Intraplate volcanism: conc

Continuing the discussion of mantle plumes in the previous two issues, **Alan D Smith** looks at mantle models.

Abstract

Models for the generation of sources for intraplate volcanism include: (i) the plume model involving isolation of subducted oceanic crust at depth in the mantle; (ii) the streaky-mantle model where ocean island basalts are derived from preferential melting of crustal components remixed into the convecting mantle MORB-source; (iii) the hydrous-peridotite model where volatile-bearing sources are generated at convergent margins from the infusion of slab-derived melts or fluids and sediment into the mantle wedge, and are superimposed on streaky-mantle heterogeneity. Only the latter satisfies geochemical constraints and produces a source with lower solidus temperature than average mantle as required by petrological evidence.

Three decades ago the introduction of plate tectonics appeared to herald a new era in the understanding of the Earth. Following in the wake of this paradigm shift was the introduction of the mantle plume hypothesis (Morgan 1971) based on the suggestion of Wilson (1963) that the sources of ocean island basalts (OIB) were thermal anomalies. The plume model offered an explanation for the origin of intraplate volcanism (IPV), whose distribution was otherwise problematic in plate tectonic theory, while also providing a reference frame for plate tectonic movements. When linked with the fate of subducted oceanic crust (Hofmann and White 1982), it also led to a geodynamic model of the Earth's interior. However, in the years that followed, geodynamics became plagued by complexities and paradoxes as observations required increasing variations to the plume model (Smith and Lewis 1999). Proponents argue this state reflects a still-incomplete understanding of plume processes (Sleep 2003), but the reality is that for three decades the model has been promoted with little constraint or critical evaluation. Such one-sided interpretation, with newer tools such as seismic tomography largely used to state agreement with, rather than test, pre-existing concepts, is suggested as the principal cause of the current muddle in geodynamics.

The plume model

The plume model envisages generation of IPV from plumes of recycled subducted oceanic lithosphere that has been isolated from mantle convection at the core–mantle boundary, mid-lower mantle or base of the upper mantle for up to 2×10^9 years (figure 1a). The model is successful in explaining the occurrence of isotopically ancient signatures in volcanism in young ocean basins. However, supposed proofs of the plume model from high $^3He/^4He$ ratios in OIB indicating a primordial component in the recycled material, or high $^{186}Os/^{188}Os$ ratios indicating interaction of plume-sources with the outer core (Brandon *et al.* 1999) are not definitive. High $^3He/^4He$ ratios could reflect a deficiency in ^4He from low U, Th (Anderson 1998) and also Sm abundances in the source region, while high $^{186}Os/^{188}Os$ ratios can be generated in pyroxenites at any depth (Smith 2003a). Arguments for thermal anomalies have not been supported by heat-flow observations (Stein and Stein 2003) or petrology, where the generation temperatures of Hawaiian tholeiites and picrites have been shown to be no greater than for their counterparts along ocean ridges (Green and Falloon 1998).

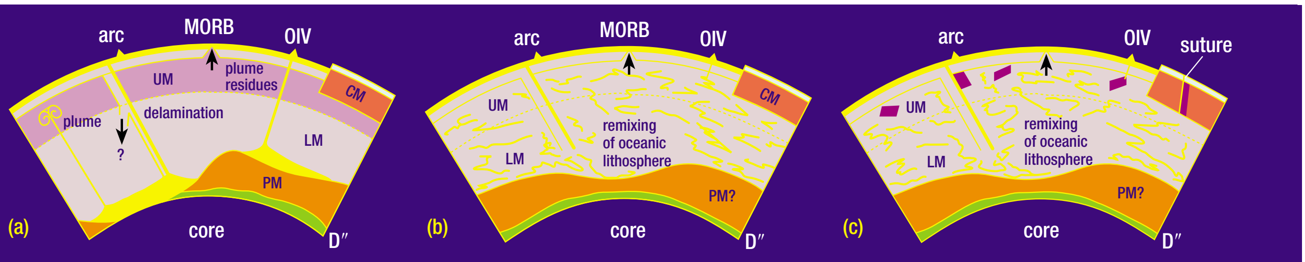
Problems also abound with regard to the geochemical suitability of recycled oceanic crust. Partitioning of Ta into slab-fluids at convergent margins causes eclogite to have higher Nb/Ta ratios than found in OIB (Kamber and Collerson 2000). Likewise, loss of Re from the slab requires unrealistic amounts of eclogite in a plume to satisfy Re–Os isotope constraints unless special melting regimes are invoked (Becker 2000), while loss of Nd results in eclogite evolving to higher $^{143}Nd/^{144}Nd$ than seen in OIB (Kogiso *et al.* 1997). Metasomatism of the base of the oceanic lithosphere has been invoked to compensate for losses of mobile elements (Niu *et al.* 2001). However, such enrichment is considered unfeasible because unless the base of the subducting lithosphere was delaminated from the crustal part of the slab, any plume source-layer would fill up long before the required time for isotopic evolution, and even if the amount of lithosphere could be accommodated, recycled basalt sources would still be precluded by the low $^{176}Hf/^{177}Hf$ ratios of HIMU OIB (Ballentine *et al.* 1997).

Possibilities without plumes

Without plumes, subducted oceanic crust and sediments can be remixed with the convecting mantle as in the streaky-mantle model of Fitton and James (1986). Although arguments have been made for subduction of relatively uniform sediment mixtures in order to fit the plume model (Vervoort *et al.* 1999), the results of Plank and Langmuir (1998) show there is enough variation in sediment composition to explain the large range of $^{176}Hf/^{177}Hf$ with respect to $^{143}Nd/^{144}Nd$ in mid-ocean ridge basalts (MORB) when recycled crust is remixed to form the depleted mantle reservoir (Smith and Lewis 1999). Arguments based on Nb/U ratios (Hofmann 1997) against crustal recycling into the MORB-source are also flawed from the failure to realize the depleted mantle is the product, not a starting composition in the mixing process. Tomographic evidence for penetration of the lower mantle by subducting slabs supports whole mantle convection, and it is suggested that the background pattern of high- and low-velocity anomalies that has been ignored in the search for plume conduits, delineates the mixing of slabs into the mantle. Possibilities are then that: (i) OIB are derived by selective melting of streaky-mantle sources, with preferential melting of recycled components producing OIB whereas greater contributions from the depleted component are involved in the generation of MORB (Fitton and James 1986) (figure 1b); (ii) OIB sources represent a further level of heterogeneity superimposed on streaky-mantle heterogeneity (figure 1c). In either case, the location of IPV can be explained by surface plate architecture and stress fields acting on the plate (Anderson 1995, Smith 2003b).

Deriving OIB by melting of streaky mantle does not encounter any difficulties with regard to explaining the antiquity of isotopic signatures, but otherwise, geochemical difficulties are the same as in the plume model. Invoking a second level of heterogeneity is readily reconcilable with longstanding petrological evidence (Green 1971, Francis and Ludden 1995, Green and Falloon 1998) that OIB are generated from volatile-bearing sources. The principal site of recycling volatiles into the mantle is at convergent margins. Processes that may occur in such regions include mixing of sediment into the mantle wedge, and the introduction of melts and fluids from the subducting slab. The possibilities are complex because of the range of slab components including sediment, basalt, serpentinite, and the dependence of metasomatic processes on factors such as the thermal regime of the slab. However, it is likely that phase changes in any sediment mixed into the mantle and devolatilization of the slab lead to the formation of hydrous minerals such as amphibole in the hanging wall of the mantle wedge. Amphibole is of particular significance from

epts, problems and proofs



1: Models for the generation of sources for intraplate volcanism (IPV). **(a)** Plume models isolate subducted oceanic lithosphere and derive mid-ocean ridge basalts (MORB) from the residues of plumes. **(b)** Streaky-mantle model remixes subducted lithosphere into the convecting mantle and derives IPV from streaks of recycled crustal material. **(c)** Hydrous peridotite model envisages the sources of intraplate volcanism are formed complementary to arc volcanism at convergent margins, with ancient isotopic signatures generated along sutures in the continental mantle. Abbreviations: CM continental mantle, LM lower mantle, PM primitive mantle, UM upper mantle.

evidence for its presence in the sources of most OIB (Francis and Ludden 1995), and from its incorporation of Nb which may reverse the fractionation of Nb/Ta in slab-fluids. Common amphibole compositions are only stable to depths of approximately 100 km, such that an enriched layer could only exist at the lithosphere–asthenosphere interface as in the perisphere model of Anderson (1995). However, convection induced in the mantle wedge by the descending slab produces a series of reactions generating phases through phlogopite to high-pressure amphibole compositions such as K-richterite which is stable to depths in excess of 300 km (Thompson 1995).

Data from xenoliths from convergent margins (Ionov and Hofmann 1995) suggest trace element features of low-pressure amphibole compositions are largely transferred to higher pressure phases. Assuming initial isotopic compositions similar to those of primitive arc volcanic rocks, it is estimated that hydrous peridotites would evolve along the HIMU-EM1 isotopic array in Pb–Pb space. The generation of different signatures is postulated to be a consequence of the metasomatic processes forming the minerals, with the higher solubilities of elements such as Th in melts suggesting that the products of melt metasomatism may evolve to HIMU, whereas the products of fluid metasomatism would evolve to EM1 compositions. Generation of the spectrum of isotopic compositions displayed by OIB would take at least 1×10^9 years, at least five times longer than the lifetime of oceanic lithosphere, requiring evolution of some sources in a long-lived reservoir such as the continental mantle. The depiction of this reservoir as a homogeneous and refractory entity in plume models is completely at odds with the existence of tectonic cycles that will produce zones of fertility along sutures, hence the association of OIB with pre-existing lineaments in opening basins as in the example of Iceland (Smith 1993, Foulger 2002). The continental mantle is likely to be also a dynamic reservoir that may erode into the asthenosphere, where the buoyancy of such material, often cited as a difficulty for entrainment into plume sources, would facilitate accumulation as source material for IPV in the shallow mantle without any need for deep recycling.

Conclusions

The success of the plume model is attributed to the completeness of the geodynamic picture it originally presented, compared to competing models based on volatile-bearing sources that rarely considered the ultimate origin of volatiles or the fate of subducted oceanic crust. The advancement of science nonetheless depends on recognition of flaws in a model as a reason for investigating alternative concepts, and the plume model is inconsistent with a range of geochemical evidence. Alternative models will of course appear incomplete in comparison when first considered, but, with even a fraction of the effort put into adding variations to the plume model, such models would not appear as unrealistic as proponents of the plume model depict them. The basis for alternative models is the petrological evidence for volatile-bearing sources which obviates any need for thermal anomalies. ●

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Peter Fellgett

Heading in the right direction

You may be aware that I have been, and am, a bitter critic of the way *A&G* was introduced. *QJ* was one of my favourite publications of our Society, and I regret its loss very keenly. As to *A&G* itself, initially it suffered from a number of coffee-table faults. These faults have now been attended to, and *A&G* is now much more professional. Most importantly you have of late been successful in attracting much better quality articles.

Now you have done a signal service to our discipline by commissioning and publishing the discussion on “plumes”. It is a standing vice of geophysics not to argue against unpalatable facts and arguments, but simply to ignore them and carry on as if they did not exist. It is hardly to be expected that a single issue of *A&G* will correct this tendency, but it will make a dent in it. Perhaps we shall hear less about “the nucleus” of a comet, and “the Oort Cloud”.

Anyway, I do congratulate you and hope that this initiative will be the first of many urging geophysicists and astronomers to wake-up to neglected facts and theories.

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