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Review

Are ‘hot spots’ hot spots?

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ABSTRACT

The term ‘hot spot’ emerged in the 1960s from speculations that Hawaii might have its origins in an unusually hot source region in the mantle. It subsequently became widely used to refer to volcanic regions considered to be anomalous in the then-new plate tectonic paradigm. It carried with it the implication that volcanism (a) is emplaced by a single, spatially restricted, mongenetic melt-delivery system, assumed to be a mantle plume, and (b) that the source is unusually hot. This model has tended to be assumed *a priori* to be correct. Nevertheless, there are many geological ways of testing it, and a great deal of work has recently been done to do so. Two fundamental problems challenge this work. First is the difficulty of deciding a ‘normal’ mantle temperature against which to compare estimates. This is usually taken to be the source temperature of mid-ocean ridge basalts (MORBs). However, Earth’s surface conduction layer is ~200 km thick, and such a norm is not appropriate if the lavas under investigation formed deeper than the 40–50 km source depth of MORB. Second, methods for estimating temperature suffer from ambiguity of interpretation with composition and partial melt, controversy regarding how they should be applied, lack of repeatability between studies using the same data, and insufficient precision to detect the 200–300 °C temperature variations postulated. Available methods include multiple seismological and petrological approaches, modelling bathymetry and topography, and measuring heat flow. Investigations have been carried out in many areas postulated to represent either (hot) plume heads or (hotter) tails. These include sections of the mid-ocean spreading ridge postulated to include ridge-centred plumes, the North Atlantic Igneous Province, Iceland, Hawaii, oceanic plateaus, and high-standing continental areas such as the Hoggar swell. Most volcanic regions that may reasonably be considered anomalous in the simple plate-tectonic paradigm have been built by volcanism distributed throughout hundreds, even thousand of kilometres, and as yet no unequivocal evidence has been produced that any of them have high temperature anomalies compared with average mantle temperature for the same (usually unknown) depth elsewhere. Critical investigation of the genesis processes of ‘anomalous’ volcanic regions would be encouraged if use of the term ‘hot spot’ were discontinued in favour of one that does not assume a postulated origin, but is a description of unequivocal, observed characteristics.

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1. Introduction

The origin of the term ‘hot spot’, also written ‘hotspot’, is obscure. It emerged in the 1970s to signify an active volcanic region that appeared to not fit the then-new plate tectonic hypothesis. It was originally understood to signify an unusually hot region in the mantle that gave rise to surface volcanism unconnected with a plate boundary [Wilson, 1963]. Development of the concept was inspired by Hawaii – a unique phenomenon, given its intraplate setting, huge present-day volcanic production rate, and exceptionally long, narrow, time-progressive volcanic chain.

The term ‘hot spot’ subsequently became inexorably linked with the plume hypothesis, which was developed to explain how ‘hot spots’ could be maintained over long periods of time [Morgan, 1971]. Mantle plumes were originally envisaged as diapirs, rising by virtue of their thermal buoyancy, from the core–mantle boundary. In this way, they tapped heat from an essentially inexhaustible reservoir, and could maintain high temperatures in ‘hot spot’ source regions for as long as necessary.

Plumes are considered to be localised heat- and melt-delivery structures, but high temperature is their most fundamental characteristic. The question whether ‘hot spots’ are really hot is thus of critical importance, because it amounts to a test of the mantle plume hypothesis. Since the turn of the 21st century, this has been seriously questioned [*e.g.*, Foulger, 2002, 2007, 2010]. This questioning arose from widespread realisation that geological and geophysical observations do not fit the predictions of the hypothesis, and it led to development of the alternative ‘plate’ hypothesis. This attributes volcanism to permissive leakage of pre-existing melt from the asthenosphere, in response to lithospheric extension consequential to plate tectonic processes. In the ‘plate’ hypothesis, variations in magma productivity are attributed to variations in source composition. Unusually high magma source temperatures are not required.

In order for a diapir to rise from the core–mantle boundary, through the mantle and to Earth’s surface through thermal buoyancy, a temperature anomaly of at least 200–300 °C is required [Courtney and White, 1986; Sleep, 1990, 2004]. The hottest part of a plume is predicted to be the centre of the head, and the tail immediately beneath. Most of the plume head is expected to be cooler, as it is predicted to entrain large amounts of normal-temperature ambient mantle as it rises and overturns. The temperature in a plume head is thus expected to reduce from a maximum at its centre over the tail, to approach ambient mantle temperature at its periphery [Campbell, 2006; Davies, 1999]. As a consequence, the highest temperatures are expected to be found near the centres of flood basalts and at currently active ‘hot spots’.

The plate hypothesis predicts that the sources of melt erupted at the surface lie mostly within Earth’s surface conductive layer, which comprises the shallowest $\sim$100–200 km [Anderson, 2007, 2010; Foulger, 2010]. Within this layer, the potential temperature (T_P – Section 3.1) generally increases with depth. Melt drawn from deep within it will thus have a higher T_P than melt that forms at shallower levels (Fig. 1). Some variation is thus expected in the source temperatures of melts erupted at ‘hot spots’, but this is expected to be largely related to depth of extraction. Lateral variation in mantle temperature is also expected. However, the predictions of the plate hypothesis contrast with those of the plume hypothesis in that the mantle is not considered to be essentially isothermal everywhere except for discrete, isolated, spot-like high-T_P anomalies of several hundred degrees Celsius. Unusually productive parts of the mid-ocean ridge system are expected to be sourced from similar depths and temperatures to those parts with average productivity. Exceptionally large melt production rates at some localities are attributed to a more fusible source composition, and corresponding differences in the geochemistry of the lavas is expected. Temperatures may be elevated by a few tens of degrees Celsius in some regions, where lithospheric structure encourages lateral flow from deeper within the conductive layer, *e.g.*, at plate boundary junctions such as ridge-transform intersections and triple junctions. Flood basalts and oceanic plateaus are not predicted to have a radial thermal structure.

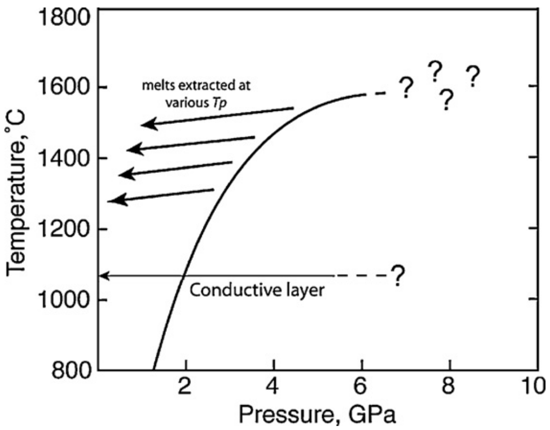

Fig. 1. Schematic diagram showing the thermal conditions in the shallow Earth. Melts drawn from deeper within the conductive layer have higher T_P than those drawn from shallower.

The term ‘hot spot’ implies localised, high temperatures. Along with the plume hypothesis, it was exported from Hawaii and became widely applied to unusual volcanic regions all over the world. Unfortunately, the expression has traditionally been used with little questioning, for many localities where there is no evidence that it describes the phenomenon in question well, and even where there is *prima facie* evidence that it does not. This is now changing. Efforts are being made to test whether ‘hot spots’ are indeed hot, and to address the difficult task of developing reliable methods to do so. Although there is a surprisingly large number of ways to estimating temperature, and variations in temperature, in the mantle, the endeavour is plagued by fundamental technical and philosophical problems. As a consequence, testing whether ‘hot spots’ are hot is a surprisingly difficult task.

Casual and widespread use of the term ‘hot spot’ has been defended on the grounds that it may simply signify active surface volcanism. This cannot be justified because volcanoes at mid-ocean ridges and subduction zones would then also qualify as ‘hot spots’. What is potentially more problematic is that its use tends to encourage the presumption, without testing, that unusual volcanic regions arise from exceptionally hot mantle source rocks. For this reason, *a priori* use of the term is undesirable.