# Discussion of

# *Global plume-fed asthenosphere flow*

by

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*17th January, 2007, Don L. Anderson*

Increasing temperature decreases viscosity, seismic velocity, thermal conductivity and density, and increases thermal expansivity and seismic attenuation. Pressure has the opposite effect and, in addition, increases the melting point. The net effect is that there will be a low-viscosity, low-velocity zone (LVZ) in the upper mantle that has a high homologous temperature. The presence of an asthenosphere is not a mystery, even in a homogeneous mantle with normal pressure and temperature gradients. A LVZ with a lid may also collect low-density, low-melting point debris from mantle differentiation and crustal delamination and will therefore be laterally heterogeneous with respect to lithology, chemistry and melting point.

A heterogeneous **partially molten asthenosphere**[1] is an alternative to the deep mantle plume model. But what is the mechanism for replacing the material that leaks out of it at hotspots? Yamamoto et al. (this volume) argue that it is replaced by upwelling plumes from the deepest thermal boundary layer (TBL). I have argued that the delamination of lower continental and arc crust, and the subduction of buoyant aseismic ridges accounts for more than the amount of magma involved in hotspot magmatism (Anderson, this volume). The subduction of oceanic crust involves an order of magnitude more material but this may sink deeper into the mantle, and may be inappropriate for recycling as OIB because of subduction-zone processing and chemistry. It however does displace deeper material upwards that may fuel the ridges. If irreversible deep subduction started late in Earth history, at current rates 70 km of basalt/eclogite will accumulate in or below the transition region every 1 Gyr and this will displace deep material upwards.

A thermal maximum and a **subadiabatic mantle**[1] are expected in a mantle heated by radioactive decay and cooled by sinking slabs; plumes and bottom heating are not required. Lateral transport of material in the asthenosphere, including entrained fertile blobs, is intrinsic to the counterflow associated with plate motions, but not with whole mantle convection. Recycling of foundered lower crust and subducted aseismic ridges is probably the primary source of fertile **olivine-free mantle and melting anomalies**; these mechanisms place long, linear mafic heterogeneities into the mantle.

In contrast to plume models, plates are driven by surface and slab forces that induce mantle convection including counterflow (Harper, 1978; Chase, 1979). This is consistent with anisotropy measurements[2]. In places where the mantle contains a melt phase or fertile streaks, volcanic chains may be the result of lithospheric stress and magma fracture rather than thermal erosion. Water and $CO_2$ affect the strength of the lithosphere, and the melting temperature and viscosity of the mantle. The homologous temperature therefore controls the dynamics of the mantle, and the amount of melting.

In the plume hypothesis (Yamamoto et al., this volume), hot material from the core-mantle boundary rises through narrow plumes and this creates a hot LVZ. The plumes are compensated by sinking of the whole mantle–in the original plume hypothesis–or by slabs. Asthenospheric flow is away from hotspots. The upper mantle is homogenized by chaotic stirring.

The alternative **top-down tectonics** model is essentially the inverse of this. Slabs and plates, not plumes, drive the system. Radioactive heating, crustal stoping, spreading and material displaced by slabs cause broad passive upwellings. LVZs are the result of the dominance of temperature over pressure and partial melting. Ubiquitous but not universal magmatism in extending regions implies a heterogeneous shallow mantle with high but variable homologous temperature; the upper mantle has not been homogenized. Very low seismic velocities and viscosities are due to mineralogy (eclogite), volatiles, fertility and partial melting. The mantle is refertilized from the top by subduction of young or thick oceanic crust, and delaminated continental crust, and from the bottom by the above-mentioned broad upwelling. Fertile blobs can be tens of km in extent. The closure of back-arc basins and the trapping of mantle wedge material are also involved. In fact, the similarity of backarc basin and continental flood basalts and OIB has suggested to some (Hooper, this volume) that the former are caused by plumes.

In the **shallow counterflow** model, flow is anti-parallel to plate motions, and toward ‘hotspots’ and upwells at thin-spots. Ridges, trenches and continents migrate over the upper mantle, fertilizing it, and sampling it at extending- and thin-plate regions. Melt potential of the mantle is a function of eclogite and volatile contents, not absolute temperature. Eclogite sinkers, and recycled material with volatiles have low-melting points and low seismic velocities. Focused upwelling is controlled by the lid, including fracture zones. Delaminated crust, even when cold, melts because of conductive heating; mantle displaced upwards melts because of pressure release. The similarity of ‘hotspot’ magmas and the lower continental crust is an argument that crustal delamination is one source of ‘plume components’.

Alternatives to the plume conjecture are now well developed and testable. They involve much more than propagating cracks, a usual strawman (e.g. Hooper, this volume). It is no longer acceptable to just assume that narrow deep mantle plumes must exist–“because there are no alternative”–and that all melting anomalies and low-velocity regions of the mantle must have high absolute temperatures.

*19th January, 2007, Alan D. Smith*

The plum-pudding plume model of Yamamoto et al. (this volume) derives MORB and OIB from a common reservoir, and is thus different to standard plume models (e.g. Hofmann and White, 1982) which are based on the concept of isotopic differences between MORB and OIB requiring distinct sources for these categories of volcanism. In this regard, the model of Yamamoto et al. (this volume) is similar to the plate model (e.g. Foulger, this volume) where subducted oceanic crust is mixed directly with the convecting mantle, and differences between MORB and OIB result from sampling of recycled materials and their host mantle (Meibom and Anderson, 2003; Smith, 2005). Why then invoke the plume stage at all?

The geochemical argument for plumes rests essentially on the interpretation of $^3$He/$^4$He ratios. Hofmann and White (1982) suggested isolation of subducted oceanic crust in plume sources shortly after remixing of such material with the convecting mantle had been indicated from banding in orogenic lherzolites (Polvé and Allègre, 1979). However, interpretation of high $^3$He/$^4$He ratios in OIB as signifying elevated $^3$He abundances from a primitive mantle reservoir (e.g. Allègre et al., 1983), led to the plume model being added to subsequent considerations of recycling crust into the convecting mantle (e.g. Allègre, and Turcotte, 1986). Thereafter, crustal recycling into the convecting mantle was relegated to an explanation for heterogeneity in the MORB-source (e.g. Saunders et al., 1988), and in the plum-pudding plume model the concept becomes redundant as the entire geochemical heterogeneity in the mantle results from plumes.

The flaw in the plume logic is however that high $^3$He/$^4$He ratios can arise from low abundances of $^4$He rather than high abundances of $^3$He (e.g. Anderson, 1998; 2000), which removes any requirement for an ultra-deep origin for intraplate volcanism. Which model then provides the more comprehensive explanation for intraplate volcanism? The plum-pudding plume model has an advantage over the standard plume model in accounting for the distribution of geochemical heterogeneities throughout the asthenosphere, without having to invoke a multitude of plumes or *ad hoc* plumbing arrangements to explain features such as non-linear age progressions in ocean island chains. However, like all plume models, it lacks a mechanism for tapping such sources away from hotspots. The plate model, on the other hand, provides a mechanism for the distribution of recycled material throughout the mantle, as well as a means of tapping such material via plate interactions.

*20th January, 2007, Don L. Anderson*

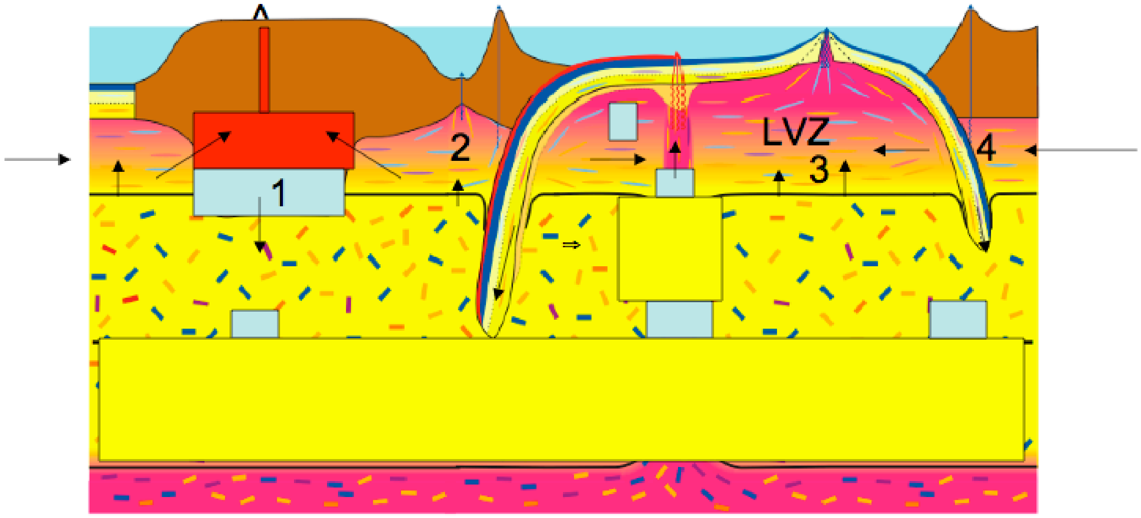
The plum-pudding plume models and the marble cake models derive MORB and OIB from a common reservoir, and are thus different from the standard reservoir models, which are based on the concept of isotopic differences between MORB and OIB requiring distinct isolated reservoirs (Smith comment, 19th January, 2007). In the marble cake model subducted oceanic crust is mixed thoroughly into the so-called convecting mantle, in order to maintain the apparent homogeneity of the MORB reservoir. Meibom and Anderson (2003) and Smith (2005) argue that a heterogeneous mantle can provide homogeneous basalts by the sampling process. If the mantle is chemically stratified (Anderson, this volume) thorough chaotic mixing is unlikely.

Recycled NMORB that is processed through subduction zones may not be a good candidate for the EM components of the mantle (Lustrino and Dallai, 2003; Niu et al., 2002). If deep subduction started only in neoproterozoic time (Stern, 2005) then oceanic crust may not be involved at all in modern magmatism. But slabs will displace deeper mantle upwards, and this is a possible source for midocean ridges. There are other plausible and voluminous sources of mafic material for OIB and other 'hotspot' magmas that cannot be ignored but are overlooked by Yamamoto et al. (this volume). These include (Figure 1):

1. Delaminated lower continental and arc crust,
2. Mantle wedge material,
3. The slow upwelling of mantle displaced by sinking slabs, and
4. Subduction of young buoyant oceanic lithosphere or aseismic ridges (Figure 1).

The fertile blob model (Anderson, this volume) is similar to the plum pudding model but the "plums" may be tens of km in extent. These fertile blobs may collect in and below the asthenosphere. Smaller blobs can be entrained in the counterflow that flows toward hotspots and ridges. Mass balance and geochemistry do not require that oceanic crust be recycled or reused at hotspots. Thus, recycled oceanic crust need not be involved in either OIB or MORB magmatism. There is no need for deep mantle plumes to explain either the physical or chemical properties of the shallow mantle.

Fertile blob & asthenospheric counterflow model



1 delaminated crust, 2 wedge, 3 broad upwelling,

4 young oceanic crust

Figure 1

*23rd January, 2007, Alan D. Smith*

Models for the isotopic evolution of recycled oceanic crust need to take into consideration both dehydration and melting of the subducting slab (Smith, 2005). Slab dehydration will result in recycled basaltic crust evolving to HIMU isotopic compositions, dehydrated sediment will evolve to EM2 (terminology of Zindler and Hart, 1986). Higher geothermal gradients and subduction of young oceanic crust favour a greater role for slab melting in the Archean (Martin, 1986). Oceanic crust that has undergone melting in subduction zones evolves toward the DM isotopic component of Zindler and Hart (1986). The convecting mantle may thus contain two types of recycled oceanic crust, with the common component between MORB and OIB being recycled dehydrated oceanic crust (Smith, 2005).

The isotopic component EM1 is also found in MORB and OIB, and I agree with Anderson (comment of 20th January, 2007) that this component may be equated with continental lower crust (see also Lustrino and Dallai, 2003), although continental mantle is a further option. Such materials can be delaminated/eroded directly into the shallow mantle during continental collision or rifting events, without any need for cycling through plume sources as depicted by McKenzie and O'Nions (1983). Entrainment of delaminated continental lower crust into ocean ridge upwelling is a possible mechanism for the generation of oceanic plateaus, but EM1 is not a ubiquitous mantle component, and I would regard the difference between MORB and OIB to result from tapping of the recycled melted oceanic crustal component beneath ocean ridges.

*31st January, Jason Phipps Morgan*

In response to Smith's comment of 23rd January, that we neglect subduction-related transformations in the scenario of a plume-fed asthenosphere, I agree that formal modeling of slab-dehydration and slab-melting processes are missing from the quantitative geochemical evolution model described in Phipps Morgan and Morgan (1999). There we noted our surprise that even with the neglect of these geologic processes the models could still reproduce many of the geochemical patterns seen in OIB, EMORB, and MORB, with obvious exceptions for the elements that have been proposed to be fractionated by slab-dehydration (e.g. Ce vs. Pb). Obviously, the processes that create the different components in a plum-pudding model need to be identified — here I only wish to note that it is likely that many enriched components exist in much more extreme forms in the mantle than is seen by their "flavoring" of erupted basalts. For example, melt-inclusions within end-member HIMU basalts can be much more extreme in isotopic composition than their host basalt (Saal et al., 2005).

If we focus on MORB rather than OIB or EMORB, we are left with several questions to be explained by a passive (non-plume-fed) upper mantle. Why does the MORB source have far less thermal variability than that introduced into the mantle by subducting slabs? To me a major challenge for both Anderson's perisphere concept and conventional upper-mantle MORB source scenarios is how to so evenly homogenize mantle temperature beneath the global ridge system given the ~600-700˚C average temperature difference between a subducting slab and the MORB source region and the fact that the MORB-source mantle, given its predicted concentrations of radioactive elements, would only warm from internal radioactivity by ~20-100 K/Ga. Likewise, a similar challenge for non-plume-fed scenarios for the MORB source is to explain why the source temperatures and crustal thicknesses are so similar beneath MORs that are near long-time subducting slabs — e.g. Juan de Fuca or Chile Rise — and those far from slabs. If plume-fed, then the MORB source would be relatively uniform in temperature, as more buoyant plume material would tend to displace any denser mantle downward so it could not upwell beneath ridges. Why are there sharp lateral transitions between volcanic and non-volcanic rifted margins, and why is there a sharp temporal transition from OIB-like "rift" basalts to the eruption of MORB during the initial formation of an ocean basin? To me this suggests that the MORB source is relatively warm and uniform in temperature, and that MORB-source asthenosphere is absent beneath non-volcanic rifted margins until it can enter by lateral flow of asthenosphere from beneath the thinner lithosphere of an adjacent ocean basin.

Regarding Anderson's comments, please note that we do not just view plume upwelling as replacing the mass "that leaks out at hotspots", but rather as the much larger upward counterflow to subducting slabs. However, we still view the subduction of a surface-cooled slab as both the main driving force for deep mantle flow and the means of reinjecting the lithologic and chemical differentiation created by near-surface melting and hydrous interactions back into the mantle where sub-solidus mantle flow may stretch and stir, but not homogenize, this geochemical plum-pudding. In many other aspects we basically agree with the concepts of Anderson and Smith of a "streaky" plum-pudding mantle as the source of oceanic volcanism, and we agree with the emerging geochemical consensus that the selective melting of lower-solidus streaks within the mantle seems to be the right explanation for the observed differences between different "flavours" of OIB and MORB.

## *References & notes*

(1) **Text in bold face** can retrieve the appropriate references when entered into *Google*. See also other chapters in this volume and

(2) http://caltechbook.library.caltech.edu/14/

Allègre, C.J., and Turcotte, D.L., 1986, Implications of a two component marble cake mantle: Nature, v. 323, p. 123-127.

Allègre, C.J., Staudacher, T., Sarda, P., and Kunz, M., 1983, Constraints on evolution of the Earth's mantle from rare gas systematics: Nature, v. 303, p. 762-766, doi: 10.1038/303762a0.

Anderson, D.L., 2000, The statistics and distribution of helium in the mantle: International Geology Review, v. 42, p. 289-311.

Anderson, D.L., 1998, The helium paradoxes: Proceedings of the National Academy of Sciences, v. 95, p. 4822-4827.

Chase, C.G., Asthenospheric counterflow: a kinematic model: Geophys. J. R. Astron. Soc., 56, 1 - 18, 1979.

Harper, J.F., Asthenosphere flow and plate motions, Geophysical Journal Royal Astronomical Society, 55, 87-110, 1978.

Hofmann, A.W. and White, W.M., 1982, Mantle plumes from ancient oceanic crust: Earth and Planetary Science Letters, v. 57, p. 421-436.

Lustrino, M. & Dallai, L. (2003): On the origin of EM–I end-member. – N. Jb. Miner. Abh. (179): 085 –100; Stuttgart.

Martin, H., 1986, Effect of steeper Archean geothermal gradient on geochemistry of subduction zone magmas: Geology, v. 14, p. 753-756.

McKenzie, D., and O'Nions, R.K., 1983, Mantle reservoirs and ocean island basalts: Nature, v. 301, p.229-231.

Meibom, A. and Anderson, D.L., 2003, The statistical upper mantle assemblage: Earth and Planetary Science Letters, v. 217, p. 123-139.

Niu, Y.-L., Regelous, M., Wendt, I., Batiza, R., O'Hara, M.J. (2002). Geochemistry of near-EPR seamounts: importance of source vs. process and the origin of enriched mantle component. Earth Planet. Sci. Lett. 199, 327–345.

Phipps Morgan, J., and Morgan, W.J., 1999, Two-stage melting and the geochemical evolution of the mantle: a recipe for mantle plum-pudding: Earth Planet. Sci. Lett., v. 170, p. 215-239.

Polvé, M., and Allègre, C.J., 1979, Orogenic lherzolite complexes studied by 87Rb-87Sr: A clue to understanding mantle convection processes? Earth and Planetary Science Letters, v. 51, p. 71-93.

Saunders, A.D., Norry, M.J., and Tarney, J., 1988, Origin of MORB and chemically-depleted mantle reservoirs: Trace element constraints: Journal of Petrology, Special Lithosphere Issue, p. 415-445.

Saal, A.E., Hart, S.R., Shimizu, N., Hauri, E.H., Layne, G.D., and Eiler, J.M., 2005, Pb isotopic variability in melt inclusions from the EMI-EMII-HIMU mantle end-members and the role of the oceanic lithosphere: Earth and Planetary Science Letters, v. 240, p. 605-620.

Smith, A.D., 2005, The streaky-mantle alternative to mantle plumes and its bearing on bulk-Earth geochemical evolution, in Foulger, G. et al., eds., Plates, Plumes, and Paradigms, Geological Society of America Special Paper 388, p.303-325, doi:10.1130/2005.2388(19).

Stern RJ (2005) Evidence from ophiolites, blueschists, and ultrahigh-pressure metamorphic terranes that the modern episode of subduction tectonics began in Neoproterozoic time. Geology 33: 557-560

Zindler, A. and Hart, S.R., 1986, Chemical geodynamics: Annual Reviews of Earth and Planetary Sciences, v. 14, p. 493-571, doi: 0.1146/annurev.ea.14.050186.002425