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Tectonophysics xx (2006) xxx – xxx
TECTONOPHYSICS
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Speculations on the nature and cause of mantle heterogeneity☆

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Received 19 August 2004; received in revised form 19 July 2005; accepted 20 July 2005

Abstract

Hotspots and hotspot tracks are on, or start on, preexisting lithospheric features such as fracture zones, transform faults, continental sutures, ridges and former plate boundaries. Volcanism is often associated with these features and with regions of lithospheric extension, thinning, and preexisting thin spots. The lithosphere clearly controls the location of volcanism. The nature of the volcanism and the presence of 'melting anomalies' or 'hotspots', however, reflect the intrinsic chemical and lithologic heterogeneity of the upper mantle. Melting anomalies—shallow regions of ridges, volcanic chains, flood basalts, radial dike swarms—and continental breakup are frequently attributed to the impingement of deep mantle thermal plumes on the base of the lithosphere. The heat required for volcanism in the plume hypothesis is from the core. Alternatively, mantle fertility and melting point, ponding and focusing, and edge effects, i.e., plate tectonic and near-surface phenomena, may control the volumes and rates of magmatism. The heat required is from the mantle, mainly from internal heating and conduction into recycled fragments. The magnitude of magmatism appears to reflect the fertility, not the absolute temperature, of the asthenosphere. I attribute the chemical heterogeneity of the upper mantle to subduction of young plates, aseismic ridges and seamount chains, and to delamination of the lower continental crust. These heterogeneities eventually warm up past the melting point of eclogite and become buoyant low-velocity diapirs that undergo further adiabatic decompression melting as they encounter thin or spreading regions of the lithosphere. The heat required for the melting of cold subducted and delaminated material is extracted from the essentially infinite heat reservoir of the mantle, not the core. Melting in the upper mantle does not requires the instability of a deep thermal boundary layer or high absolute temperatures. Melts from recycled oceanic crust, and seamounts—and possibly even plateaus—pond beneath the lithosphere, particularly beneath basins and suture zones, with locally thin, weak or young lithosphere. The characteristic scale lengths—150 to 600 km—of variations in bathymetry and magma chemistry, and the variable productivity of volcanic chains, may reflect compositional heterogeneity of the asthenosphere, not the scales of mantle convection or the spacing of hot plumes. High-frequency seismic waves, scattering, coda studies and deep reflection profiles are needed to detect the kind of chemical heterogeneity and small-scale layering predicted from the recycling hypothesis.

Keywords: Eclogite; Mantle; Plumes; Ocean islands; Heterogeneity

1. Mantle homogeneity; the old paradigm

The large scale structure of mantle convection is controlled by surface conditions—including continents, effects of pressure on material properties, recycling and the mode of heating (Anderson, 2001, 2002a,b; Tackley,

☆ Presented in the Seismic Heterogeneity in the Earth's Mantle: Thermo-Petrological and Tectonic Implications Conference held on 26–28 February 2004 at the Royal Danish Academy of Sciences, Copenhagen.

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0040-1951/$ - see front matter
doi:10.1016/j.tecto.2005.07.011

1998; Phillips and Bunge, 2005). Global tomography and the geoid characterize the large scale features. Higher frequency and higher resolution techniques are required to understand the smaller scale features (e.g., Fuchs et al., 2002; Thybo et al., 2003), and to integrate geophysics with tectonics and with mantle petrology and geochemistry.

Numerous papers have addressed the role of the lithosphere in localizing volcanism and creating volcanic chains (Jackson and Shaw, 1975; Jackson et al., 1975; Favela and Anderson, 2000; Natland and Winterer, 2004). The lithosphere is heteorogeneous in age, thickness and stress and this plays a large role in the localization of magmatism. On the other hand, the upper mantle is generally regarded as being extremely homogeneous (e.g., Hofmann, 1997; Helffrich and Wood, 2001). The intrinsic chemical heterogeneity of the shallow mantle, however, is now being recognized (Fitton, 1980; Niu et al., 2002; Korenaga and Kelemen, 2000; Lassiter and Hauri, 1998; Janney et al., 2000). This heterogeneity is recognized as contributing to the isotopic diversity of magmas. I take the next step and attribute melting anomalies themselves to lithologic heterogeneity and variations in fertility. The volume of basalt is related more to lithology of the shallow mantle than to absolute temperature. Thus, both the locations of volcanism and the volume of volcanism are attributed to shallow-lithospheric and asthenospheric-processes, processes that are basically athermal and that are intrinsic to plate tectonics. This is such a dramatic shift from current orthodoxy that I include Speculations in the title.

Much of mantle geochemistry is based on the assumption of chemical and mineralogical homogeneity of the shallow mantle, with so-called Normal Midocean Ridge Basalt (N-MORB) representative of the homogeneity and depletion of the entire upper mantle source ("the convecting upper mantle") (DePaolo and Wasserburg, 1976; White and Hofmann, 1982). The entire upper mantle is perceived to be a homogeneous depleted olivine-rich lithology approximating pyrolite (pyroxene–olivine-rich rock) in composition. All basalts are formed by melting of such a lithology. Venerable concepts such as isolated reservoirs, plumes, temperature–crustal thickness correlations and others are products of these perceived constraints. Absolute temperature, not lithologic diversity, is the controlling parameter in current models of geochemistry and geodynamics, and in the visual or intuitive interpretations of seismic images (e.g., Albarede and van der Hilst, 1999).

The perception that the mantle is lithologically homogeneous is based on two assumptions: 1) the bulk of the upper mantle is roughly isothermal (it has constant potential temperature) and 2) midocean ridge basalts are so uniform in composition ("the convecting mantle" is geochemical jargon for what is viewed as "the homogeneous well-stirred upper mantle") that departures from the basic average composition of basalts along spreading ridges and within plates must come from somewhere else. The only way thought of to do this is for narrow jets of hot, isotopically distinct, mantle to arrive from great depths and impinge on the plates.

The fact that bathymetry follows the square root of age relation is an argument that the cooling plate is the only source of density variation in the upper mantle. The scatter of ocean depth and heat flow—and many other parameters—as a function of age, however, indicates that something else is going on. Plume influence is the usual, but non-unique, explanation for this scatter. Lithologic (major elements) and isotopic homogeneity of the upper mantle are two of the linchpins of the plume hypothesis and of current geochemical reservoir models. Another is that seismic velocities, anomalous crustal thicknesses, ocean depths and eruption rates are proxies for mantle potential temperatures. I suggest in this paper that the asthenosphere is variable in melting temperature and fertility (ability to produce magma) and this is due, in part, to recycling of delaminated continental crust and lithosphere and anomalous oceanic crust. In addition, seismic velocities are a function of lithology, phase changes and melting and are not a proxy for temperature alone. Some lithologies melt at low temperature and have low seismic velocities without being hotter than adjacent mantle. Dense eclogite, for example, can have appreciably lower shear velocities than peridotite at the same temperature.

2. Background

The apparent isotopic homogeneity of MORB has strongly influenced thinking about the presumed homogeneity of the upper mantle and the interpretation of 'anomalous' sections of midocean ridges (e.g., Goslin et al., 1998). The homogeneity of MORB does not, however, imply a homogeneous well-stirred upper mantle (e.g., Meibom and Anderson, 2003). The need to subdivide MORB [N-MORB, T-MORB, E-MORB, and P-MORB, for example] and the numerous 'plume-influenced' or 'anomalous' sections of ridges, are indications that the basalts erupting along the global spreading ridge system are not completely uniform. It is common practice to avoid 'anomalous' sections of the ridge when compiling MORB properties, and to attribute anomalies to 'plume-ridge interactions'. In general, anomalies along the ridge system—elevation, chemistry, physical properties—are part of a continuum and the distinction between 'normal' and 'anomalous' ridge segments is arbitrary and model dependent.

Other assumptions in current models are that the mantle below the plates is adiabatic, has high Rayleigh number and is well-stirred—even chaotically stirred. Mantle inhomogeneities in this model become stretched, thinned and folded, and reduced in size, so that the upper mantle is essentially homogeneous (Allegre and Turcotte, 1985). A conflicting but often parallel assumption is that all slabs sink readily through the 'depleted upper mantle' without affecting its chemistry (e.g.,Helffrich and Wood, 2001). Global tomographic models have been interpreted by some as implying whole mantle convection, with easy transfer of material between upper and lower mantles, in both directions (Grand et al., 1997; Montelli et al., 2004).

Seismic scattering is one way to detect recycled crust and fertile patches in the upper mantle. The controversial evidence for strong seismic scattering in the lower mantle (Helffrich and Wood, 2001) has been used to support the whole mantle convection model. Newer and more powerful techniques and data (Shearer and Earle, 2004; Baig and Dahlen, 2004) contradict this simple interpretation and support a chemically stratified mantle. It appears that the upper mantle is the stronger scatterer of seismic energy and the lower mantle—below 1000 km depth—is rather bland except in D″.

3. Mantle heterogeneity; toward a new paradigm

It is increasingly clear that the upper mantle is heterogeneous in all parameters at all scales. The parameters include seismic scattering potential, anisotropy, mineralogy, major and trace element chemistry, isotopes, melting point, and temperature. An isothermal homogeneous upper mantle, however, has been the underlying assumption in much of mantle geochemistry for the past 35 years (e.g., Zindler et al., 1984; Meibom and Anderson, 2003). Derived parameters such as degree and depth of melting and the age and history of mantle 'reservoirs' are based on these assumptions. There is now evidence for major element (Butler et al., 1993; Natland, 1989; Korenaga and Kelemen, 2000), mineralogical (Dick et al., 1984, 2001; Dick, 1989; Niu et al., 2002; Salters and Dick, 2002), trace element (Fitton, 1980; Cousens, 1996; Weaver, 1991; Hofmann and Jochum, 1996) and isotopic heterogeneity (e.g., Anderson, 1989a,b; Gerlack, 1990), on various scales (grain size to hemispheric) and for lateral variations in temperature and melting point.

One must distinguish 'fertility' from (trace element) 'enrichment', although these properties may be related (e.g., Anderson, 1989b). Fertility implies a high basalt–eclogite or plagioclase–garnet content. Enrichment implies high contents of incompatible elements and long term high Rb/Sr, U/Pb, Nd/Sm etc. ratios. Because of buoyancy considerations, the most refractory products of mantle differentiation—harzburgite and lherzolite—may collect at the top of the mantle and bias our estimates of mantle composition (Fig. 1). The volume fractions and the dimensions of the 'fertile' components—basalt, eclogite, pyroxenite, piclogite—of the mantle are unknown. There is also no reason to suppose that the upper mantle is equally fertile everywhere or that the fertile patches or veins in hand specimens and outcrops are representative of the scale of heterogeneity in the mantle. I use 'eclogite' in the following as a term for any garnet and clinopyroxene-rich fertile rock or assemblage that has too little olivine — <40 vol.%—to qualify as a peridotite. Technically, 'eclogites' have a restricted jadeite content and sometimes are restricted to metamorphic assemblages. Pyroxenites and piclogites are more general terms but I will use 'eclogite' for all of these. Eclogites can be recycled or delaminated crust, cumulates, refractory residues or trapped melts. They are denser than some peridotites and ultramafic rocks in the upper mantle but reach density equilibration at various depths in the upper mantle and transition zone (Fig. 1).

There are two kinds of heterogeneity of interest to petrologists and seismologists, radial and lateral. Melting and gravitational differentiation stratify the mantle. Given enough time, a petrologically diverse Earth, composed of materials with different intrinsic densities, will tend to stratify itself by density (Fig. 1). Plate tectonic processes introduce lateral heterogeneities, some of which can be mapped by geophysical techniques. Convection is thought by many geochemists and modelers to homogenize the mantle although this is far from proved. Free convection driven by buoyancy is not the same as stirring by an outside agent. Melting of large volumes of the mantle, as at ridges, however, can homogenize the basalts that are erupted, even if they come from a heterogeneous mantle (Fig. 2).

There are numerous opportunities for generating (and removing) heterogeneities associated with plate tectonics. The temperatures and melting temperatures of the mantle depend on plate tectonic history and processes such as insulation and subduction cooling. Thermal convection requires temperature gradients—cooling from above and subduction of plates can be the cause

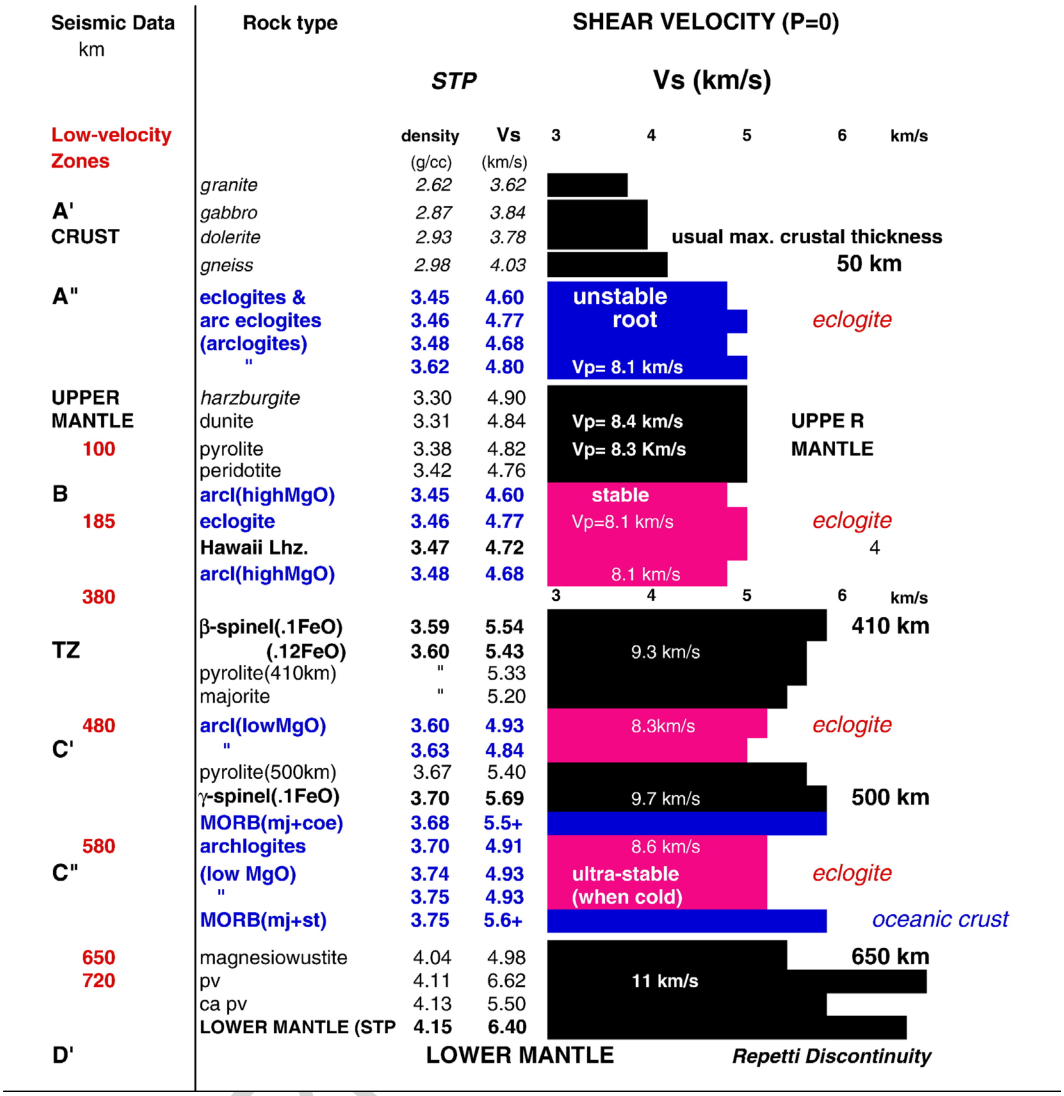

Fig. 1. The density and shear-velocity of crustal and mantle minerals and rocks, at STP, are tabulated and arranged according to increasing density. This approximates the situation in an ideally chemically stratified mantle. The materials are arranged in order of increasing density, except for the region just below the continental Moho where the potentially unstable lower crustal cumulate material is formed. The STP densities of peridotites vary from 3.3 to 3.47 g/cc; eclogite densities range from 3.45 to 3.75 g/cc. The lower density eclogites (high-MgO, low-SiO_2) have densities less than the mantle below 410-km and will therefore be trapped at that boundary, even when cold. Eclogites come in a large variety of compositions, densities and seismic velocities. Eclogite has a much lower melting point than peridotites and will eventually heat up and rise; shallow eclogitic bodies may be entrained by spreading ridges. If the mantle is close to its normal (peridotitic) solidus, then eclogitic blobs will eventually heat up and melt. Eclogite can settle to various levels, depending on composition; the deeper eclogite bodies have low-velocity compared to similar density rocks. Velocity decreases do not necessarily imply hot mantle. LVZs have been found by seismology at various depths above 720-km; these are noted on the figure.

of these temperature gradients. The mantle would convect even if it were not heated from below. Radioactive heating from within the mantle, secular cooling, density inhomogeneities and the surface thermal boundary layer can drive mantle convection. An additional important element is the requirement that ridges and trenches migrate with respect to the underlying mantle. Thus, mantle is fertilized, contaminated and extracted by migrating boundaries—a more energy-efficient process than moving the mantle to and away from stationary plate boundaries, or porous flow of magma over large distances. However, lateral return flow of the asthenosphere, and entrained mantle flow, are important elements in plate tectonics. Embedded in these flows can be fertile patches. Even if they are confined to the asthenosphere these patches will move

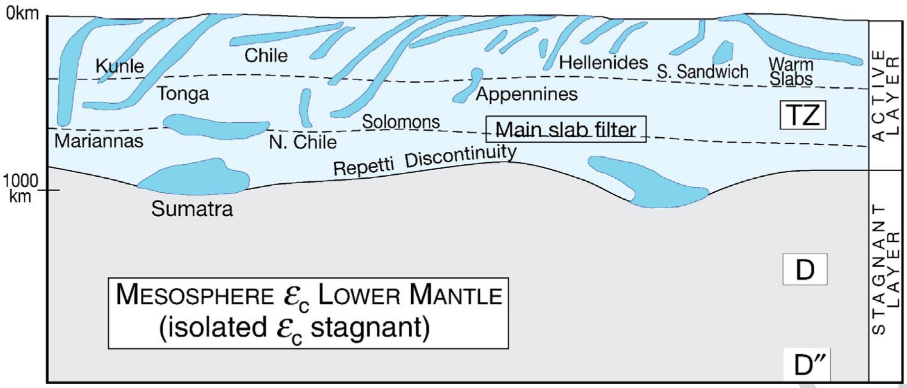

Fig. 2. Slabs of all ages enter the mantle and equilibrate at various depths. Most slabs are trapped above 650 km but some older slabs penetrate to greater depths, possibly as deep as 1000 km (Wen and Anderson, 1995). Young oceanic plates that are caught in and below continental collision zones (Foulger 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.

more slowly than plates and plate boundaries, giving the illusion of fixed hotspots.

4. Source of mantle heterogeneity

Oceanic plates including basalts (often hydrothermally altered), mafic and ultramafic cumulates and depleted harzburgitic rock, are constantly formed along the 60,000 km long mid-ocean spreading ridge system. The mantle underlying diverging and converging plate boundaries undergoes partial melting down to depths of order 50–200 km in regions up to several hundred kilometers wide, the processing zone for the formation of magmas—MORB, backarc basin basalts, and island arc basalts. Midplate volcanoes and off-axis seamounts process a much smaller volume of mantle, and the resulting basalts are therefore—as a consequence of the central limit theorem—much more heterogeneous. Before the oceanic plate is returned to the upper mantle in a subduction zone, it accumulates sediments and the harzburgites become serpentinized. Plateaus, aseismic ridges and seamount chains also enter subduction zones but their fate is uncertain. Young plates, or slabs with thick oceanic crust, will not sink far into the mantle and are likely to reside in the shallow mantle after subduction (Fig. 2). About 15% of the current surface area of oceans is composed of young (<20 My) lithosphere approaching trenches (Rowley, 2002, see Fig. 3) and in young back-arc basins. More than 10% of the seafloor area is composed of seamounts and plateaus. Seamounts constitute up to 25% by volume of the oceanic crust (Gerlack, 1990). This material, if subducted at all (Oxburgh and Parmentier, 1977; Van Hunen et al., 2002) will warm up on short times scales and become buoyant. The basaltic parts may melt, even if the ambient mantle temperature is well below the normal mantle solidus. Thick oceanic plateaus may accrete to continental margins and some may get trapped in suture zones between converging cratons. The delamination of over-thickened continental crust also introduces fertile material into the asthenosphere; this is warmer and perhaps thicker than subducted oceanic crust, and will equilibrate faster. These warm delaminates are potential fertile spots and can create melting anomalies. They may account for 5% of all recycled material (Cin-Ty Lee, personal communication, 2005). The subduction of anomalous oceanic crust, and the delamination of dense lower crust have the volumes required to explain the rates of hotspot and LIPs (Large Igneous Provinces) volcanism, without invoking the recycling of ‘normal’ oceanic crust although this too may be involved.

The distribution of ages of subducting plates is highly variable. There is a large amount of material of age 0–20 and 40–60 Myr at subduction zones (Rowley, 2002). Young oceanic plates and plates with thick crust must cool at the surface for long periods of time before they become negatively buoyant (Fig. 4) and they may become trapped in the shallow mantle. The younger plates will underplate continents, become flat slabs and thermally equilibrate in the shallow upper mantle. The rate at which this young crust enters the mantle is about 2 to 4 km^3/yr (Rowley, 2002). Delaminated eclogitic cumulates enter the mantle at rates of 1.5–6 km^3/yr (Cin-Ty Lee, personal communication). The global rate of ‘hotspot’ volcanism is ~2 km^3/yr (Phipps Morgan, 1997). This encourages us to think that ‘melting anomalies ‘ may be due to fertile patches of subducted

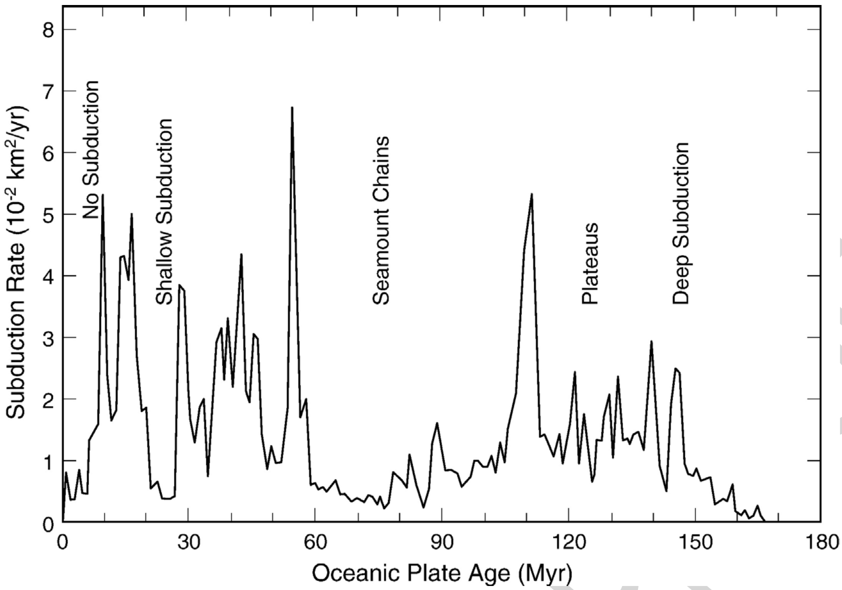

Fig. 3. The age distribution of oceanic plates about to enter subduction zones. The younger plates will not sink deep and will thermally equilibrate rapidly. The older plates will sink deeper, and will take longer to equilibrate (after Rowley, 2002).

oceanic crust that was young or thick at the time of subduction or delaminated lower crustal material from continents. The fate of older plates and deeper slabs need not concern us for the moment. Evidence for deep subduction (Grand et al., 1997) does not imply that all subducted material sinks into the lower mantle (Anderson, 1989a, 2002a). Fig. 1 indicates the possible relative depths to which recycled components may sink. Fig. 2 is a schematic illustration of the possible fates of slabs of different ages. I speculate that only very old and very cold oceanic lithosphere will subduct below the 650 km phase change boundary and that even this will be trapped by a chemical and viscosity barrier near 1000 km (Anderson, 2002a). Subducted oceanic crust accumulates at a rate of only 70 km thickness per Gyr so it can all be easily stored at the base of the transition region (Anderson, 1989b).

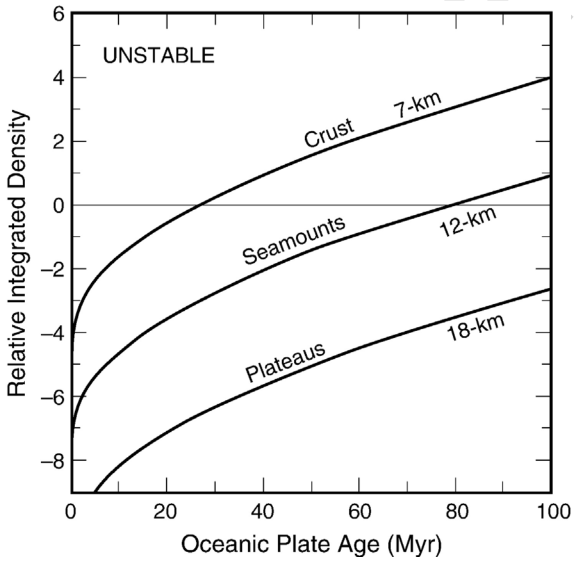

Fig. 4. Buoyancy of plates as a function of age and crustal thickness. Young plates, plates with thick crust (seamount chains, plateaus) and delaminated continental crust may stay in the shallow mantle and be responsible for melting anomalies (after Van Hunen et al., 2002).

5. Fate of recycled material

Convection and diffusive equilibration are extremely sluggish. Once in the mantle crustal materials and depleted residues of different ages are mechanically juxtaposed, but not chemically mixed or vigorously stirred. They start to warm up by conduction of heat from the surrounding mantle (Fig. 5). The resulting state of the upper mantle is a highly heterogeneous assemblage of enriched and depleted lithologies representing a wide range in chemical composition, melting point and fertility and, as a result of different ages of these lithologies, widely different isotopic compositions. Large-scale chemical heterogeneity of basalts sampled along midocean ridge systems occur on length scales of 150 to 1400 km. This heterogeneity exists in the mantle whether a migrating ridge is sampling it or not. Fertile patches, however, are most easily sampled at ridges and may explain the enigmatic relations between

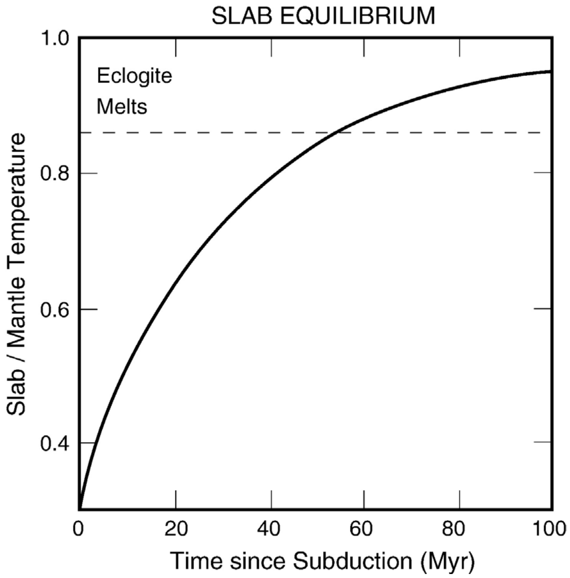

Fig. 5. Heating rates of subducted or delaminated material due to conduction of heat from ambient mantle. Delaminated continental crust starts hot and will melt quickly (modified from a figure provided by Seth Stein, 2003). The reappearance of delaminated continental crust after some tens of Myr may explain the oceanic plateaus in the Indian and Atlantic oceans.

physical and chemical properties along ridges (Goslin et al., 1998).

Because of the highly heterogeneous nature of recycled and delaminated material one does not expect simple relations between bathymetry, crustal thickness, geoid, seismic properties and geochemistry (e.g., Goslin et al., 1998). In the plume hypothesis, plumes are concentrated upwellings of high temperature and unique chemistry and there should be strong correlations between physical and chemical properties along ridge segments affected by plumes. On the other hand, buoyant recycled material can be fertile or infertile and partially molten or not, and need not be at high absolute temperatures. What has been attributed to plume–ridge interactions could also be attributed to asthenosphere–ridge interactions with a heterogeneous variably fertile mantle taking the place of point sources of thermal and chemical pollution. The complex relationships between physical and chemical properties along ridges pose problems for the plume hypothesis (e.g., Goslin et al., 1998) or, for that matter, any hypothesis that attributes hotspots to high temperature.

Mantle heterogeneity is not due to random or unknown effects. It is due to recycling and delamination of materials of known chemistry, dimensions and ages —in most cases. These materials were all at or near the surface of the Earth or the base of the crust. They mostly remain and evolve at shallow depths. They are sampled as ridges move about and as fissures open up (e.g., Natland and Winterer, 2004). The variations in volume and chemistry observed at so-called hotspots may reflect the distribution, sources and ages of the fertile components of subducted and delaminated material.

Subducted and delaminated material contributes to the chemical and lithologic heterogeneity of the shallow mantle and is recovered at leaky transform faults, extensional regions of the lithosphere, by migrating ridges and upon continental breakup. In contrast, very old and cold lithosphere (Fig. 3) is more likely to sink deeper into the mantle, where it can reside for longer periods of time. However, even thick slabs contribute some of their sediments and fluids, and possibly their crusts, to the shallow mantle during subduction. Continental lithosphere, refractory products of melt extraction, back-arc basins, and delaminated crust may all contribute to the lithologic diversity of the shallow mantle.

The fate of crustal fragments in the mantle depends on the heating rate vs. the sinking rate; the oldest plates are expected to sink the deepest, and the fastest. Delaminated continental crust is already warm so it will equilibrate with mantle temperatures on a short time scale. The time between subduction and island arc formation is too small for recycled crust to warm up and melt and contribute substantially to arc volcanism, except where young slabs, or ridges, subduct. This does not rule out subsequent melting of recycled basalt and eclogite as a contributor to the heterogeneity of the asthenosphere and to ocean island basalts, seamounts and melting anomalies along midocean ridges. Fig. 5 illustrates the approximate heating rates of subducted slabs. Normal oceanic crust may start to melt after about 60 million years (Myr), if it stays in the upper mantle, while delaminated continental crust may melt and reappear after only 20–40 Myr.

Middle-aged plates reside mainly in the bottom part of the transition region, near and just below 650 km. Plates that were young (<30 Myr) at the time of subduction (e.g., Farallon slab under western North America) and slabs subducted in the past 30 Myr may still be in the upper mantle (Wen and Anderson, 1995, 1997). Old, thick slabs appear to collect at 750–900 km (Wen and Anderson, 1997; Becker and Boschi, 2002). The quantitative and statistical methods of determining the depth of subduction (Wen and Anderson, 1997; Becker and Boschi, 2002), are superior to the visual analysis of selected color tomographic cross-sections–qualitative chromotomography (e.g., Albarede and van der Hilst, 1999; Grand et al., 1997; Montelli et al., 2004). A chemically stratified mantle will have some deep high-velocity patches and some will appear to correlate with shallower structures; this does not prove they are slabs from the surface, or cold dense materials. Cold eclogite at depths greater than about 200-km may show up as LVZs.

The source of heat for large-scale eclogite melting is the huge volume of warm mantle enveloping a subducting slab or a piece of delaminated crust. Subducting slabs in narrow closing ocean basins and backarc basins are much thinner than those at the subduction margins of old, huge plates, and do not require much reheating to become neutrally buoyant and even partially molten in the shallow mantle (Foulger et al., 2005; Foulger and Anderson, 2005). Most of them will not sink into the lower mantle; their readily fused basaltic crust adds to the fertility of the upper mantle. Although the densest eclogites are denser than much of the upper mantle (Fig. 1) they may thermally equilibrate at transition zone depths (Anderson, 1989b).

Hellfrich and Wood (2002) presented a complex geochemical model involving whole mantle convection, convective homogenization of the upper mantle, slab fragments in the deep mantle and hidden reservoirs. According to these authors, the excess density of all slabs carries them into the lower mantle and they argue that chemical stratification is an increasingly difficult position to defend. The present paper presents a simple alternative recycling model that acknowledges the heterogeneity of the upper mantle and the wide range of recycled materials. The recognition that the upper mantle discontinuities are phase changes (Anderson, 1967) does not imply that the mantle is chemically uniform or convects as a unit. Chemical boundaries can be complex, or non-existent as seismic discontinuities (Fig. 1). Velocity jumps can be small, and even negative, even if the density contrasts are large enough to imply stable, or irreversible, stratification (Anderson, 2002a).

6. Scale of mantle heterogeneity

In the plume model isotopic differences are attributed to different large (400–2000 km in extent) reservoirs at different depths. In the marble cake and plum pudding models the characteristic dimensions of isotopic heterogeneities are centimeters to meters. Meibom and Anderson (2003) attribute chemical differences between ridge and nearby seamount and island basalts to the nature of the sampling of a common heterogeneous region of the upper mantle. In order for this to work there must be substantial chemical differences over dimensions comparable to the volume of mantle processed in order to fuel the volcano in question, e.g., tens to hundreds of kilometers. Chemical differences along ridges have characteristic scales of 200 to 400 km (Graham et al., 2001; Butler et al., 1993). Inter-island differences in volcanic chains, and seamount chemical differences, occur over tens of kilometers, e.g., the Loa and Kea trends in Hawaii. If heterogeneities were entirely grain-sized or kilometer-sized, then both OIB and MORB would average out the heterogeneity in the sampling process. If heterogeneities were always thousands of kilometers in extent and separation, then OIB and MORB sampling differences could not erase this. Therefore, there must be an important component of chemical heterogeneity at the tens of kilometer scale, the scales of recycled crust and lithosphere. The hundreds of kilometer scales are comparable to the segmentation of ridges, trenches and fracture zones, and the scales of delaminated crust along island arcs (Cin-Ty Lee, personal communication, 2005). Chunks of slabs having dimensions of tens by hundreds of kilometers are inserted into the mantle at trenches. They are of variable age, and equilibrate and are sampled over various time scales (Fig. 2). Some of them are seamount chains. The lateral dimensions of plates, and the separation distances of trenches and aseismic ridges are also likely to show up as scale lengths in chemical and physical variations along ridges.

The Central Limit Theorem (CLT) is essential in trying to understand the range and variability of mantle products extracted from a heterogeneous mantle. In the standard geochemical model, differences are ascribed to separate reservoirs and convective homogenization of some (Hofmann, 1997). The lower mantle is taken as the main isolated reservoir because of its remoteness and high viscosity. The crust, lithosphere, and perisphere are also isolated in the sense that isotopic anomalies can develop outside 'the convecting mantle'. Depending on circumstances, small domains—tens to hundreds of kilometers in extent—can also be isolated for long periods of time until brought to a ridge or across the melting zone. Mineralogy, diffusivity, and solubility are issues in determining the size of isolatable domains. When a multicomponent mantle warms up to its solidus —not necessarily the same as the surrounding mantle— the erupted magmas can be variable or homogeneous; this is controlled by sampling theory, the statistics of large numbers and the CLT. Even under a ridge the melting zone is composed of regions of variable melt content. The deeper portions of the zone, and those regions on the wings, will experience small-degrees of melting but these will be blended with high-degree melts under the ridge, prior to eruption. Magma cannot be considered to be uniform degrees of melting from a chemically uniform mantle. Blending of magmas is an alternate to the point of view that convection is the main homogenizing agent of mantle basalts. There are also differences from place to place and with depth, i.e., large-scale heterogeneities; Samoa doesn't necessarily represent just a different way of sampling the same mantle that the EPR does. For example, the perisphere concept (Anderson, 1989b) places an enriched-metasomatised-layer at the top of the mantle but this is attenuated or absent beneath ridges. The base of the plate collects melts from the asthenosphere (ponding) and may become such an enriched layer. A certain amount of chemical (density) stratification can be expected between the time of insertion of material into the mantle, and its retrieval by a volcano.

The isolation time of the upper mantle is related to the time between visits of a trench or a ridge. With current migration rates a domain of the upper mantle can be isolated for as long as 1 to 2 Gyr. These are typical mantle isotopic ages and are usually attributed to a convective overturn time. Either interpretation is circumstantial.

7. Spectral analysis results

Geoid anomalies over the Pacific plate show linear undulations (e.g., Wessel et al., 1994). Spectral analyses have revealed a broad range of dominant wavelengths, in the geoid and bathymetry, centered on wavelengths of 160, 225, 287, 400, 560, 660, 750, 850, 1000, 1100, and 1400 km (Wessel et al., 1994, 1996; Cazenave et al., 1992). Although these have been interpreted as the scales of convection and thermal variations they could also be caused by density variations due to chemistry and, perhaps, partial melt content. Several of these spectral peaks are similar in wavelength to chemical variations along the ridges, i.e., perpendicular to the spreading direction. The shorter wavelengths may be related to thermal contraction and bending of the lithosphere. The longer wavelengths probably correspond to lithologic (major element) variations in the asthenosphere and, possibly, fertility and melting point variations.

Intermediate-wavelength (400–600 km) geoid undulations have been detected after filtering of the Seasat altimeter data [Baudry and Kroenke, 1991; Maia and Diament, 1991]. These lineations are continuous across fracture zones and some have linear volcanic seamount chains at their crests.

Profiles of gravity and topography along the zero-age contour of oceanic crust are perhaps the best indicators of mantle heterogeneity. These show some very long wavelength variations, ~5000 and ~1000 km, but also abrupt changes (Goslin et al., 1998). Ridges are not uniform in depth, gravity or chemical properties. Complex ridge–plume interactions have been proposed (Goslin et al., 1998), the assumption being that normal ridges should have uniform properties. The basalts along midocean ridges are fairly uniform in composition but nevertheless show variations in major oxide and isotopic compositions. Long-wavelength variations have been determined along an approximately 1100 km section of the southern East Pacific Rise and 33,000 km of the Atlantic–Indian ocean ridge system (Butler et al., 1993; Goslin et al., 1998; Graham et al., 2001). Major and minor element chemistry shows spectral peaks with wavelengths of 225 and 575 km. The length scales of the mantle compositions being melted are uncorrelated with those of magmatic temperature variations. Indicators of the degree and depth of partial melting show a strong spectral peak near a wavelength of 430 km. There is significant power in the concentration spectrum of Na_2O —an index of the amount of melting assuming a homogeneous mantle—near 260 km and of FeO—an index of depth of melting, again, assuming homogeneity —near 200 km, bounding the average spectral peak for the oxides at 225 km. There appears to be strong coupling between the degree and depth of melting, and magmatic temperature or composition at length scales around 225 and 400–600 km, about the wavelengths of geoid undulations observed in the vicinity of the East Pacific Rise. In general, one cannot pick out the ridge-centered and near-ridge hotspots from profiles of gravity, geoid, chemistry and seismic velocity. This suggests that short wavelength elevation anomalies, e.g.,'hotspots', do not have deep roots or deep causes. Some hotspots have low seismic velocities at shallow depths, shallower than 200 km (Ritsema and Allen, 2003; Goslin et al., 1998), consistent with low-melting point constituents in the asthenosphere. Deeper LVZ may be compositional, e.g., eclogite.

Helium isotope data for MORB glasses recovered along 5800 km of the southeast Indian ridge reveals structure at length scales of 150 and 400 km (Graham et al., 2001) that may be related to intrinsic heterogeneity of the mantle. Isotope variations in igneous rocks are generally interpreted in terms of convective mixing in the upper mantle, on the one hand, and unassimilated deep mantle material on the other. High $^3He/^4He$ ratios at some ocean islands, along with lower and relatively uniform values in mid-ocean-ridge basalts (MORBs), are assumed to result from a well mixed upper-mantle source for MORB and a distinct deeper-mantle source for ocean island basalts. Alternatively, this could be a result of sampling and magma mixing under the volcano (Meibom and Anderson, 2003). Large variations in magma output along volcanic chains occur over distances of hundreds to thousands of kilometers; most chains—often called ‘hotspot tracks’—are less than a thousand kilometers long. I interpret these dimensions as the characteristic scales of mantle chemical and fertility variations. This provides a straightforward explanation of the order of magnitude variations in volcanic output along long volcanic chains and along spreading ridges.

8. Composition of OIB sources—eclogite?

Subducted or delaminated basalt converts to eclogite at depths greater than about 50–60 km. Ocean crust includes extrusives, dikes, sills and an extremely diverse gabbroic layer (Jim Natland, personal communication, 2003). Recycled oceanic crust including volatiles and lower crustal cumulates may be a suitable source for compositionally distinct and diverse ocean island basalts. The bulk composition of abyssal gabbro approximates primitive Icelandic tholeiite, which also has the trace-element characteristics of olivine gabbro cumulates, not basaltic liquid (Natland and Dick, 2001). If the enriched material in the sources of OIB is oceanic crust or seamounts it is likely to be an eclogite phase assemblage throughout much of the deeper part of the melting zone. The possible roles of garnet pyroxenite and eclogite in the mantle sources of flood basalts and ocean islands (e.g.,Anderson, 1989b) have recently become a matter of renewed interest (Takahashi and Nakajima, 2002, Yasuda et al., 1994; Lassiter and Hauri, 1999; Yaxley, 2000). The possibility that the shallow mantle is lithologically variable, containing materials with higher latent basaltic melt fractions than lherzolite, means that the mantle can be more-or-less isothermal on a local and regional scale, yet at given depth closer to the solidi of some of the lithologies than others. In this situation, thick lava piles can be attributed to fertile patches in the shallow mantle that are capable of producing more than the average amount of basaltic melt through a given range of pressures and temperatures (Tsuruta and Takahashi, 1998; Yaxley and Green, 1998; Kogiso et al., 1998). These collect under, and erupt through, weak, thin parts of the lithosphere, or places where it is under less lateral compression than elsewhere (e.g., Natland and Winterer, 2005), usually on or near past, present or future lithospheric boundaries (e.g., Favela and Anderson, 2000; Lundin and Doré, 2004). Fertile patches can also account for melting anomalies along the global ridge system. Thus, if the upper mantle is sufficiently heterogeneous, plumes and high absolute temperatures are not required as an explanation for melting anomalies (e.g., Foulger et al., 2005; Foulger and Anderson, 2005). The viability of the plume hypothesis, then, boils down to the viability of the assumption that the upper mantle is homogeneous.

9. Isotopic constraints

Sometimes the mantle is assumed to consist of fertile streaks that carry the enriched isotopic signature in a more depleted matrix (Fitton, 1980; Allegre and Turcotte, 1985; Gerlack, 1990; Sleep, 1984; Weaver, 1991; Zindler et al., 1984). These are called “veined”, “plum pudding”, and “marble cake” mantle models, or small-scale heterogeneity models. Convective mixing is considered to be effective in reducing the sizes of heterogeneities (Allegre and Turcotte, 1985); there is a general consensus that the mantle is heterogeneous on scales from grains and grain boundaries to kilometers. There is less consensus on the need for larger scale heterogeneity until we get up to very large scale features, which have been given names such as DUPAL and SOPITA and attributed to the deepest mantle (Hart, 1984) but which may also be due to delamination of continental crust or subducted aseismic ridges.

Usually, the isotopic differences between ridge and island basalts are attributed to completely different reservoirs rather than to large-scale upper mantle heterogeneities (see Meibom and Anderson, 2003 for a review). A prediction of the small-scale heterogeneity models is that low degree melts should be derived mainly from the more fertile streaks and as the extent of melting increases the contribution from the depleted matrix should increase. An intimate relationship between the enriched and depleted components is assumed. However, there is no observed relationship between isotopic composition and inferred extent of melting (Anderson, 1989b). When such a relationship does exist, as in Hawaii, it is more often the reverse of what this model predicts: the most enriched signatures are found in what are interpreted as the highest degree melts. Melts from the fertile streaks also tend to equilibrate with the olivine-rich regions. This “alternative” to mantle plumes can be rejected. Nevertheless, the fertility model, in some form, is attractive since the inferred temperatures of hotspot magmas are generally in the MORB range or less than 70 °C hotter than the average MORB. Even Iceland, by some estimates, is only about 100 °C hotter than the normal MAR lavas to the south (Foulger et al., 2005; for review see www.mantleplumes.org).

Many of the problems associated with the plum pudding and marble-cake models are avoided if the plums or marbles are of the dimension of recycled crust, e.g., 5 to 30 km (Meibom and Anderson, 2003). If subducted seamount chains, aseismic ridges and oceanic plateaus contribute to upper mantle heterogeneity, then lateral dimensions of thousands of kilometers can be achieved. 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—in the large—mantle with small-scale heterogeneity involving fusible enriched veins. Single hand specimen rocks are probably not representative of the source of basalts. More likely the source region ('reservoir') is tens to 100s of kilometers in extent and basalts are hybrids of variable melt fractions of various rock types or assemblages from various depths and the composite source region would not be familiar as a 'rock'. The above scale is interesting in that it is accessible to sampling by seismic waves. Current models of mantle geochemistry are based on 1D Earth models; global seismic discontinuities are treated as the boundaries of reservoirs. Global tomography also treats only large scale heterogeneities. I suggest here that much smaller heterogeneities, accessible only to high-frequency seismic waves, are responsible for petrological and geochemical diversity.

10. Decompression melting

Decompression melting of upwelling mantle already near its melting point is one of the most effective ways of generating large volumes of melt. Upwelling can be passive—midocean ridges for example—or active-thermal boundary layer instabilities. Flux induced melting above slabs also induces adiabatic ascent and increased melt volumes. Volcanism is often controlled by lithospheric structure, which by itself may trigger buoyant melting. For example, asthenosphere that flows beneath a fracture zone from older, thicker lithosphere to younger, thinner lithosphere will rise and can undergo some small initial amount of decompression melting. Asthenosphere that flows toward a thin spot of the lithosphere may melt as it upwells (Sleep, 2002).

Another possible trigger for melting—and adiabatic ascent—is the gradual conductive heating of the basaltic or eclogitic portions of subducted slabs (Fig. 4). Since these melt at temperatures well below the solidus of peridotite or "normal" mantle, sinking or neutrally buoyant slabs can experience "buoyant decompression melting" as they warm up. Since a small amount of melt can reduce the seismic velocities a cold slab can actually become a low seismic velocity anomaly, even as it is still sinking. Low velocity regions in seismic images are usually regarded as hot regions but they could be materials with lower melting points than the surrounding mantle. In mantle slightly cooler than the average melting temperature, buoyant decompression melting may occur spontaneously at "fertile patches"; if these patches are entrained in mantle flow some initial upwelling can trigger melting, and melting may become self-sustaining.

Raddick et al. (2002) examined buoyant decompression melting in a layer initially at rest and at its melting temperature over some portion of its depth. Melting occurs in upwellings that organize from perturbations in melt fraction, perhaps due to variations in the melting temperature. Buoyant decompression melting occurs beneath spreading centers where the extra buoyant can enhance the passive upwelling generated by plate spreading (Scott and Stevenson, 1989; Sotin and Parmentier, 1989) resulting in upwelling distributed along the ridge axis (Parmentier and Phipps-Morgan, 1990). Tackley and Stevenson (1993) examined spontaneously generated melting driven by melt and thermal buoyancy in an initially stationary mantle, appropriate for melting beneath plate interiors away from ridges. They inferred that the areal density of Pacific seamounts may be explained by spontaneously generated buoyant melting.

Melting and melt extraction cause density changes equivalent to several hundred degrees of temperature change, which is much larger than temperature variations within upwellings since melting absorbs heat. While the compositional buoyancy resulting from melt extraction can drive upwelling, depletion effects may also inhibit the buoyant melting process. Beneath spreading centers, where plate spreading carries away the residue of melting, compositional buoyancy drives upwelling in addition to that due to plate spreading (Sotin and Parmentier, 1989). In the absence of spreading, buoyant residual material accumulates at the top of upwellings thus reducing the rate of upwelling and eventually suppressing further melting. This assumes that peridotite melting, rather than eclogite melting, is involved, or that the residual refractory part of the basalt source region is much greater than the easily melted part. If partial melting of large eclogite blobs is involved, the residual, more refractory material, is dense. The idea of buoyant decompression melting of a lithologically diverse mantle provides a ready mechanism for generating melting anomalies and midplate volcanism, even without large variations in absolute temperature. This plus cooling plates and sinking slabs may drive mantle convection.

11. Implications from seismology

A variety of evidence suggests that there might be barriers to convection at depths of about 650 km and 900–1000 km. The best evidence is the discovery of high-velocity patches in the mid-mantle that correlate with past subduction. The relationship between subduction and seismic tomography has been studied extensively. The good correlations between the large-scale seismic heterogeneity in the mantle and subduction during the Cenozoic and Mesozoic (e.g., Anderson, 1989b) appears to be the result of the cooling effects of subduction. Scrivner and Anderson (1992) and Ray and Anderson (1994) found good correlations between integrated slab locations since Pangea breakup and fast velocities in various depth ranges above ~1000 km. Wen and Anderson (1995) estimated subducted volume and correlated it with tomography throughout the mantle. They found significant correlations in the depth interval 900–1100 km. The good correlations that are found for slabs which subducted between 0–30 Ma and tomography can be explained by the accumulation of slabs beneath the Kurile, Japan, Izu–Bonin, Mariana, New Hebrides and Philippine trenches. The existence of a chemical boundary near 1000 km might induce convective stratification. A jump in viscosity near this depth has also been inferred. Although a negative Clapyron slope (near 650 km depth), a jump in viscosity or a moderate chemical change may not serve to stratify convection, the combination may.

Some authors have claimed a correlation of certain features of the lower mantle with a few hotspots (e.g., Lay et al., 1998; Lay, 2005). Ray and Anderson (1994) pointed out that hotspot locations were no better correlated with lower mantle tomography than were ridge locations. Hotspots correlate best with tomography in the shallow mantle (100–400 km). Correlations between surface tectonics and tomography decrease rapidly with depth (see also Becker and Boschi, 2002).

Wen and Anderson (1997) showed that dynamic topography is mainly due to density variations in the upper mantle, even after the effects of lithospheric cooling and crustal thickness variation are taken into account. Layered mantle convection, with a shallow origin for surface dynamic topography, is consistent with the spectrum, small amplitude and pattern of the topography. Layered mantle convection, with a barrier about 250 km deeper than the 650 km phase boundary, provides a self-consistent geodynamic model for the amplitude and pattern of both the long-wavelength geoid and surface topography. The long-wavelength lithospheric stress patterns may be controlled by the deep mantle, but shorter wavelength features in the stress field will mimic upper mantle tomography. The locations of volcanoes appear to be controlled by stress and lithospheric fabric, not temperature (Jackson and Shaw, 1975; Jackson et al., 1975; Natland and Winterer, 2004).

12. Implications for seismology

Surface observations suggest that there is a lot of power in the 150 to 600 km wavelength band for both physical properties (geoid, bathymetry) and chemical (isotopes and major elements) properties. If this is due to subducted material we also expect power—and seismic scattering—at the scales of subducted crust and lithosphere, tens of kilometers in dimension, separated by hundreds of kilometers. These scales are inaccessible to conventional global and regional tomography. The scattering potential of the upper mantle is probably not uniform, radially or laterally. The depth distribution of scatterers will tell us something about the fates of slabs and the nature of the chemical anomalies that may be responsible for melting anomalies. Since subducted basaltic crust melts at a much lower temperature than peridotite, the partial melt zones that have been held responsible for anisotropy and anelasticity of the asthenosphere may be tens of kilometers in extent rather than grain boundaries. Inhomogeneities of order kilometers in dimension may show up in seismology and ocean island basalt chemistry, but are likely to be averaged out at midocean ridges. There is no conflict between homogeneous MORB and a heterogeneous mantle.

The central limit theorem also applies to seismology. The mantle appears much more homogeneous when averaged over long distances or long wavelengths than at high frequency or for local experiments. In order to connect mantle geochemistry with seismology it is therefore essential to measure local high-frequency scattering and coda characteristics.

13. A laminated mantle?

The opposite extreme of a well-stirred homogenous mantle is a mantle that is stratified by intrinsic density. Convection can be expected to homogenize the mantle if the various components do not differ much in intrinsic density, usually considered to be of the order of 2% or 3%. The Earth itself is stratified by composition and density (atmosphere, hydrosphere, crust, mantle, core) and the crust and upper mantle are stratified as well. The layer at the base of the mantle is intrinsically dense. Does this kind of chemical stratification by intrinsic density extend to the mantle? What does a chemically stratified crust and mantle look like?

Fig. 1 shows the shear velocity in a variety of rocks and mineral arranged according to increasing density. This represents a stably stratified system. Many of the chemically distinct layers differ little in seismic properties and sometimes a denser layer has lower seismic velocity (LVZ) than an overlying layer. Eclogites occur at various depths because they come in a variety of compositions. The deeper eclogite layers are low-velocity zones, relative to similar density rocks. Cold dense eclogite will melt as it warms up to ambient mantle temperature, and will become buoyant. The ilmenite (il) form of garnet and pyroxene is only stable at cold (slab) temperatures and will rise as it warms up. Thus, the stable stratification of a chemically zoned mantle is only temporary. This kind of mantle will convect but it is a different kind of convection than the homogeneous mantle usually treated by convection modelers. It is mainly driven by the differences in density between basalt, melt and eclogite. Note that sinking eclogite can be trapped above the various mantle phase changes, giving low-velocity zones. Although mantle stratification is unlikely to be as extreme or ideal as Fig. 1 it is also unlikely to be as extremely homogeneous or well-mixed as often assumed. Crustal type seismology is required to see this kind of structure (see other contributions in this issue).

One final point; recycled MORB will have a particularly high density below about 720-km because the high silica content gives a large stishovite content if MORB–eclogite can be pushed into the lower mantle. Cold oceanic crust may also partially transform to dense perovskite-like phases, allowing it to sink below 650-km. Cumulate gabbros, the average composition of the oceanic crust and delaminated continental crust have much lower silica contents and this reduces their high-pressure densities. The controversy regarding the fate of eclogite involves this point. Delaminated lower continental crust also starts out warmer than oceanic crust and will therefore not sink as deep.

14. Temperature variations

I have emphasized the role of fertility variations in generating melting anomalies. A convecting mantle, of necessity, has temperature variations as well. Petrological and geophysical estimates of temperature variations in the mantle are modest, much less than the 1000 °C or so variations expected in the thermal boundary layer at the core–mantle boundary or the >200 °C excesses required in the plume hypothesis (e.g., Anderson, 2000; Foulger et al., 2005). Large-scale temperature fluctuations in an internally heated 3D spherical mantle with pressure dependent viscosity and mobile continents, reach 80 °C (Phillips and Bunge, 2005), about the range of temperature inferred from petrology for both ridges and hotspots. High temperatures are usually attributed to plumes but they are also intrinsic to convection without bottom heating. On the other hand, lateral and temporal temperature variations are very small for bottom-heated calculations, the situation required for generating thermal plumes.

15. Discussion

In order to produce a melting anomaly, a source of melt and local lithospheric extension are required, as at plate boundaries. Source heterogeneity causes variations in magma composition and volume. Fertility spots, wetspots and lithospheric stress heterogeneity are natural results of plate tectonics and can explain ‘hotspots’ and ‘melting anomalies’ without deep-mantle thermal plumes. A patchy distribution of recycled eclogitized oceanic crust—including subducted seamounts and seamount chains—and delaminated oceanic crust, is the most obvious way to explain what have been called ‘hotspots’; they might better be called ‘fertility spots’.

Evidence does not, in general, require or favor localized high temperatures at hotspots. The absence of heat-flow and thermal anomalies at hotspots implies the presence of athermal mechanisms to explain melting and geochemical anomalies. Ocean island-like basalts are far more widely distributed than just along linear island chains, indicating that melting conditions are more widespread than assumed in the plume model. Midocean ridge basalts and OIB have the same range of inferred temperatures (www.mantleplumes.org). These thermal constraints are satisfied by realistic spherical convection calculations, with continental insulation and internal heating, but no heating from below, and therefore, no upwelling plumes.

Regional differences in bulk lithologic heterogeneity of the asthenosphere, including harzburgite, lherzolite, and eclogite, provides a diversity of melt productivity and crustal thickness in different places without requiring great variability in mantle temperature, consistent with the small range in eruptive temperatures of MORB and OIB (1220–1320 °C). Eclogites are not a single rock type but include recycled crust, cumulates and restites with various compositions and melting temperatures. They vary quite a bit in density and in their ability to sink deeply into the mantle.

Source heterogeneity combined with the central limit theorem gives high variance and extreme values for OIB and seamount chemistry compared to average MORB (Gerlack, 1990; Meibom and Anderson, 2003). A homogeneous product does not require a homogeneous or well-stirred source. There is no a priori reason why melts or low-melting point solids have to arise from the deep mantle via narrow plume conduits. Slab fragments are widely available in the shallow mantle (Meibom and Anderson, 2003). Delaminated lower crustal fragments may also be widely available and these enter the mantle at much higher temperatures than oceanic crust.

The proposed model—which I call ‘the plate model’—is an alternative to plumes and high temperatures; it involves recycling, and the non-uniform properties of the lithosphere and asthenosphere. The lithosphere has complex architecture and consists of older plate fragments, multiple scars representing fracture zones and deactivated plate boundaries, and thin spots under which asthenosphere can upwell, melt and pond. In this model, volcanic features are related to the stress field and preexisting fabric in the plate rather than localized regions of high temperature in the mantle. Some volcanic chains may represent incipient plate boundaries.

The asthenosphere is also far from uniform. It consists of subducted slabs of various ages, thicknesses and melting points; they were of various ages, including very young ages, and crustal thicknesses as they entered the trench. About 19 seamount chains and aseismic ridges are currently approaching subduction zones; they will not easily be mixed into the mantle and may not sink very deep (e.g., Oxburgh and Parmentier, 1977; Gerlack, 1990; Van Hunen et al., 2002). There are also numerous seamounts (Wessel, 2001) that will create fertility spots when they subduct. Delaminated lower continental crust is a source of large warm chunks of eclogite. Subducted fragments equilibrate—and melt—at various depths. Recycling contributes to chemical and isotopic heterogeneity of the source regions of basalts but it also contributes to the fertility and productivity of the mantle. Temperature variations are long wavelength while chemical heterogeneity can be of the scale of slabs and the source regions of volcanoes. Melting anomalies appear to be primarily due to high homologous, not absolute, temperature.

Migrating ridges, leaky transform faults and other extending regions, move across and sample the heterogeneous asthenosphere. In the standard model a vigorously convecting mantle brings homogenized asthenosphere to the ridge; melting anomalies are due to upwelling of deep hot plumes through the asthenosphere, rather than due to intrinsic heterogeneity of the upper mantle. When a new ridge forms at a suture—the remnant of an old ocean basin—we expect a transient burst of excessive magmatism, representing the melting of trapped oceanic crust, which is not only more fertile than the average mantle at a mature ridge, but has a much lower melting point (Foulger et al., 2005; Foulger and Anderson, 2005).

Regional differences in bulk lithology—harzburgite, lherzolite, eclogite—and in the amount and age of subducted crust, provides a diversity of melt productivity in different places without requiring great variability in mantle temperature, consistent with the small range in eruptive temperatures of MORB and OIB. If enriched patches are also fertile then OIB chemistry and volumes can be explained without invoking variable degrees of partial melting of a homogeneous source. A single mechanism can explain both the anomalous chemistry and volumes at ‘hotspots’. Melting anomalies appear to be relatively fixed, not because they are deep, or embedded in high-viscosity or stationary mantle, but because the return flow associated with plate tectonics occupies a larger volume than the plates. Seismic scattering, and coda studies have the potential to resolve some of these issues. Attenuation and anisotropy may also reflect small-scale heterogeneity of the type discussed in this paper, rather than grain-scale effects.

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Acknowledgments

I appreciate the useful reviews of George Helffrich, Karl Fuchs, Gillian Foulger and Ron Clowes. I thank Hans Thybo for his hospitality in Copenhagen. The ideas in this paper owe much to discussions with Jim Natland, Gillian Foulger, Dean Presnall and Jerry Winterer, and the availability of their preprints. I also acknowledge useful discussions with Cin-Ty Lee.

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