FIGURE 1: The dome of St. Peter's Basilica. The author suggests that domes, cathedrals and plates are held together by the St. Peter Principle.

LARGE IGNEOUS PROVINCES AND THE LITHOSPHERE

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ABSTRACT

Tectonic plates stay together for a reason; they are strong because of lateral compression; a cathedral without buttresses to keep its rocks under compression becomes a pile of rock. Plates serve to keep magma in the mantle. Incipient plate boundaries and LIPs form where the lithosphere is extending, probably assisted by magma fracture. New rifts often experience a burst of magmatism, suggesting a fertile shallow mantle. Locations of rifts are controlled by lithospheric conditions, and the volumes of magmas by mantle fertility, ponding, and focusing. Recycled materials melt because of low melting temperatures and the large heat bath provided by the mantle itself.

(keywords; LIPs, plumes, hotspots, lithosphere, eclogite)

INTRODUCTION

Very large igneous provinces (LIPs)–continental flood basalts and oceanic plateaus–are enigmatic. In absolute terms the volumes of these are enormous, but the local mantle does not seem to be hot. LIP eruptions generate about 1 cubic kilometer of basalt per year for a million years, but midocean ridges generate far more; 20 km^3 per year for hundreds of millions of years. If the 10-20 km thick crust of a typical LIP is the result of processing an area 3 times larger than the surface area, then only a 20-40 km depth-section of the mantle needs to be partially melted and drained. Normal mantle geotherms are thought to be well above the solidus of upper mantle fertile peridotite from about 30 to 60 km depth–the major melting interval for oceanic ridges. What is it then that is responsible for the episodic giant outpourings of lava? Does the lithosphere act as a stress valve, or is the mantle unusually fertile in places? The depth extent of melting and the amount of melt will be much greater if the local mantle has a lower melting point and a smaller interval of extensive melting than peridotite; can such fertile mantle be responsible for melting anomalies?

The inferred temperature of magma in the North Atlantic large igneous province is almost indistinguishable from that of normal mid-ocean ridge basalts, MORB (Korenaga and Kelemen, 2002). There is also little evidence from uplift, heat flow or seismology for high temperatures under LIPs (Stein and Stein, 2003; Czamanske et al., 1998; Anderson et al. 1992). Clift [2004] [see also www.mantleplumes.org] has shown that the mantle under oceanic plateaus is consistent with normal mantle temperatures. All of this implies that lithospheric stress or architecture, and mantle fertility, rather than high temperature, may be responsible for LIPs. The challenge is to find mechanisms that can explain the volume of basalt without particularly high temperatures.

O'Hara (2004) pointed out that the standard model of an ascending hot, fertile peridotite source, leaves unanswered several questions: Why do trace elements of so-called hotspot magmas imply small degrees of melting, while the local abundance of magma implies extensive melting or exceptionally large source regions? Why is there little evidence of hot, low-density residual peridotite under LIPs (e.g. Anderson et al., 1992)? How is the need for buoyancy to be reconciled with the high subsolidus density of fertile source materials with high melting temperatures? Where does the enthalpy of melting come from and how is it concentrated, given that heat will be conducted out of the hot rising mass? [see also www.mantleplumes.org]. To this list can be added; What happens to the seamount chains, aseismic ridges –and other plates bearing thick-crust–that enter trenches?

CONSTRAINTS & PARAMETERS

Large erupted volume is often taken as proxy for high absolute temperature. However, the tectonic and petrological contexts must be considered in any theory of massive volcanism. The introduction of low-melting point components–from above–into normal-temperature mantle can generate melting without high absolute temperatures. Rifting and relative motion of a variable thickness plate over the asthenosphere can also generate upwelling and melting at thin spots. Fertility, melting point, recycling, ponding, scales of mantle heterogeneity and lithospheric conditions are issues that do not arise in simple fluid dynamic simulations of LIPs. These are the issues I address in this paper. Lithospheric architecture and stress, and variable mantle fertility, may be more important than mantle temperature or conditions at the core-mantle boundary.

LITHOSPHERE

Mechanically, the Earth's lithosphere is similar to the giant dome of St.Peter's cathedral (Figure 1). It is a thin shell composed of material with no intrinsic tensile strength yet it holds itself together. Heat rises to the top and collects under the dome. St. Peter's dome is an appropriate illustration because of the connection between Peter and petrology. 'Peter' means 'rock', the barrier against deep forces from the underworld (Matthew 16:18). Rocks are strong in compression and weak in extension–the St. Peter Principle. Domes and arches and cathedrals survive because they are built to be under compression.

The lithosphere ('rocky shell') is composed of strong regions of lateral compression (plates) and weak regions of lateral extension (plate boundaries and incipient plate boundaries). The lithosphere manages to collect heat and magma under it and these are spilt out when a plate cracks or fails. Ponded magma can–under appropriate stress conditions–cause even strong, thick lithosphere to fail–with only minor heating or stretching–a process known as magma or hydraulic fracture.

The lithosphere has several roles to play in the origin of large igneous provinces. For the most part, the lithosphere keeps magma in the mantle. Lithospheric stress and architecture localize magmatism, rifting and delamination, and allow magma to ascend in some places but not in others; geometrical effects focus magmatism and induce small-scale convection (King and Anderson, 1998). Buoyant mantle materials drain toward and collect at thin spots of the lithosphere. Flaws and rifts in the lithosphere cause and trap asthenospheric upwellings (Sleep, 2002) and low-density melts–"upside down drainage". Sleep argues that the locations of LIPs and thin spots are not related to mantle upwellings, but are controlled by the lithosphere. The main question is whether incipient melting is the natural state of the mantle. Drainage and ponding mechanisms apply to low-density and low-melting point regions of the asthenosphere as well as to hot upwelling mantle.

When the variation of melting temperatures of mantle materials and the actual variation of temperature are combined, we can expect large parts of the mantle to be partially molten, but some regions will be more productive than others. What happens to all the magma? Why aren't there volcanoes everywhere? When a partially molten zone corresponds with a plate boundary or rift, the magma escapes. When the overlying plate is thick or under lateral compression, it traps the melt; it is difficult to rupture thick lithosphere with normal plate tectonic forces but the buoyancy of large ponds of buoyant magma make this possible. Lateral flow of the asthenosphere and local channeling and ponding at lithospheric boundaries appear to be important, even essential, in the creation of LIPs (e.g. Sleep, 2002). Extrusion itself is controlled by the stress-state of the plate, not the temperature of the asthenosphere. The lithosphere may also play a more active role, by delaminating, particularly during continental assembly or breakup [e.g. http://www.mantleplumes.org/LithDelam.html;http://element.ess.ucla.edu/publications/1979_delamination/1979_delamination.htm].

Delamination

Delamination–removal of the lower parts of the crust, lithosphere or thermal boundary layer (TBL)–may produce extensive melting under continents (Elkins-Tanton and Hager, 2000) since the underlying mantle can rise to shallower depths and depressurize, producing melt by adiabatic decompression melting. The cold removed material sinks into hotter ambient mantle and, in turn, can also melt. The interesting twist is that material that was sub-solidus at shallow depth–or experienced only small degrees of melting and melt removal–can melt extensively when placed back into ambient mantle. Thus, there are two ways to generate melting in the mantle; one is to bring hot material adiabatically up from depth until it melts; the other is to insert low-melting point materials–slabs and delaminates–into the mantle from above and allow the mantle to heat them up. Moderate and shallow upwelling, say from beneath a thick craton to an adjacent thinner accreted terrain, rift or suture, can then be a source of magma (Raddick, 2002).

SOURCE OF MANTLE HETEROGENEITY

Subduction and delamination are probably the main mechanisms producing mantle heterogeneity [Figure 2]. What is the fate of this material? It can sink out of the upper mantle, it can get stirred back into it, or it can maintain its integrity while warming up. The retention of essentially pristine blocks of crust is an alternative to both complete homogenization with mantle peridotite–the veined and marble-cake models–and complete separation–the geochemical reservoir model (Meibom and Anderson, 2003).

Young plates, slabs with thick crust, subducted seamount chains and plateaus will not sink far into the mantle and they are less likely to be stirred into the mantle. Some are trapped in sutures or become accreted terranes or ophiolites. About 15% of the surface area of plates currently approaching trenches is very young (<20 Myr) lithosphere (Rowley, 2002); more young lithosphere is in back-arc basins. About 20 seamount chains and aseismic ridges are currently entering subduction zones; these will become low-melting point fertile blobs when they enter the mantle. This material, if subducted at all (Oxburgh and Parmentier, 1977; van Hunen, 2001) will warm up on short times scales and become neutrally buoyant. The basaltic parts will eventually melt, even if the ambient mantle temperature is well below the normal mantle solidus [Fig. 3].

The fertile blob model

Sometimes the mantle is assumed to consist of small-scale fertile streaks or veins that carry the enriched isotopic signature in a more depleted matrix. There is a general consensus that the mantle is heterogeneous on scales less than a km but that larger scale heterogeneities are eliminated by vigorous stirring. A prediction of the small-scale well-stirred models is that low-degree melts should be derived mainly from the fertile streaks; as melting increases the contribution from the refractory portions should increase. In natural magmas, there is no relationship between isotopic composition and inferred extent of melting. Often the most enriched signatures are found in the highest degree melts. Melts from the fertile streaks also tend to equilibrate with the olivine-rich regions, buffering the amount of melting. This alternative to mantle reservoirs and plumes is therefore not satisfactory. Nevertheless, the variable fertility model, in some form, is attractive since the inferred temperatures of hotspot magmas are generally in the MORB range, less than 70 degrees hotter than average MORB [http://www.mantleplumes.org/TopPages/ThermalTop.html], plus there is abundant isotopic and petrological evidence for recycled crustal components in 'hotspot' magmas. If the current proportions of anomalous crust in the ocean basins are representative, then the mantle may contain 10-25 % of material that not only has a melting point hundreds of degrees lower than normal mantle peridotite but is potentially more buoyant and fertile than normal subducted slabs.

Meibom and Anderson (2003) argued that heterogeneities in the mantle are large-scale and that the apparent homogeneity of MORB is due to the melting and sampling processes at ridges (see also Gerlack, 1990). If large-scale concentrations of basalt/eclogite exist in the mantle–fertile blobs–then anomalies in melt volumes as well as in isotopic anomalies can be explained by recycling and mantle heterogeneity. Large volumes of basalt may result from melting of a particularly fertile source rather than by large degrees of melting of a particularly hot and deep source. Many of the problems associated with the plum-pudding and marble-cake models of small-scale mantle heterogeneity are avoided if the fertile blobs are large, comparable to the dimension of seamount chains or oceanic plateaus. Locally, the volume of melt is related to the amount of the low-melting component available, not to the degree of partial melting of a homogeneous mantle with small-scale heterogeneity involving fusable enriched veins. Clearly, a subducted seamount chain or aseismic ridge is more fertile–can provide more basalt–than a piece of ordinary recycled oceanic crust.

Excess fertility

Reheated–but possibly anomalous–oceanic crust may be the primary mantle source for LIPs and other regions that have been called 'melting anomalies' or 'hotspots'. Basalt is introduced into the shallow mantle in considerable amounts and in large chunks. The rate of anomalous crust subduction is comparable to the rate of anomalous magmatism. High-pressure melting experiments on analogues of subducted oceanic crust (Ito and Kennedy, 1974; Yaxley et al., 2000) suggest that 60-80% melting is required to reproduce compositions of Icelandic tholeiites; this amount of melting occurring at temperatures less than the onset of melting in peridotite. This large amount of melting is usually considered impossible since melts drain out long before the rock is this molten, assuming that the surrounding rock is permeable and partially molten. Ponding, melt blending, buoyant decompression melting, melt retention, slab entrainment and deep melting of eclogite may all be involved (Raddick et al., 2004; O'Hara, 2004; Korenaga, 2004).

Recycled crust has a much lower melting point than peridotite. The upper parts of subducted slabs warm up to ambient mantle temperatures on a time-scale of tens of Myr by conduction of heat from the surrounding mantle; they may therefore exist in the upper mantle in a state of nascent or partial melting of the crustal part. Gabbro-eclogite has the interesting property that it can go from a state of nascent melting to extensive melting as the temperature is raised less than 100 degrees or as it adiabatically ascends a distance of only 30 km. Whether the melt can escape or not depends on its composition, viscosity, interfacial tension, compressibility and depth. Korenaga demonstrated that sublithospheric convection driven by surface cooling can bring up dense fertile mantle without a thermal anomaly.

RATES

The current global rate of small-scale 'hotspot' volcanism is ~2 km^3 /yr, about 10 % of the global basalt production at ridges and crustal recycling at trenches. The integrated LIP flux over hundreds of millions of years is only about one-twentieth of this. Therefore, something other than recycling and remelting of normal oceanic crust must be involved. About 10 % of the seafloor area and 25 % of oceanic crustal volume, is composed of seamounts and plateaus (Gerlack, 1990). Plates which were young (< 30 Ma) at the time of subduction and slabs subducted in the past 30 Myr are apparently still in the upper mantle (Wen & Anderson 1995).

The rates of 'anomalous', or non-ridge, volcanism can also be compared with the rates that 'anomalous' crust approaches trenches. The global rate at which young crust on buoyant lithosphere enters the mantle is about 2 to 4 km^3 /yr (Rowley, 2002). The volume of basalt involved in a LIP is equivalent to the volume of the last 300 km of crust subducted at a 3000 km long continental margin. If part of this contains seamount chains or plateaus then the available volumes will be much larger. Delaminated crust and lithosphere–for which no flux estimates are available–may also contribute to the variable fertility of the mantle.

Niu and O'Hara (2003) argue that normal oceanic crust cannot be the major source for midplate volcanism because 1. extensive melting is implausible, 2. melting of eclogite alone cannot produce picrite melts, 3. subducted normal MORB is isotopically too depleted, 4. subduction-zone dehydration makes recycled oceanic crust an unsuitable source, and 5. subducted oceanic crust is too dense. Pure N-MORB or normal oceanic crust is an unlikely candidate for the LIP source but the fertile packages caught up in collision zones, delaminated crust, gabbroic cumulates, young buoyant plate and subducted anomalous crust may be suitable candidates for the sources of 'melting anomalies'. Korenaga (2004), Foulger et al. (2005) and O'Hara (2004) present mechanisms for overcoming the objections to the eclogite melting hypothesis, at the same time avoiding the problems associated with hot peridotite sources raised by O'Hara (2004).

BUOYANT DECOMPRESSION MELTING

Thermally equilibrated recycled crust, does not have to heat up much or rise very far before it is extensively molten. Old thick oceanic plates may sink rapidly out of the shallow mantle (Wen and Anderson, 1995) but young and thick-crust plates may be entrained in the asthenosphere. Asthenospheric mantle encountering thin spots in the lithosphere–or rifts–will upwell and melt, or melt more extensively (e.g. Raddick et al., 2002; Sleep, 2002). A prediction of this mechanism is that magmatism will be more extensive on the thin plate side of fracture zones, transform faults and sutures. This is not always the case (Sleep, 2002) so variations in mantle fertility and melting point–plus the stress-state of the plate–may also be involved.

Buoyant upwellings are usually thought to originate from accidental perturbations in a deep hot thermal boundary layer. They can also originate from local perturbations in melt fraction (Raddick et al., 2002; Tackley and Stevenson, 1993) due to variations in melting temperature. One possible trigger is the gradual conductive heating of the gabbroic and eclogitic portions of subducted slabs and delaminates. Since these melt at temperatures well below the solidus of peridotite or "normal" mantle [Fig. 3], slabs can experience "buoyant decompression melting" as they warm up. Although sub-solidus eclogite is dense, it will only sink rapidly if it occurs in large blobs, if it can decouple from any underlying buoyant harzburgite, or if it is part of a thick cold slab.

DISCUSSION

The mantle is inhomogeneous in melting temperature and fertility because of plate tectonic processes. 'Melting anomalies', such as LIPs, may be due to large, low melting point, fertile patches (Chauvel and Hémond, 2000; Korenaga et al., 2002; Meibom and Anderson, 2003; Foulger et al., 2005) rather than high absolute temperatures. Excess fertility–and buoyancy–will be associated with the subduction of aseismic ridges and seamounts. The locations and properties of continental flood basalts and volcanic margins are consistent with this hypothesis. Oceanic plateaus may also tap large fertile patches of subducted or delaminated anomalous crust. Heat flow, uplift-subsidence histories and the tectonic context of plateaus are consistent with such athermal processes. The localization and the transient nature of volcanism imply lithospheric processes and structure rather than heat and material influx from the core-mantle boundary. Ponded magma assists the rifting which is a prerequisite for the eruption of LIPs.

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Matthew.. 16:18 “And I say also unto thee, that thou art Peter [the rock], and upon this rock I will build my church [cathedral]; and the gates of hell [the underworld; Pluto] shall not prevail against it.”

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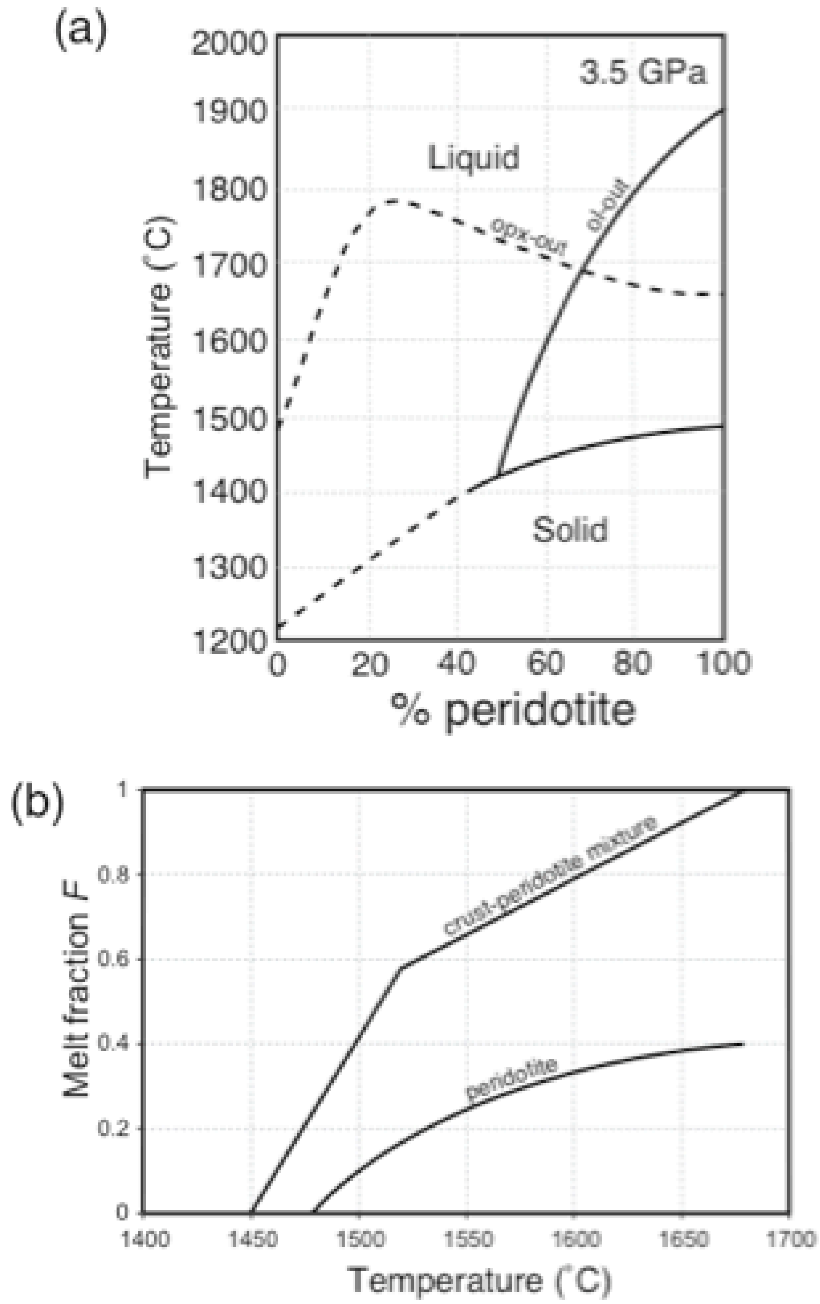

(a)
3.5 GPa
Liquid
Solid
opx-out
ol-out
Temperature (˚C)
% peridotite
2000
1900
1800
1700
1600
1500
1400
1300
1200
0
20
40
60
80
100
(b)
crust-peridotite mixture
peridotite
Melt fraction F
Temperature (˚C)
1
0.8
0.6
0.4
0.2
0
1400
1450
1500
1550
1600
1650
1700

Figure 3: a) Solidus and liquidus for a peridotite mantle containing varying percentages of oceanic crust (adapted from Yaxley, 2000), b) Relationship between melt fraction F and temperature for fertile peridotite and a mixtureof 30% oceanic crust and 70% fertile peridotite. The higher average dF/dT and lower solidus temperature for themixture results in enhanced melt productivity at a given temperature (derived from data in Yaxley, 2000; adapted from Foulger and Anderson, 2004). Note that the volume of melt is not strictly a function of mantle temperature.

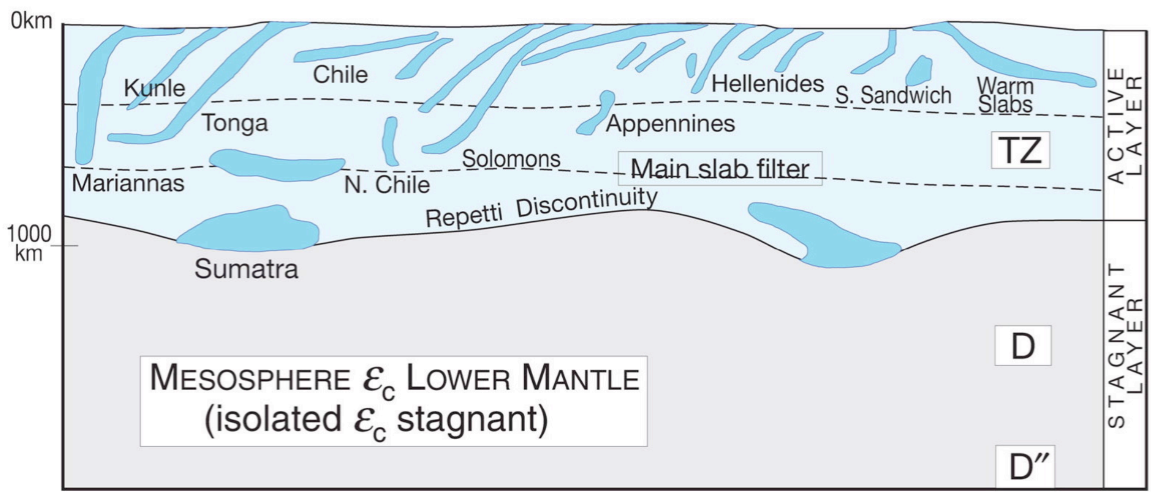

Figure 2: Slabs and delaminates of all ages enter the mantle and equilibrate at various depths. Most slabs are trapped above 650 km but some older slabs penetrate to greater depths, possibly as deep as 1000 km (Wen and Anderson, 1995). Young oceanic plates that are caught in and below continental collision zones (Foulger et al., 2005) and subducted seamount chains may provide the fertile mantle blobs that are tapped upon continental breakup and by oceanic plateaus. The eclogitic portions of slabs will be above their solidi at ambient upper mantle temperatures.