Plumes: The Overview

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ABSTRACT

"There has been a tendency to regard plumes, which are postulated to cause hotspots, as a distinct, secondary mode of convection somehow decoupled from the main, plate scale flow. However, such a mode of flow has never been observed in any self-consistent numerical or laboratory experiment. Plumes always occur as part of the main, and only, convective system. A problem is plumes that must simultaneously satisfy requirements of being stationary in position and fairly weak, <6% of surface heat flux." (Tackley et al., 1994)

The plume hypothesis has not yet been cast in a form where it can be tested, or falsified. Currently it has low empiric content and high probability (i.e., it predicts everything). Many of the phenomena which have been attributed to plumes appear only to require access to the mantle, extensional stresses in the plate, lithospheric boundaries or normal mantle convection. About 50% of the upper mantle has such low seismic velocities that the presence of a fluid phase is implied, probably a melt phase, and all that is required to generate magmatism is appropriate plate conditions. Even the coldest, highest seismic velocity, sublithospheric upper mantle will melt upon adiabatic ascent, if the plate is removed or broken. The large-scale lateral variation of seismic velocity in the mantle can almost entirely be explained by continental insulation, cooling by past subduction, volatile fluxing by subduction and lithospheric thickness variations. For example, the non-Pacific hemisphere mantle has been repeatedly cooled by slabs, over several supercontinental cycles, and the shallow mantle has been repeatedly fluxed by volatiles. This mantle cannot mix readily with the Pacific mantle and large chemical, physical and thermal domains are established and maintained. In addition, thick cratonic lithosphere has both a geometric and thermal effect on convection, dictating, to a large extent ,the locations of downwellings and upwellings. Previous subduction tiles over the base of the system which is therefore cooled from below in places. This does not occur in Rayleigh-Bénard convection with temperature independent properties, because thermal boundary layers are only marginally buoyant and do not decouple from background flow.

Plate tectonics on a sphere is intrinsically episodic; boundary conditions change as ridges and trenches migrate and annihilate and as cratons move about, separate and coalesce. Extensional boundaries becomes sites of magmatism; leaky transform faults can generate age progressive volcanism. Motions of, and stresses in, plates are mainly controlled by boundary forces (slab pull, ridge push). Mantle convection is also strongly influenced by plates and slabs. The *active* contribution of mantle convection, including a possible plume component is difficult to detect or justify.

Given the various plate tectonic controls on thermal conditions, stress state and magmatism, what is the role of thermal instabilities in a deep thermal boundary layer and what is the evidence for the active, narrow upwellings that have been invoked to explain various phenomena? First of all, all geophysical observables (geoid, topography, heat flow and tomography) on the scale of swells can be explained by variations above about 250 km and do not require a deep plume explanation. Even the l=6 (~6000 km dimension) variations in topography and geoid are readily explained by upper mantle convection.

The strong correlations between regions of excess magmatism (flood basalts, plateaus, aseismic ridges and ridges) and lithospheric discontinuities (ridges, sutures, triple junctions and transforms) suggests a strong lithospheric influence and a relationship between what have been called hotspots or plumes and normal mantle convection. Intraplate, or midplate, volcanism is a misnomer since all large igneous provinces started at plate or terrane boundaries and often remain (hotspot tracks) at plate boundaries (aseismic ridges) for a large fraction of their history. Most of the boundaries and extensions across them long

predate the excess magmatism; for example, plate separation often propagates toward "hotspots" (Red Sea-Afar; North Atlantic-Iceland) and are therefore not caused by the "hotspot." The regions of excess magmatism often occur when the propagating rift encounters a thick craton, and can therefore tap deeper mantle. The small dimension of hotspots is often attributed to the underlying convection (plume) but is often due to the narrowness of a rift or a suture (i.e., plate control).

Many large igneous provinces are clearly related to such tectonic processes as ridge-trench collision, pull-apart at pre-existing sutures, migrating triple-junctions and plate reorganizations. Many are clearly opportunistic, or passive, upwellings rather than the result of a deep, narrow, active upwelling. Both hotspots and ridges occur over large regions of the upper mantle which, from a tomographic point of view, are slower than average. These large, hot domains have not experienced subduction cooling since before the breakup of Pangea and, possibly, for several supercontinent cycles. In this respect, they are "normal", or uncooled mantle. Since upwelling mantle, under almost all conditions, will melt, or melt further, upon ascent through the upper 200 km of the mantle, there is an active component to passive upwelling (i.e., an extra burst of buoyancy is available). This also makes it difficult to disentangle *active* and *passive* upwellings. The volume of melt delivered depends on lithosphere thickness, mantle fertility, volatile content and previous history, small-scale convection, temperature and, where appropriate rifting rates. The proximity of all continental flood basalt provinces to Archean craton boundaries suggests that small-scale convection due to lateral temperature gradients (Pekeris convection) is involved. In plume theories, thick lithosphere suppresses melting; in Pekeris theory, a craton edge promotes small-scale convection and rapid delivery of mantle through the melting zone (King and Anderson, 1995).

It appears that the upper mantle and the plates control the phenomena that have been attributed to thermal instabilities in a thin layer above the core.

Plate tectonic forces and surface loads (e.g., volcanoes) control the stress and motions of plates and cause rifting and continental breakup. Subduction and slab cooling cause uplift and subsidence. Small-scale convection associated with "edge effects" (e.g., craton boundaries) often occurs in places where plumes have been invoked. The distribution of slabs and cratons modulates or drives intermediate scale convection. Large scale flow appears to still record the influence of Pangea and past subduction. It seems improbable that D", thermal instabilities can over-rule the driving forces of the plates and the upper mantle. Global synchroneity is a natural consequence of plate control but not of small-scale convection in D".

It is often said that scientific theories should be falsifiable (Karl Popper) by making predictions about future observations. If the predictions are not confirmed, the theory is abandoned. Reality is quite different. Adopting or rejecting a theory are not the only possibilities. There is a third one: amending it. Only a little imagination is required but there is a price to be paid; the theory gradually looses its initial simplicity. There should not be too many tooth fairies (ad hoc hypotheses). Plume theory now encompasses fossil plumes, plume families, secondary plumes, double plume heads, tilted plumes, plume channeling, incubating plumes, impact plumes, diverted plumes, depleted plumes, decapitated plumes, jumping plumes, migrating plumes (TPW), cold spots and wetspots. At some point, it is necessary to stop invoking tooth fairies and to confront the baggage laden theory with radical alternatives.

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