by plume models[15]. It is no longer generally argued that all, or even many, hotspots are due to deep plumes, but lower mantle conditions are considered by many investigators as essential to the rationalization of observations[12]. However, tectonics and shallow low-melting heterogeneities, rather than excess temperatures, may be responsible for hotspots[2,11].

To satisfy global constraints, narrow plumes must have ascent rates and temperatures much greater than the broad upwellings associated with plate tectonics and normal mantle convection[3,13]. Required excess temperatures are 200–300 °C and velocities are one-half to tens of metres per year. The absence of evidence for such high values has been rationalized in several ways[12], but, taken at face value, supports a plate tectonic and lithologic, rather than thermal, explanation for hotspots.

Uranium-series geochemistry may provide insight that is independent of previous arguments[12]. Bourdon *et al.*[12] interpret U-series model data as independent evidence for thermal plumes and evidence that hotter plumes are stronger. Plumes are modelled as if they originated in a deep thermal boundary layer[12] heated from below, although the data do not constrain anything deeper than about 60–100 km. Shallow processes[9–11] and homologous temperature (T_H) variations[2,3] are not considered (plume simulations use a homogeneous mantle); modelling assumptions and parametrizations to date do not permit a shallow or non-thermal interpretation. Shallow chemical buoyancy can mimic effects of temperature, including isotope gradients. Could U-series data discriminate between buoyant decompression melting of shallow fertile blobs[1,10] and deep thermal plumes? Model velocities are comparable to plate and passive upwelling velocities, and much less than 0.5 m yr^{-1}.

Melt retention buoyancy in low-melting silicates (fertile blobs) is the equivalent of 300–600 °C temperature excess[4]; lowering the solidus or raising the temperature provide equivalent buoyancies[3]. Fertile blobs absorb mantle heat and turn into buoyant diapirs[2]. High-T_H blobs can melt deeper, rise faster and retain melt longer than subsolidus ambient mantle (low-T_H) rising passively under ridges. Lateral flow of material beneath the lithosphere has been taken as evidence for plumes[5], but is equally consistent with spreading of chemically buoyant or high-T_H blobs.

Hawaii has conflicting petrological[8,14], fertility and tectonic[10,11] interpretations and cannot be understood in terms of temperature alone. Eruption rates peak at the large-offset 300-km-wide Molokai fracture zone[11]. A plausible explanation involves underplating, decompression melting of 'eclogite' at lithosphere steps[10] and ascent through Molokai fracture zone conduits. The time between melt extraction and eruption, under these conditions, is unlikely to be similar to ridges.

If hotspots involve tectonic and T_H variations, then conventional fluid dynamic constraints on depth, temperature and velocity are removed. Temperatures of thermal plumes cannot be arbitrarily low[3,13]. Processes that utilize composition, internal heating, lateral flow, stress and ponding to localize volcanism can operate at lower temperatures[1,9]. The definition of mantle plume, to be useful, should recognize the difference.

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Received 21 March; accepted 3 October 2007.

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doi:10.1038/nature06376

Bourdon et al. *reply*

Replying to: D. L. Anderson & J. H. Natland *Nature* **450,** doi:10.1038/nature06376 (2007)

Anderson and Natland's comment[1] does not question our results regarding the velocity structure of mantle upwellings based on uranium-series[2]. We stated clearly that our results do not provide direct measurements of the depth from which hotspot volcanism starts; we have not made unjustified claims by saying we have identified deep mantle plumes[2]. However, our results do shed light on the still incompletely understood causes of hotspot volcanism[2].

Many responses to the criticism of the plume model[1] have been published[3,4] and we shall not reiterate these arguments, which refute a low mantle temperature beneath hotspots based on petrology. First, Anderson and Natland argue that buoyancy beneath 'hotspots' could be explained by fertile blobs. In general, buoyancy is driven by contrast in temperature, fertility and melt fraction[5]. As fertility is usually associated with a higher iron content (and hence a greater density), the effect of melting out the fertile (dense) component will not increase the buoyancy relative to ambient mantle. Thus, the only source of extra buoyancy one can consider in the model of Anderson and Natland[1] is buoyancy due to melt retention (or melt fraction ϕ). In this respect, U-series provide clear clues on the melt fraction during melting and all studies show that it should not exceed a few permil (ref. 2). Hence, the effect of a fertile source on the melt fraction (for $\phi = 0.003$) should in fact be limited and be equivalent to an excess temperature of 10 °C. For these reasons, we do not think a fertile blob can be the source of buoyancy beneath hotspots.

Second, if the increased melting rates were due to the presence of fertile blobs, then there should be a correlation between clear indices of enrichment, such as radiogenic isotopes, and U-series activity ratios. For two localities we used (the Galapagos and the Azores), such a correlation does not exist. Furthermore, as fertility is associated with enrichment in water (at least in the Galapagos and the Azores), this will decrease the melting rate of the blob by at least a factor of ten, which could easily compensate the effect of increased fertility on melting rates. These combined effects would fail to explain the U-series observations. We do not believe that fertile blobs can be a general explanation.

Third, although the mantle upwelling rates determined using U-series may not be entirely reliable in absolute terms, when compared with mid-ocean-ridge settings, they clearly indicate faster upwelling near the centre of the plume than beneath adjacent ridges. This is evident in the Azores region[2,6] (where the spreading rate is slow) but also in the Galapagos (A.S. *et al.*, manuscript in preparation), where the spreading rate is faster. The case of the Azores is particularly interesting because it shows that despite the relatively small buoyancy flux, the mantle is upwelling faster than beneath the nearby Mid-Atlantic Ridge. Furthermore, estimates of mantle upwelling velocities beneath Hawaii[7] do show that velocities of up to several metres per year are estimated.

Last, the temperatures of hotspot magmas have been widely discussed (see ref. 8 for a critical review of ridge and hotspot mantle temperatures) and these consistently indicate that temperatures are hotter than that of the ambient mantle, even when the variability of normal potential temperatures of mid-ocean-ridge basalts (120 °C; ref. 7) is taken into account. Although we did not focus on a comparison with ridges[2], U-series unfailingly indicate higher temperatures beneath hotspots than at mid-ocean ridges[9].

Anderson and Natland[1] favour the idea that all plumes originate from the core–mantle boundary. But must they? The elegant experiments of Davaille *et al.*[10] show that imagining plumes as narrow conduits from the core–mantle boundary might be a narrow view of convective patterns in the mantle.

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doi:10.1038/nature06377