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Recycling of oceanic crust and the origin of intraplate volcanism

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Source models for intraplate volcanism (IPV) include vertical introduction of material from deep in the mantle (plume model), contamination of the shallow mantle (perisphere and continental mantle delamination models) and derivation by selective partial melting of oceanic crust recycled into the depleted mantle (SUMA/streaky mantle models). The plume hypothesis became the ruling model after a flawed interpretation of helium isotope data in the mid 1980s that led to plumes being imposed on models for crustal recycling into the depleted mantle. This incorporation of otherwise competing concepts, is the cause of unnecessary complexity in modern geodynamic models. The plume model cannot explain all manifestations of IPV and a comprehensive explanation can only be found by invoking the alternative options, combined with their tapping by plate tectonic processes.

KEYWORDS: intraplate volcanism, crustal recycling, mantle plumes, marble-cake mantle, SUMA model, pyroxenites.

INTRODUCTION

In a plate tectonic framework, there are three categories of volcanism: ocean ridge, arc and intraplate. While the origins of ocean ridge and arc volcanism are readily explained by plate tectonics, intraplate volcanism (IPV) has generally been considered to be imposed on plate motions by mantle plumes from the deep interior of the Earth. From the number of studies where plumes are invoked as an *a priori* assumption, there can be little doubt that the plume hypothesis now dominates geodynamic models of the Earth's interior. However, some four decades after plumes were proposed by Morgan (1971), doubts have been increasing as to the validity of the plume concept.

Skeptics focus on the *ad hoc* nature and number of variations of the plume model, the neglect/violation of physics in the concept, and the fact that few examples of IPV show the predicted large-igneous province/volcanic chain features of the classical plume head/tail model (e.g. Anderson 2005a, 2013; Foulger 2010, 2012). Significantly, there would have to be an unrealistically large number of plumes to explain all IPV. Proponents of the plume model attempt to circumvent this problem by invoking flow of plume material or contamination of the shallow mantle with plume residues (e.g. Phipps Morgan & Morgan 1999), but this does not circumvent the fundamental issue that non-plume mechanisms are still required to tap such sources. Thus, the plate loading models, propagating fractures and stress field concepts (e.g. Jackson & Shaw 1975; Walcott 1976) that were abandoned as the plume model gained popularity, are now recognised to be needed even in modern plume models. The implication of such, however, is that the plume model is superfluous, particularly as these mechanisms can grouped into what is termed the 'plate model' (Foulger 2002, 2007), where all categories of volcanism can be explained as part of plate tectonics.

A number of recent papers have detailed how the plate model can explain features attributed to plumes (e.g. Anderson 2005a; Foulger 2007). However, a question that needs to be asked is why should it have taken so long for the plume model to be challenged? Did the plume hypothesis become established because of merit or because of a lack of opposition? The aim of this study is to examine the foundations of the plume model and its alternatives from the perspective of sources, as it is argued that adoption of the plume model controlled not only thinking regarding the origin of intraplate volcanism, but also models for the depleted/MORB-source mantle.

VERTICAL INTRODUCTION OF OIB SOURCES: THE MANTLE PLUME MODEL

The plume model invokes vertical introduction of source material for IPV. The model arose from the postulation of Wilson (1963) that the source of Hawaiian lavas was a thermal anomaly or 'hotspot.' Morgan (1971) proposed such otherwise unsupported thermal anomalies were conduits of upwelling lower mantle, thus formulating the concept of plumes. However, the modern incarnation of the plume model can be attributed to Hofmann & White (1982), who proposed plumes were composed of

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recycled oceanic crust plus related peridotites. The Hofmann & White (1982) model provided an explanation for the non-primitive mantle-like isotopic compositions that were found in ocean island basalts (OIB) after Morgan's (1971) model was formulated, and also appeared to offer a solution to an ongoing debate regarding the fate of subducted oceanic crust.

The concept of storing subducted oceanic crust in thermal boundary layers on which the Hofmann & White (1982) model was based had been proposed by Dickinson & Luth (1971) as an alternative to models (Armstrong 1968; Tatsumoto & Knight 1969) in which subducted oceanic crust was recycled back toward mid-ocean ridge systems by convection within the upper mantle. Polvé & Allègre (1980) supported recycling as envisaged by Armstrong in their interpretation of pyroxenite bands in orogenic lherzolite massifs as subducted oceanic crust that had been stretched out and thinned by several orders of magnitude. The pyroxenite bands and their lherzolite matrix found in such massifs were termed 'marble-cake mantle' by Allègre & Turcotte (1986). However, rather than competing with the Hofmann & White (1982) model, Allègre & Turcotte (1985, 1986) combined both fates for subducted oceanic crust in what was to become the forerunner of today's 'standard geodynamic model.' This decision to combine the models was made following the interpretation of Allègre *et al.* (1983) of high $^{3}He/^{4}He$ ratios in Hawaiian lavas as an excess of primordial ^{3}He. The latter could be explained if He migrated into subducted oceanic crust in a thermal boundary layer overlying a primitive mantle reservoir. The possibility that was not considered by Allègre & Turcotte (1985, 1986) was that high $^{3}He/^{4}He$ ratios could reflect a deficiency in ^{4}He (i.e. a low U+Th source), rather than an excess of ^{3}He (Anderson 1998). The ^{4}He-deficiency interpretation is supported by the predominance of EM1 Pb isotopic signatures in IPV with high $^{3}He/^{4}He$ ratios (e.g. in Hawaiian lavas), and was acknowledged in contemporary studies of basalts from other oceanic settings, but was not applied to OIB (e.g. Zindler & Hart 1986).

Rather than the plume model being evaluated critically, the focus switched to examining the scope of plume applications, along with the implications for the depleted mantle MORB-source. Recycling crust into the depleted mantle was resisted in some models on the basis that trace element signatures in Atlantic and Pacific MORB did not indicate the involvement of a crustal component (Rehkämper & Hofmann 1997; Hofmann 1997). Other authors suggested subducted oceanic crust was predominantly recycled into the depleted mantle (Saunders *et al.* 1988; Davies 1990; Christensen & Hofmann 1994). This was partly to avoid unrealistic volumes of oceanic crust accumulating in thermal boundary layers, and partly to explain seamount basalts and E-MORB compositions which unlike OIB, were considered to be derived from oceanic crust recycled into the depleted mantle (Zindler *et al.* 1984; Saunders *et al.* 1988; Niu & Batiza 1997; Donnelley *et al.* 2004). The result was two types of plume-dominated geodynamic model (Figure 1a, b). The geodynamic complexity has been further exacerbated by Niu & O'Hara (2003), who argue that the lower metasomatised peridotite portion of the lithosphere is a more suitable source for OIB from geochemical and mineral physics considerations, and that subducted oceanic crust is largely trapped in the transition zone or lower mantle.

DERIVATION OF OIB AND MORB FROM A COMMON SOURCE: THE SUMA AND STREAKY MANTLE MODELS

After the plume and marble-cake models were both accepted as the fate of subducted oceanic crust, Pb isotopic compositions similar to both MORB and OIB were found in the pyroxenite layers in orogenic lherzolite massifs (Hamelin & Allègre 1988). The implication that both types of volcanism could be derived from the depleted mantle was not followed up, as further studies suggested only a small proportion of the pyroxenite layers had the geochemical characteristics of recycled MORB (Kornprobst *et al.* 1990). Instead, the majority of orogenic lherzolite pyroxenites were interpreted to have formed as high-pressure cumulates of melts that had intruded the peridotites, although the origin of intruding melts remained vague. A lack of a clear relationship between radiometric ages and thickness of the pyroxenite layers was also used against the marble-cake concept (Pearson *et al.* 1993; Pearson & Nowell 2004). Modern studies consider pyroxenites to be a key component in the source of OIB, but the pyroxenites are considered to form in plumes (Sobolev *et al.* 2005).

The petrological arguments made against the marble-cake concept can, however, be readily countered as melting of recycled oceanic crust would be likely at some stage during entrainment by mantle convection (Anderson 2006), such that survival of MORB-like compositions would be considered unlikely. The high pressure cumulates in the orogenic lherzolites can be considered a product of such melting (Smith 2009): during normal mantle upwelling, the dry eclogite solidus would be intersected by an ocean ridge adiabat at around 120 km depth. Melts would react with the overlying mantle to form pyroxenites, some of which would subsequently play a role in MORB-generation. However, altered eclogite or recycled sediment compositions would melt earlier, with the melts reacting with mantle peridotites to form pyroxenites at around 180 km depth. These deeper-formed pyroxenites have MgO contents intermediate between MORB and peridotites, and would be suitable as a source for the generation of OIB melts (Smith 2009). The problem noted by Niu & O'Hara (2003) of recycled crust having too low MgO content to be a source for OIB is thereby avoided. Such pyroxenites would be able to survive melting along the flanks of ocean ridge upwelling and become incorporated into the shallow off-axis mantle as source for IPV (Smith 2009) (Figure 1c).

After dismissal of the marble-cake concept, subducted oceanic crust recycled directly into the depleted mantle was not considered as a source for IPV until the statistical mantle assemblage (SUMA) model of Meibom & Anderson (2003). The SUMA model invokes a greater proportion of recycled oceanic crust in the generation of OIB relative to MORB. The principal difference with the marble-cake model, is that the mantle is considered to be

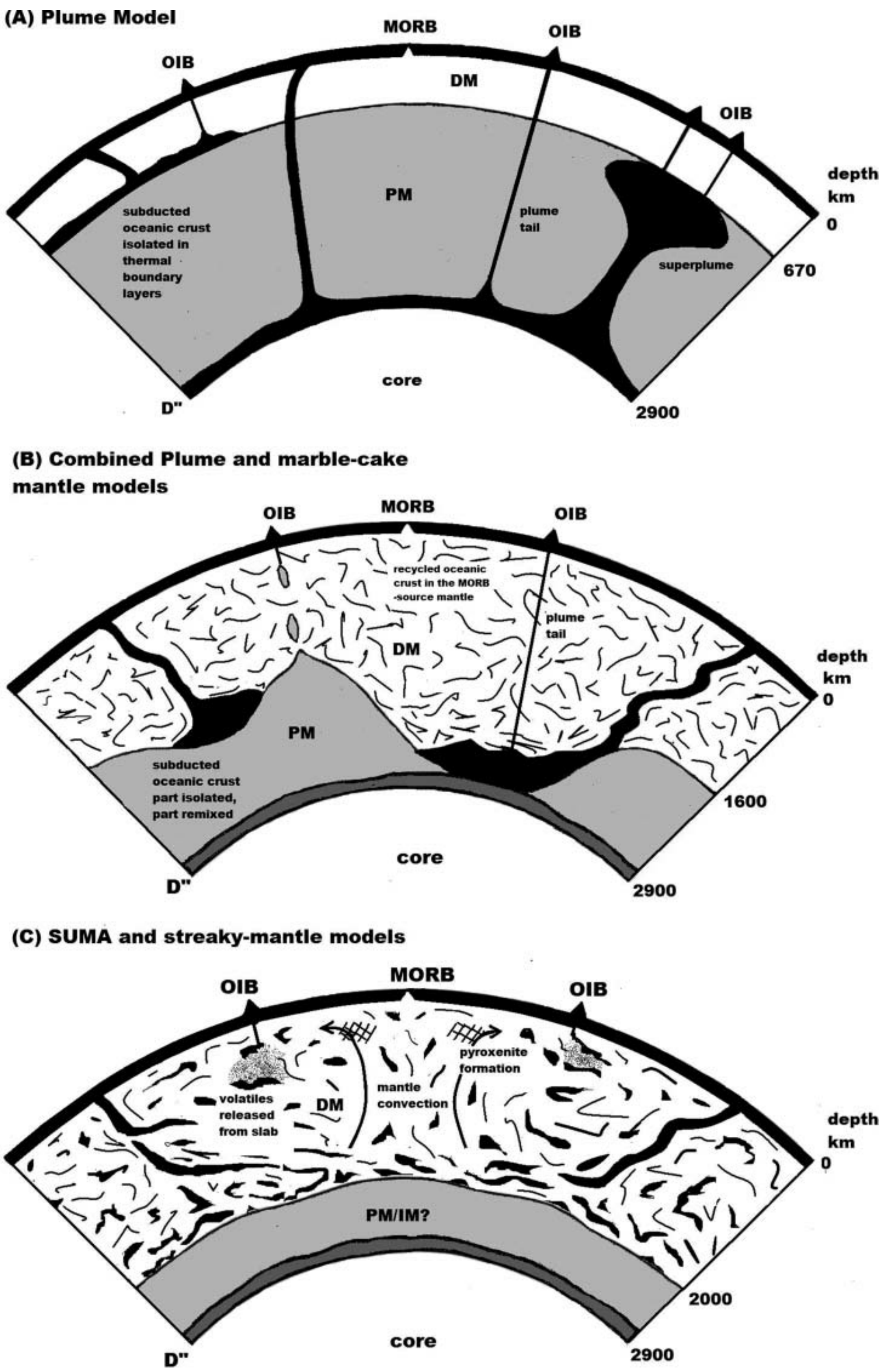

Figure 1 Schematic illustration of mantle geodynamics and recycling of oceanic lithosphere. (A) Simple plume model (e.g. Hofman & White 1982; Allègre & Turcotte 1985). Subducted oceanic crust is isolated in thermal boundary layers. The depleted mantle (DM) is considered to be a residue from generation of the continental crust from a primitive mantle (PM) reservoir that is now restricted to the lower mantle. (B) Plume model incorporating marble-cake recycling (e.g. Allègre & Turcotte 1986; Davies 1990). IPV is derived from plumes. Recycled oceanic crust in the DM is restricted to acting as a source for seamount basalts and E-MORB. As subducted oceanic crust is present within the DM, the amount of PM crust involved in mantle depletion is increased relative to that in the simple plume model; hence the volume of the primitive mantle reservoir is reduced. (C) SUMA/Streaky mantle models (Meibom & Anderson 2003; Smith 2005). Subducted oceanic crust is remixed entirely into the DM. Note the greater size range of heterogeneities compared with that in the marble-cake model. OIB melts are suggested to be generated when volatiles released from young slabs pervade recycled crust and/or pyroxenites at shallow levels in the off-axis mantle. The OIB-source pyroxenites are formed around 180 km depth along the flanks of convective unpwellings in the mantle. Any primitive mantle that has been unaffected by crustal extraction is restricted to deep in the lower mantle. Alternatively the deepest mantle can be considered as isolated mantle (IM), which may or may not include deeply subducted slabs.

less homogenised in the SUMA model. Heterogeneities of recycled oceanic crust up to 100 km in size were predicted in the SUMA model. The size and orientation of the heterogeneity would determine the volume and rate of melt production. Smaller heterogeneities or a mantle region rich in recycled crust could serve as the source for OIB, whereas entrainment of poorly mixed or accumulations of recycled crust into ocean ridge upwelling could generate oceanic plateaus (Smith 2009). As MORB and OIB do not form simple endmembers in isotopic space, the SUMA model was envisaged to work in conjunction with the shallow recycling of additional materials, such as delaminated lower crust or continental mantle (e.g. Anderson 2005b; Ishikawa *et al.* 2007).

A further variation of recycling into the depleted mantle was the streaky mantle model of Smith (2005), where it was proposed that oceanic crust that underwent dehydration as it was subducted was the predominant component in the source of IPV. Such material was envisaged as having been recycled into a depleted mantle that was buffered predominantly by recycling of oceanic crust that had undergone melting on subduction during the first half of Earth history. The recycled melted slab component was suggested to have a more refractory composition, and to isotopically mimic the depleted mantle end-member whose heterogeneity has otherwise been considered the product of the extraction of the continental crust. The difference between OIB and MORB was considered the result of melting of this more refractory component during the generation of MORB. The size range of the recycled components was considered variable as in the SUMA model, although the largest heterogeneities would likely be of dehydrated subducted crust owing to the younger average age for this component.

Melting of recycled crust/pyroxenite components in the SUMA and streaky mantle models can be ascribed to fluxing of the shallow intraplate mantle by volatiles released from recently subducted slabs (Smith 2009). Water can be transported to the transition region in cold slabs (Ivanov & Litasov 2013). Similarly, CO_2 can be transported to this region in carbonated eclogite (Dasgupta *et al.* 2004). As the newly subducted slabs undergo thermal equilibration with the mantle, volatiles are released which then migrate upwards. OIB-type melts are suggested to be produced when volatiles pervade recycled oceanic crust and associated pyroxenites that have been transported into the intraplate mantle by large-scale convection (Smith 2009) (Figure 1c).

FORMATION OF OIB SOURCES BY CONTAMINATION OF THE SHALLOW MANTLE

A third option is to consider the source material for IPV to be a contaminant of the shallow mantle. Such sources could arise as a result of subduction processes (Ringwood 1990), as in the perisphere model of Anderson (1995), or result from delamination of thermal boundary layer continental mantle during continental breakup or continental collision (Smith & Lewis 1999). Delamination would occur mainly along pre-existing sutures where the lithospheric structure is heterogeneous and weak (Gorczyk *et al.* 2013). When a plate undergoes compression, continental mantle from the suture region may be injected into the asthenosphere where it may melt, with the resulting volcanism inheriting signatures of both continental mantle and asthenospheric sources (Elkins-Tanton 2007). An example would be the extrusion tectonics model of Flower *et al.* (1998) for southeast Asia, where Cenozoic volcanism has been attributed to re-activation of sutures following the India–Asia collision.

Conversely, when a plate is subject to extension, continental mantle along a suture becomes thinned, with localised convection developing that may generate large-igneous provinces along the suture being reactivated (Gorczyk *et al.* 2013). It has been noted that intraplate volcanic lines within opening ocean basins (e.g. Atlantic) extrapolate into sutures that crosscut the margins of the basin (Smith 1993). This feature may be explained by progressive delamination and cycling of material toward the axis of rifting from the crosscutting sutures as the basin opens. The longevity and volume of IPV within the basin are thus related to the structure of the lithosphere bounding the basin, while the geochemical signature of the IPV is linked to the age of the sutures (Smith 1993; Foulger *et al.* 2005). DUPAL isotopic signatures as found in the South Atlantic and Indian Ocean IPV can thus be ascribed to contamination of the asthenosphere with ancient continental mantle from under South America, Africa and India, rather than equatorial plume upwelling (Smith & Lewis 1999).

The difficulty with invoking delaminated continental mantle as a ubiquitous source for intraplate volcanism is explaining volcanism in long-lived ocean basins such as the Pacific. Such material could however be a potential source if there were westward drift of the lithosphere relative to the mantle (Smith & Lewis 1999). Such drift was suggested before the advent of the plume model when plate motions were modelled relative to the Antarctic plate. The latter can be considered fixed as it is centred on the Earth's rotation axis. Interest in the concept diminished with introduction of the hotspot reference frame, but if plumes do not exist, plate motions relative to the hotspot frame are not valid. Allowing for westward plate drift, the sources of Pacific IPV could potentially be related to continental mantle delaminated during rifting around 350 million years ago along eastern Gondwana, or during continental collisions that led to the formation of Asia approximately 250 million years ago (Smith & Lewis 1999). Given the time frames, it is likely any such material would now have been greatly dispersed, although this would be consistent with the view of Machida *et al.* (2009) of the Pacific mantle now being 'depleted in contaminants' relative to Indian Ocean mantle.

In their original versions, both the perisphere and continental mantle-source models were presented as independent models. However, the production of perisphere sources can be considered a first-stage mantle enrichment process resulting from the recycling of oceanic crust. Sutures in the continental mantle mark the sites of plate convergence and as such would be optimal locations for retention of the geochemical imprint of slab-derived fluids. The topography of sutures would also make them preferred sites for invasion of melts generated from the more fertile components in the depleted mantle (Smith & Lewis 1999; Gorczyk *et al.* 2013). The continental mantle delamination and perisphere models can therefore be treated as extensions of the SUMA and streaky mantle models.

CONCLUSIONS

There is general agreement that recycled oceanic crust is an important component in the source of IPV. Such crust is usually considered to have been recycled through plumes. However, the history of the plume hypothesis shows it became the ruling model based on a one-sided interpretation of helium isotope data in the 1980s. The plume model was combined with an alternative explanation for the fate of subducted oceanic crust, but there was no competing model at the time for IPV. The plume hypothesis thus never underwent rigorous evaluation, as it did not itself challenge any pre-existing theory. Three decades later there is still no definitive evidence for plumes: thermal anomalies, geochemical models for interaction with the Earth's core, and tomographic evidence for plume sources/traces in the mantle have all been countered (e.g. Anderson 2005a; Meibom 2008; Foulger 2010). Hence, there is no mandate that subducted oceanic crust must be recycled to any extent by plumes.

The marble-cake model that competed with the plume concept of storage of subducted oceanic crust in thermal boundary layers was simplistic. More modern interpretations suggest the banding in orogenic lherzolites on which the model was based, in conjunction with multiple generations of intra-mantle pyroxenite veins, means that such material represents a late stage of remixing of subducted oceanic crust. The simple marble-cake model can be modified by including subducted oceanic crust in the early stages of remixing and invoking melting of the crustal components when entrained by large-scale mantle convection to form the pyroxenite compositions observed in orogenic lherzolites. A modified marble-cake mantle model would thus have the requisite components and size range of heterogeneities for the generation of IPV from the depleted mantle.

Both the plume and alternative SUMA/streaky mantle models require the 'plate model' for tapping of the source materials. The differences are thus in the extent of such reliance; with the plume model it is partial, and with the marble-cake/SUMA/streaky mantle models it is complete. The latter, however, is not a weakness; it allows the plate model to provide the only comprehensive explanation for IPV, and all categories of volcanism to be linked with plate tectonics. The interpretation of high ^{3}He/^{4}He ratios solely as an excess of ^{3}He that led to the requirement to include plumes in geodynamic models was thus perhaps the most significant decision influencing geodynamic thinking after the advent of plate tectonics, as its consequence was to add an unnecessary complexity to the understanding of both the origin of IPV and the evolution of the depleted mantle.

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