Review: Intraplate Magmagenesis - An Alternative to Plumes

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ABSTRACT

Plate tectonics allows for the interpretation of ~90% of all volcanism, along with its occurrence at plate margins; however remaining intraplate 'hotspots' are traditionally perceived as unexplainable in this context. Morgan (1971; 1972) proposed one of the most currently accepted theories for the origin of such melt extraction anomalies, mantle plumes. However there remain several problems with its universal application, and alternative melt generation mechanisms have been proposed, particularly for those areas where fundamental predictions of the plume hypothesis are not met. The purpose of this review is to consider this alternative plate theory as applied to the Hoggar Swell and Ontong Java Plateau in light of such failings. It is thought the plate theory offers an elegant solution to magmatism at these (and likely further) localities, owing to a more satisfactory explanation of observations and its complimentary relationship to plate tectonics.

1. INTRODUCTION

Following the advent of the plume theory and later supporting evidence (see section 2) it was widely applied to explain all intraplate magmatism (with the number of proposed plumes reaching 5,200; Malamud and Turcotte, 1999), despite observations in many areas not matching those hypothesized. Instead the theory was adapted and/or elaborated *ad-hoc* at each locality in order to account for such variability; this may be thought normal scientific development were it not for the contradictory nature of adaptations between different areas. Thus today lists of proposed plume underlain localities have dwindled to <70 (e.g. Morgan and Phipps Morgan, 2007) and there is still no overall/generic plume model. Further, over half of the 49 most cited hotspots fail to meet more than one of the deep mantle plume characteristics (Courtillot et al., 2003), albeit these are somewhat arbitrary.

The plate theory provides an alternative explanation which in recent times is receiving more attention. It encompasses a wide range of shallow magma generation mechanisms which all result from in-plate lithospheric extension.

A brief overview of both theories is presented, followed by a discussion of the plate mechanisms proposed for two key localities.

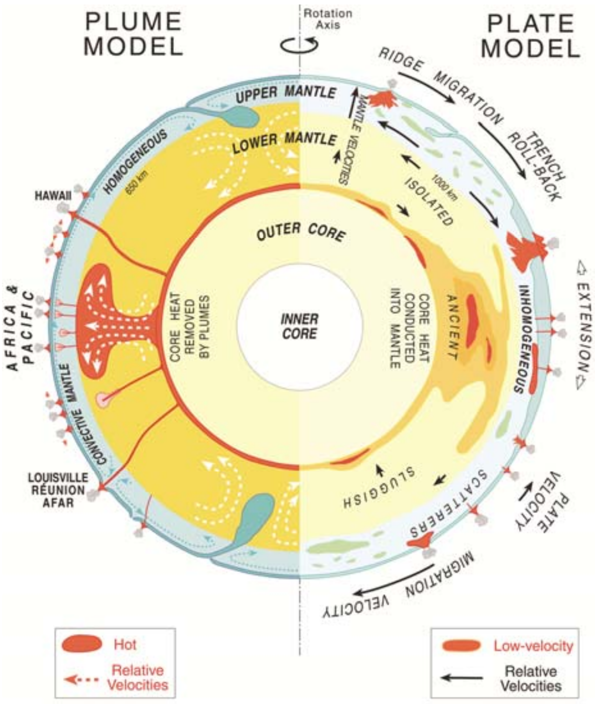


Fig. 1 - From Anderson (2005). Plume model with homogenous mantle and two discrete plume types discussed in text, plate model showing heterogeneous mantle as a result of plate tectonic recycling within the transition zone. This produces varying degree melts at a shallow level beneath extensional areas of the lithosphere, note more sluggish motion of lower mantle and restricted, if any, recycling.

2. THE PLUME THEORY

Morgan (1971; 1972) following the work of Wilson (1963) developed the plume hypothesis as a possible universal explanation of time progressive volcanic chains each connected to intraplate or on-axis hotspots whose locations seemed to be relatively fixed to one another. The overall concept is that a plume represents a thermal instability originating from the core-mantle boundary which, owing to negative buoyancy, transports hotter primordial deep mantle material to the surface, through an otherwise homogeneous and convecting mantle. However some workers (e.g. Courtillot et al., 2003) recognise two types of plume (depicted on left of fig. 1), those narrow direct conduits from the core to the surface, and those broad upwellings which are hindered at the transition zone, feeding smaller areas through it to the surface. Typically mushroom shaped, plumes have a large flattened head and narrow hot tail.

Foulger (2010) demonstrates how plume theory was boosted by the discovery in hotspot volcanics of high $^{3}He/^{4}He$ ratios (taken by many to indicate primordial lower mantle origin) and experimentally produced plumes using fluids of different densities. The result was a believed overzealous application of plumes to every melt extraction anomaly, even where much evidence was lacking. To illustrate this take the predictions of plume theory recently summarised by (Campbell, 2005):

- Initial domal uplift of area
- Flood basalt eruption (owing to plume head)
- Existence of narrow conduit to the core mantle boundary (plume tail)
- Time-progressive volcanic chain (representing plate movement over dwindling tail magmatism)
- Hot source material

However, also shown in Foulger (2010), no single proposed plume shows all these characteristics and variable criteria are used by different workers. Further, the very existence of a plume conduit has yet to be proved unambiguously in any seismic studies, despite recent attempts in Hawaii by Wolfe et al. (2009).

The result is that many intraplate melt extraction anomalies may wrongly have been assigned a plume related origin, including the examples discussed later, meaning alternative plate theory mechanisms must be invoked.

3. THE PLATE THEORY

This theory (Anderson, 2001; Foulger, 2007, 2010; Foulger and Natland, 2003) proposes that melt extraction anomalies/hotspots are a result of various shallow based melt generation mechanisms, ultimately related to plate tectonic processes. It postulates that where the lithosphere is in extension/subject to tensile stresses, volcanism will occur (Anderson, 2001; Favela and Anderson, 1999).

The degree of such melt generation is controlled by the fertility/composition of the source material and presence of any pre-existing melt, meanwhile eruption rates are also dependent upon thickness of the lithosphere and applied stress (Foulger 2010).

As depicted on the right of fig. 1, a heterogeneous mantle resulting from plate tectonic recycling (via melt extraction, subduction and delamination etc.) is fundamental to the plate theory. For a given temperature, where lithospheric stress and extension occurs over fertile mantle (e.g. recycled crust, metasomatised areas etc.), pre-existing melt and/or compositions with a lower solidus, a large melt volume will be produced compared to those depleted infertile areas with a higher solidus.

The exact mechanism of melt generation is also inherently variable between locations owing to both mantle and lithosphere heterogeneity combined with each individual stress field. A good generic summary of the main mechanisms is given in Foulger (2010).

The plate theory too however faces its own problems, particularly the apparent distinct nature of geochemical reservoirs, although it is argued this is a statistical perception and at odds to known recycling via plate tectonics (Meibom and Anderson, 2004).

Note the following examination of two melt extraction anomalies is not an attempt to disprove the existence of plumes on earth (if this were the case perhaps Hawaii or Yellowstone would have been discussed). Instead it is intended to describe some of the alternative melt generation mechanisms proposed as part of the plate theory, and how these provide a better fit to the main observations compared to the plume hypothesis previously universally applied to all hotspots.

4. HOGGAR, CENTRAL SAHARA, ALGERIA

4.1 OVERVIEW

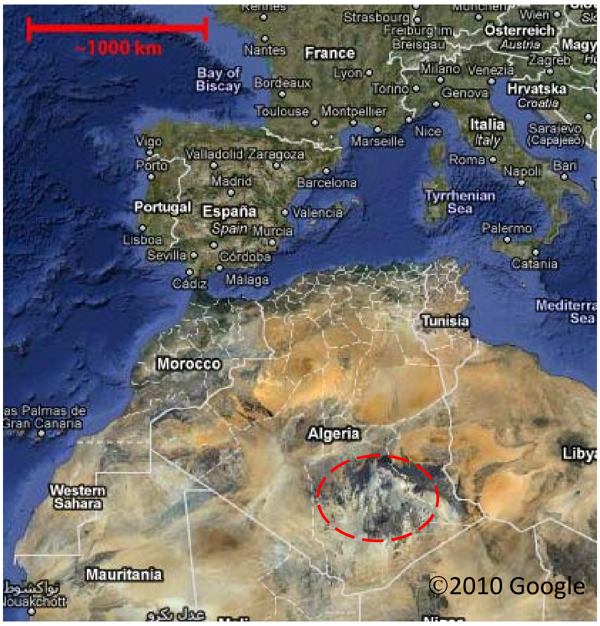


Fig. 2 - Dashed ellipse marks broad area of Hoggar volcanism, at centre of the Hoggar Swell in Algerian Sahara.

The Hoggar swell and associated Cainozoic (35 Ma to near present; Aït-Hamou et al., 2000) igneous rocks cover an area of more than 10,000 km^2 in the Tuareg shield of the Algerian Sahara, fig. 2. The shield itself is a composite of Archean to Neoproterozoic (i.e. Precambrian) terrains formed during the 750-550 Ma Pan-African orogeny (Black et al., 1994). This marked the oblique convergence of the west African craton with the Saharan metacraton to the east, causing the central Hoggar microcontinent (LATEA craton), caught between the two, to experience transpressional escape tectonics, accommodating northwards extrusion. See also figs. 3 and 4. This led to the development of N-S orientated mega-shear zones within it, i.e. metacratonization.

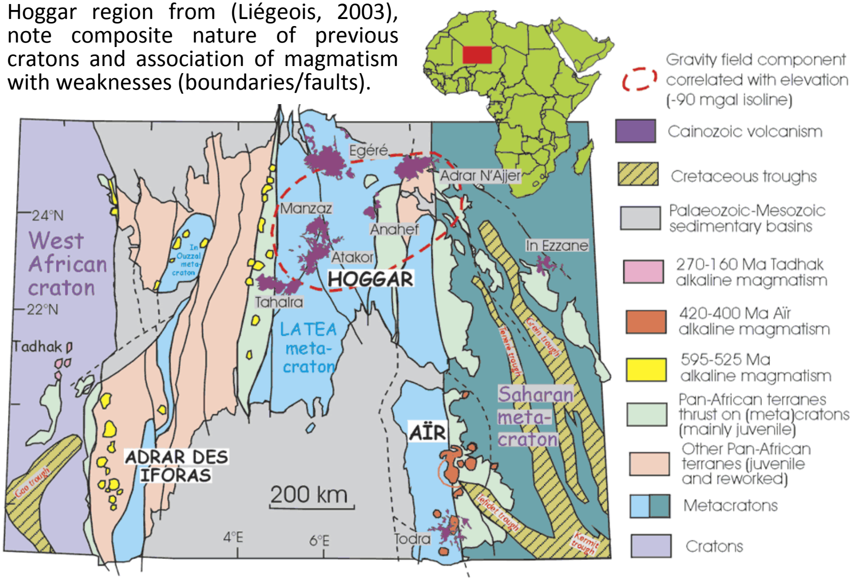
Note the term metacraton was defined for the Saharan metacraton by Abdelsalam et al. (2002) as a craton remobilised/slightly destabilised during later orogeny.

Toward the end of orogeny, the LATEA metacraton experienced transtension (Azzouni-Sekkal et al., 2003) followed by formation of shallow brittle conjugate strike-slip faults in which the NW-SE dextral system was dominant (Ball, 1980).

4.2 OBSERVATIONS/CONSTRAINTS

A general geological map is provided as fig. 3. From this it can be seen all magmatism is concentrated either along the margins of the three component Precambrian terrains or, as with the most recent Cainozoic melts, within the central LATEA metacraton broadly along lithospheric scale mega-shears. Toward the surface however the Cainozoic volcanics become more locally controlled by the NW-SE/NE-SW trending conjugate strike-slip faults (Liégeois et al., 2003).

Fig. 3 - Geological overview map of Hoggar region from (Liégeois, 2003), note composite nature of previous cratons and association of magmatism with weaknesses (boundaries/faults).



Also with regard to tectonics there is a marked correlation between the timing of key events during the Africa-Europe collision (as reported by Guiraud and Bosworth, 1997) and magmatic episodes. Most volcanism occurring either at the same time or <2 Ma afterwards.

Of the Cainozoic rocks, three distinct generations can be found. The oldest are those 600 m thick tholeiitic basalts from fissure eruptions between 30-35 Ma (Aït-Hamou et al., 2000). The intermediate stages between 20-12 Ma and 7-4 Ma were predominantly basaltic eruptions, but 18% was of the more alkaline trachytic and phonolitic trends (Rognon et al., 1983). The most recent volcanism was from 3 Ma to the upper Palaeolithic (i.e. near 0 Ma) and entirely alkaline (Aït-Hamou et al., 2000).

The geochemistry of the Cainozoic rocks and xenoliths from within those late alkaline varieties (Beccaluva et al., 2007) shows the early tholeiites to have type 1 enriched mantle (EM1) isotopic signatures and the later alkaline rocks to be toward the HIMU field. The actual xenoliths are of strongly metasomatised spinel lherzolite in which trace element modelling shows the principal metasomatic fluids to be alkaline carbonate melts, themselves with a HIMU signature. Further, the extent of xenolith metasomatism is positively correlated to observed deformation (Liégeois et al., 2003), indicating fluids/melts were preferentially injected into large fracture zones.

Cainozoic volcanism was associated with uplift of the Pan-African terrain as part of the Hoggar swell during the Cainozoic, as attested by Cretaceous sediments currently found at elevations of 2-3 km (Rognon et al., 1983).

Geophysical investigations show the Hoggar swell is host to a -90 mGal Bouguer gravity anomaly (Lesquer et al., 1988), fig. 3. Measured heat flow (Lesquer et al., 1989) averages a standard 50 mWm^{-2} and decreases as basement elevation increases. Indeed only one thermal anomaly is present at 63 mWm^{-2} centred upon the Atakor volcanism. Anomalously low P-Wave velocity zones are restricted to the upper 300-400 km and likely reflect a modified but now cooled upper mantle (Ayadi et al., 2000), this also shows there is no large scale uplift of hot asthenosphere. More minor low velocity zones do however still exist locally and are thought remnants of hotter material from recent volcanism.

4.3 THE PLUME THEORY PROBLEM

A mantle plume was suggested (Aït-Hamou et al., 2000; Aït-Hamou and Dautria, 1994) for this area based on the observed correlation between elevation of the Hoggar Swell and the gravity anomaly of Lesquer et al. (1988). However the overall inverse correlation between heat flow and elevation shows that thermal buoyancy generated by a plume cannot be the cause of the Hoggar swell.

In all other aspects, as stated, Hoggar is also unexplainable via the plume hypothesis, with no geochemical evidence either indicating nor requiring the involvement of a plume. Seismic tomography shows only near surface anomalies/processes. Other features such as a pre-cursory flood basalt or a time progressive volcanic track are non-existent.

4.3 PLATE THEORY MECHANISMS

Two melt generation mechanisms within the context of the plate theory have been proposed for Hoggar - Liégeois et al. (2003) and Beccaluva (2007). Both agree that Cainozoic volcanism is a direct result of lithospheric extension, allowing the passive upwelling of asthenosphere which consequently undergoes decompression melting. This is envisaged to result from reactivation of weaknesses in the Pan-African metacraton owing to the current Africa-Europe collision, particularly of the joins between previous terrains and those mega-shears.

The mechanism of Liégeois et al. (2003) is based upon such weak brittle reactivation of these fractures allowing linear delamination along them at the base of the lithosphere. Asthenosphere (possibly more fertile) at the lithosphere-asthenosphere boundary then upwells into the crust through these fractures, (leading to decompression melting). The change in magma type i.e. tholeiitic to alkaline is accounted for via the degree of melting which occurs, with smaller melt fractions through time.

Cenozoic uplift is interpreted as the simple isostatic adjustment to density lowering of the upper mantle following melt extraction and extensive metasomatism.

The mechanism is based upon a very similar successful model of magmatism proposed to account for the genesis of earlier granitoids. These were emplaced and extruded in the same area with similar distribution, i.e. along transpressional (Liégeois et al., 2003) and later transtensional (Azzouni-Sekkal et al., 2003) lithosphere scale mega-shears, and the boundaries between Precambrian terrains, all developed in the Pan-African orogeny. The only difference in application to the Cainozoic activity is the reduced scale of volcanism (perhaps owing only to fracture reactivation opposed to initiation), and the added constrains of recent observations. A summary is presented in fig. 4.

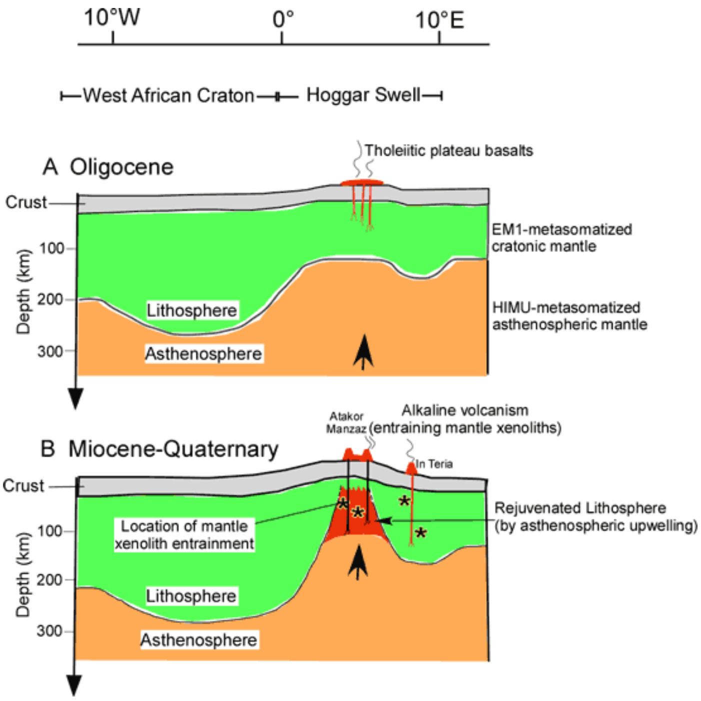
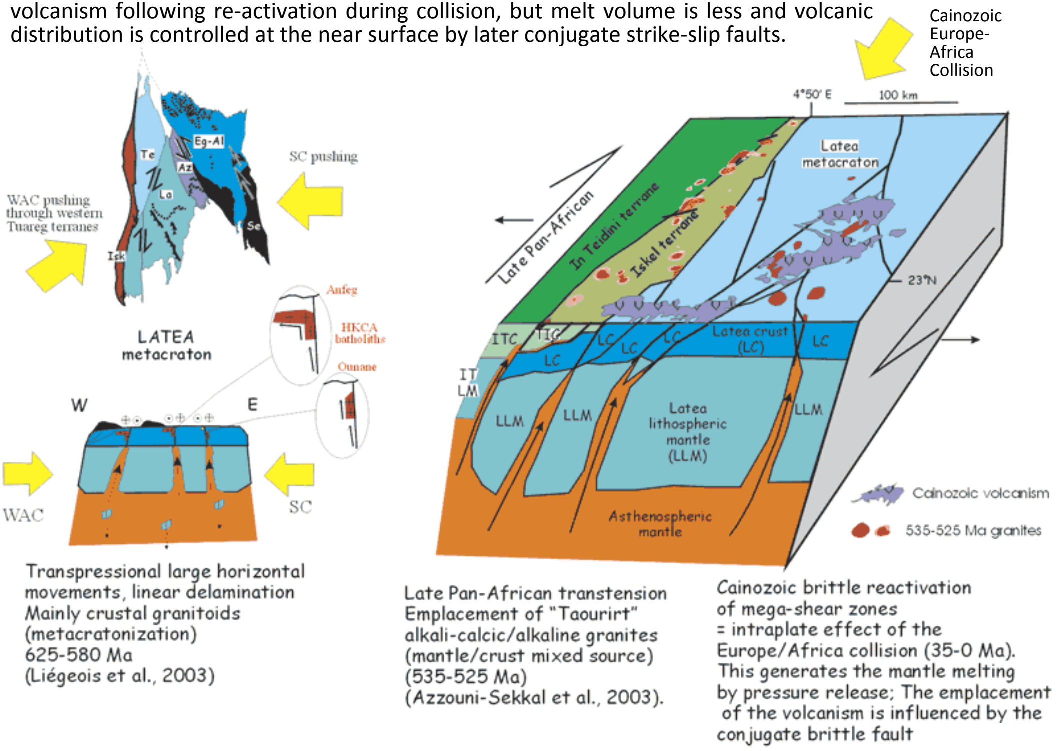


Fig. 5 - Schematic from Beccaluva et al. (2007). A - Initial upwelling of EM1 mantle owing to extension generates tholeiites. B - Uplift of asthenosphere with HIMU signature produces swell and rejuvenates lithosphere passing on its isotope characteristics, this melts forming Cainozoic volcanics.

Beccaluva (2007) present a slight variant of this theory given consideration of their geochemical data. Here initial extension results in the passive upwelling of EM1 metasomatised lithospheric mantle, generating the early tholeiites. However the contrast in thickness between the Hogga area and even older surrounding lithosphere, here the west African craton, initiates EDGE type convection beneath the overall Pan-African composite metacraton. The result is upwelling of asthenosphere, likely with a HIMU signature owing to the presence of subducted/recycled oceanic crust (believed capable of residing in the upper mantle here, e.g. Beccaluva et al., 2005). This produces the Hoggar swell and gravity anomalies whilst 'rejuvenating' the lithospheric mantle to give a HIMU metasomatised source; upon partial melting this produces local alkaline melts accounting for the small present day thermal anomaly over Atakor. A summary is presented in fig. 5.

Note the EDGE acronym in the above paragraph refers to another mechanism which is part of plate theory (**E**dge **D**riven **G**yres and **E**ddies). The concept (as in fig. 6) is of convection cells developed within the asthenosphere owing to abrupt lateral thickness changes at the base of the lithosphere, e.g. as above at the junction of two intracratonic terrains or at passive cratonic margins (King and Anderson, 1998). Convection is generated as warm asthenosphere

Fig. 4 - Schematic from (Liégeois, 2003) in which initial granitoids are emplaced along mega-shears and fractures following linear delamination at their base (allowing upwelling of asthenosphere). A similar mechanism is predicted for the Cainozoic volcanism following re-activation during collision, but melt volume is less and volcanic distribution is controlled at the near surface by later conjugate strike-slip faults.



(usually beneath oceanic plates) is cooled by the thickened cratonic lithosphere next to it and so sinks. This may even lead to erosion of the cratonic lithosphere and its recycling back into the mantle.

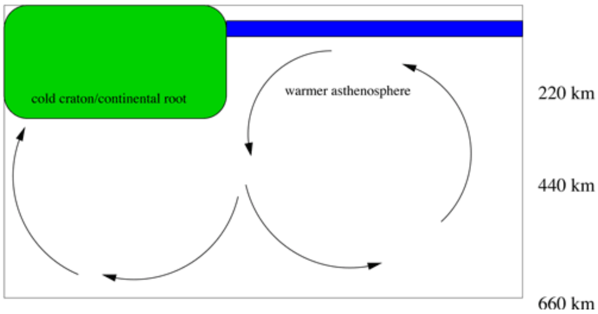


Fig. 6 - Cartoon from King and Anderson (1998) showing the concept and predicted flow of EDGE convection.

5. THE ONTONG JAVA PLATEAU (OJP)

5.1 OVERVIEW

Located in the Pacific this is the largest oceanic plateau on earth with a surface area of 2 x 10^6 km^2 (Fitton et al., 2004), comparable to the size of Alaska at 1.5 x 10^6 km^2. If suggestions that the Manihiki and Hikurangi plateaus were initially part of it (Taylor, 2006; Worthington et al., 2006) are correct then the total volume of basalt would amount to some 100 x 10^6 km^3.

Even though the vast majority of the OJP lies well below sea level, it is one of the better studied oceanic plateaus owing to multiple sampling by the Ocean Drilling Program and obduction onto the Solomon Islands, e.g. the island of Malaita is composed of OJP basalt (Fitton and Godard, 2004; Petterson et al., 1997).

5.2 OBSERVATIONS/CONSTRAINTS

The entire OJP is of basaltic composition with N-MORB type concentrations of incompatible elements but OIB type signature. It was emplaced mainly off-axis in two geochemically similar, very short magmatic episodes, the most major being the initial period between 120-124 Ma involving high degrees of partial melting (Mahoney et al., 1993; Tejada et al., 2002). Minor activity occurred at ~ 90 Ma and there is no evidence for a north-south age progression.

The plateau was extruded onto oceanic crust only 15-30 Ma old, i.e. relatively young (e.g. Ingle and Coffin, 2004; Sliter and Leckie, 1993) producing an overall crust of ~33 km thickness (Richardson et al., 2000). With regard to geophysics the latter authors also show the plateau is underlain by a well developed, but shallow, low-velocity zone extending to 300 km depth.

Roberge et al. (2005) use dissolved CO_2 and H_2O in basaltic glasses to estimate paleoeruption depths of between 1.1 km below sea level for the central plateau and 2.2-3.0 km deep for the north-eastern edge. Uplift was therefore unusually limited to between 2.5-3.6 km above the surrounding seafloor and never resulted in sub-aerial eruption. They agree with Ingle and Coffin (2004) and Sliter and Leckie (1993) that post-emplacement subsidence of the plateau is also anomalous at only ~1.5 km since ~122 Ma.

The OJP is isotopically very homogenous with respect to Nd-Pb-Sr-Hf and incompatible elements in general (Castillo et al., 1994; Mahoney et al., 1993; Tejada et al., 2002). Despite this, minor variations in trace element patterns allowed two isotopically distinct basalts to be identified, the Kwaimbaita and Singgalo (Tejada et al., 2002). Both are believed products of varying degrees of partial melting of the same source.

5.3 THE PLUME THEORY PROBLEM

A plume theory is traditionally assigned for the origin of the OJP (e.g. Fitton and Godard, 2004; Tarduno et al., 1991) assuming the plume head resulted in the creation of the OJP while the plume tail is presently represented by the Louisville hotspot (e.g. Antretter et al., 2004; Richards et al., 1989). Owing to its large extent superplumes have even been envisaged (e.g. Larson, 1991).

However plate reconstructions (Neal et al., 1997) and geochemical data (Mahoney et al., 1993) are inconsistent with such a relationship to Louisville. Indeed there are several further significant problems in application of the plume theory: *(note only additional references to those above are given in this summary)*

- Lava was erupted deep underwater contrary to the substantial thermal uplift predicted by a plume head, this should have led to eruption subaerially or at sea level (Neal et al., 1997, and references therein).
- Post-emplacement subsidence is also anomalously low at ~1.5 km compared to theoretical predictions of ~3 km (Roberge et al., 2005).
- After initial volcanism at ~122 Ma there was a hiatus of ~30 Ma followed by more minor eruption of compositionally identical material at ~90 Ma, clearly in violation of the dynamic variability associated with various plume phases.
- There is no age variation across the plateau and no volcanic seamount chain to represent the tail stage of any plume.
- The postulated plume would sample peridotite source mantle and require $T_p > 1500^oC$ (Fitton and Godard, 2004); this would however produce larger degree melts than observed and contradicts observations of limited uplift.

Of note an impact theory has also been proposed for OJP magmatism (Ingle and Coffin, 2004) but as discussed by Korenaga (2005) this is even more unlikely than a plume origin and is generally out of favour.

5.4 PLATE THEORY MECHANISM

Several non-plume shallow based mechanisms have been suggested. These include a theory based on Anderson's (1995) perisphere model; the term refers to a layer envisaged in the upper mantle, at near solidus conditions, with enhanced fertility compared to typical depleted MORB sources. For the OJP it was proposed (Anderson et al., 1992) a ridge jump occurred, suddenly tapping the adjacent perisphere and resulting in large scale rapid melting. However, as argued by Tejada et al. (2004) the area was already close to a spreading ridge so any perisphere should have been depleted previously. Also the prediction of high volatile content in the volcanic rocks is not met, actually being measured as very low (Roberge et al., 2004).

The most up-to-date and favoured plate mechanism is that of Korenaga (2005), one of the only models to account for the OJP's subsidence history. To begin, subducted oceanic plate undergoes delamination into constituent crust and lithosphere within the upper mantle. The now eclogitized crust fragments 'pond' at the base of the transition zone (660 km) owing to their neutral buoyancy at this position. These fragments are expected to be unevenly distributed, in-keeping with the overall prediction of a heterogeneous mantle in the plate theory.

Next the spreading centre (which the OJP formed near to) migrates over time toward this denser than normal, fertile/eclogite bearing mantle. It is known this spreading centre was super-fast (Larson, 1997) and possibly associated with a ridge triple junction (Neal et al., 1997).

As a result a large dynamic flow field is generated in the mantle, exerting a viscous stress capable of entraining fragments of this fertile material up toward the ridge. However owing to the lower solidus position of such compositions compared to the entraining peridotite matrix, they melt earlier and thus rise off-axis to form the OJP (fig. 7a).

The volume of the OJP does however require a considerable area of typical thickness ocean crust to be recycled, calculated by Korenaga at ~2,400 km^2 assuming 100% melting of the fertile fragments, although only ~50% average melting is predicted.

The isotopic homogeneity of the OJP is therefore explained in this model by recycling a (large) mass of similar aged oceanic crust opposed to strong mixing in a plume head. The lower concentration of incompatible elements compared to N-MORB is interpreted as depletion at the subduction zone.

Subsidence patterns are predicted, with only limited initial uplift owing to the dense nature of emplaced material, followed by development of convective instabilities during cooling (on the timescale of tens of millions of years) which results in delamination of material back into the mantle. The consequence is reduced subsidence and influx of residual mantle which might then generate further volcanism as observed at ~90 Ma (fig. 7b).

As support for this theory Tejada et al. (2002) show that trace element modelling using eclogite type source material provides an equally good fit to OJP data as pyrolite (i.e. peridotite). Ishikawa et al. (2007) have however produced evidence for and against both this mechanism and that of a plume.

In summary Korenaga's (2005) theory can therefore explain many more of the observations except the low-velocity zone, but this is not accounted for in other current theories either.

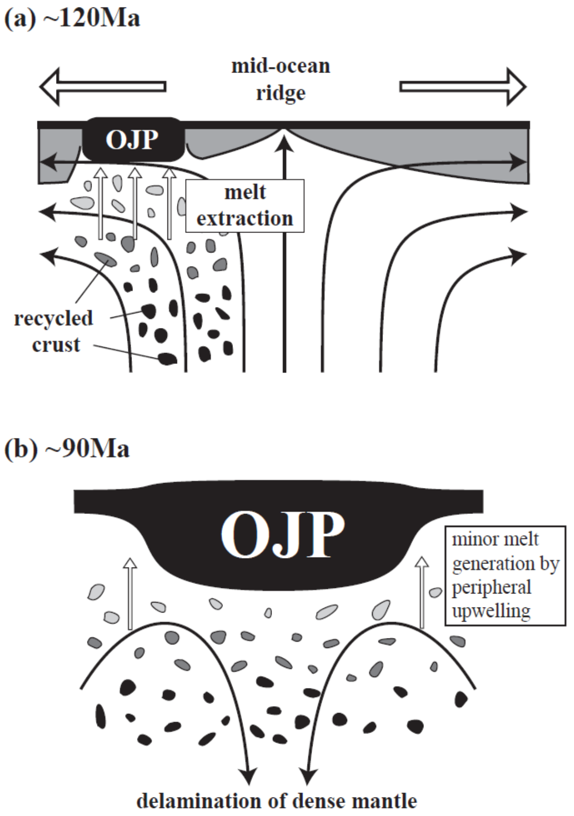


Fig. 7 - Schematic from Korenaga (2005). 7a - Dense and fertile heterogeneities are entrained in dynamic flow from ridge, melting earlier than peridotite and thus give off-axis volcanism. 7b - Cooling creates convective instabilities causing delamination of some material and allowing renewed upwelling, possibly responsible for second magmatic episode at ~90 Ma.

6. CONCLUSION

The above illustrates successful application of plate theory melt generation mechanisms to localities where the only past alternative has been plume based.

These are not the only cases and many other scenarios with further mechanisms for shallow level magma generation exist. For example the Anatolian melt anomaly (Keskin, 2005), where an area of Eurasian plate behind the collision zone between Arabia and Eurasia experienced uplift followed by volcanism from 8-1.5 Ma. This was initially interpreted as a mantle plume (Pearce et al., 1990) but is now known, as supported by geological, geophysical and geochemical data to result from either slab break-off of previously entirely subducted oceanic plate, fig 8. (Keskin, 2003) or lithospheric delamination (Keskin, 1994; Keskin et al., 1998). Regardless the key result is upwelling of hot asthenosphere into the mantle wedge.

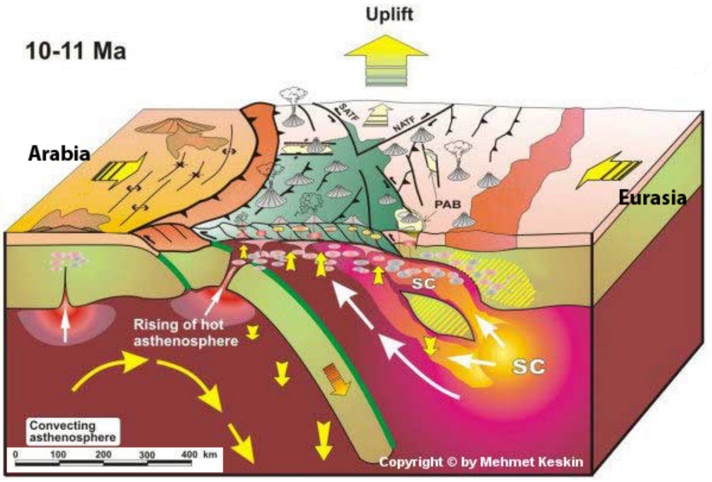


Fig. 7 - Example of slab break-off mechanism as applied to Anatolia, modified from Keskin (2005) after Keskin (2003).

Hence although a large number of further such melt generation mechanisms exist within the plate theory, there is still a limited number of critical factors, namely the melt source from a heterogeneous mantle, temperature, applied stress field and geometry and composition of the lithosphere. The variability in mechanisms therefore simply reflects the natural complexity of these systems opposed to the often contradictory *ad-hoc* corrections which characterise previous attempts of universal application of the plume hypothesis.

It is important to note the exact details of each developed plate type mechanism may not be correct (e.g. uncertainty between mechanisms in Anatolia, finer details of Korenaga's OJP hypothesis), with most awaiting further observations and research. However their ability to account for more of the current observations than previous theories surely indicates the overall logic is sound.

In summary plate theory provides a comprehensive framework in which to interpret the vast majority, if not all, melt extraction anomalies/hotspots and for many locations is the most capable of explaining observations given also geophysical and geochemical constraints. It is complementary to the plate tectonic paradigm and in-keeping with observations of continuum deformation in which the earth's surface is clearly seen as a dynamic mass and not a series of 'rigid plates' subject to *normal* volcanism only at their margins. Indeed what is classed as normal volcanism may need to be re-considered once such a suite of new possible shallow-level magma generation mechanisms becomes more accepted.

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