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Ultradeep continental roots and their oceanic remnants: A solution to the geochemical "mantle reservoir" problem?

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ABSTRACT

High-resolution global seismic tomography (Vs) models reveal high-velocity domains beneath cratonic crust in Africa that extend to depths of 300–400 km. These high-velocity domains show a distinct contrast with the characteristics of "normal" asthenosphere and are interpreted as depleted, buoyant roots that formed in the Archean and have been metasomatised over time, but have remained attached to the overlying crust. Such deep roots are impediments to free horizontal convection in the upper mantle. The movement of magmas and other fluids in such regions may be more vertically constrained (a shallow lava lamp regime), creating a geodynamic environment conducive to interaction of such magmas with the boundaries of deep mantle domains that would carry old "crustal" geochemical signatures. The tomographic models and the new world magnetic-anomaly map show that these continental roots, overlain by thinned continental crust, locally extend well out under the deep Atlantic Ocean basin. However, such high-velocity domains are not confined to the basin margins, but are scattered randomly through the basin, some quite distant from the continental margins of South America and Africa. These high-velocity domains are interpreted to be remnant lithospheric fragments isolated by disruption of the ancient continental regions during rifting. This interpretation is supported by the old Os depletion ages of mantle peridotites from mid-ocean ridges and oceanic islands. Basaltic magmas near such high-velocity domains carry the geochemical signatures (EM1, EM2) of interaction with refertilised cratonic mantle. The interaction of rising magmas with fragments of ancient lithospheric mantle can explain such geochemical signatures and obviates the need for complex models in which these geochemical reservoirs are isolated and preserved in the convecting mantle.

1. Introduction

1.1. Background

Our view of the Earth is changing dramatically with the rapid development of planetary- and lithosphere-scale seismic tomography at increasingly higher resolution. These images show heterogeneity in seismic wave speeds at many scales and they imply the presence of large discrete thermal and compositional domains below the recognised lithosphere. The images suggest that subducting slabs penetrate deep into the Earth; some pond at intermediate discontinuities (e.g. Replumaz et al., 2004; Li et al., 2008) while others may descend ca 2900 km to near the core–mantle boundary (e.g. Burke and Torsvik, 2004 and references therein). These observations raise fundamental questions about the nature of mantle convection and its relationship to plate tectonics, which envisions relatively thin plates moving about on generally horizontal convection currents in the mantle.

Some seismic tomography models (e.g. Simons et al., 1999; Gung et al., 2003; Fishwick, personal communication, July 2008; Kustowski et al., 2008; Begg et al., 2009) show "roots" of seismically distinct mantle extending significantly below the estimated lithosphere–asthenosphere boundary (at about 200 km) beneath the old parts of some continents, similar to the extent of the "tectosphere" proposed by Jordan (1988).

New geochemical data suggest that some of these roots are very ancient and may represent formation of significantly larger volumes of lithosphere in Archean times than conventionally accepted (e.g. Griffin et al., 2008; Begg et al., 2009). Such deep persistent continental roots are difficult to reconcile with the prevailing concept of dominantly horizontal flow in the upper part of the convecting mantle. What is the role of these roots in controlling continental dynamics, plate motions and ultimately the internal circulation of the Earth? It has become clear that the present continents have been assembled from fragments of still older continents (e.g. Bleeker, 2003), stitched together by younger mobile belts with much thinner "roots". These new insights can provide a better understanding of the thermal and mechanical processes that control continental assembly and breakup.

This contribution presents data from a high-resolution global seismic tomography model (Begg et al., 2009) for Africa and the

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Atlantic Ocean basin and integrates these with the new global magnetic-anomaly map data (Korhonen et al., 2007) for this region, with geochemical data for ocean–island basalts, and with studies on the nature and age of lithospheric domains in oceanic regions. These datasets provide a new framework for interpreting the structure and origin of the upper mantle beneath both African Archean terranes and the Atlantic Ocean, and the origin of different geochemical fingerprints for some ocean–island basaltic provinces.

1.2. Isotopic signatures and the convection question

Plate tectonic theory, developed in the 1960s (Wilson, 1963), has provided Earth scientists with a conceptual framework in which to analyse the observed distributions of earthquakes and volcanoes at the Earth's surface and served well for over four decades. However, it best describes the pattern we observe at the surface and assumes the moving plates are thin, with a maximum depth of about 200 km, and has not answered the major question of how the near-surface tectonic phenomena are coupled to and driven by processes deeper in the planet's interior. Thus, different views of how the Earth functions as a system have evolved over the past 30 years, each centred on different types of data (geophysical, geochemical, petrological) and different timescales. New data and interpretations allow us to see more clearly into the deep Earth and formulate new concepts for more realistic geodynamic modelling.

The strength of the continental cratonic shields is linked to the thermal and compositional structure of their lithosphere, reflecting the history of vertical heat and mass transfer processes that have built them through time (Sandiford and McLaren, 2002). By contrast, tectonic models emphasise the significance of large-scale horizontal (and rotational) transport, a perception reinforced by seismic reflection techniques, which are excellent at imaging horizontal or shallowly-dipping structures.

Old lithospheric mantle domains are buoyant and gravitationally resistant to recycling into the deeper mantle without prior geochemical transformation to more fertile and denser compositions (Griffin et al., 1999; Poudjom Djomani et al., 2001; O'Reilly et al., 2001, O'Reilly and Griffin, 2006). The dating of mantle events by *in situ* Re–Os analysis of individual sulfide grains (O'Reilly et al., 2008) can be integrated with zircon geochronology and Hf isotopic analysis to reveal relationships between crustal tectonism and mantle dynamics. The few detailed studies so far show remarkable synchronicity of large-scale crust–mantle events (e.g. Griffin et al., 2004), demonstrating the common coupling of lithospheric mantle and overlying crust for geologically long timescales (e.g. Griffin and O'Reilly, 2007 and references therein).

The geochemistry of volcanic rocks reveals a variety of source types within the mantle, and these have been interpreted as indicating chemically distinct reservoirs within the convecting mantle (e.g. Hofmann, 1997). However, the physical nature and the location of these reservoirs, and their relationship to dynamic models, is a matter of considerable debate. The long-term isolation of at least some of these geochemical deep reservoirs required by the isotopic data appears to conflict with geophysical data indicating inevitable mixing (e.g. Coltice and Schmalzl, 2006 and references therein). If subducted slabs penetrate the lower mantle, they must bring young crustal material into the deep Earth, and material from the deep Earth must be recycled into shallower levels to compensate. Newly exploited geochemical systems such as Re–Os whole-rock and sulfide analysis (Shirey and Walker, 1998; Burton et al., 2000; Schaefer et al., 2002; Pearson et al., 2002; Carlson, 2005; Aulbach et al., this issue) and the ability to measure isotope ratios of key elements such as thallium and lithium (e.g. Nielsen et al., 2007; Tomascak et al., 2000) greatly enhance our ability to address the questions of the longevity of geochemical reservoirs and the source(s) of different components. At this stage, such data are tantalisingly limited, but are helping to shape constraints on relevant hypotheses.

Lithosphere-scale seismic tomography provides a new opportunity to explore the lithosphere and deeper regions beneath continents, and developments in understanding mantle composition and thermal state allow us to start to interpret these deep Earth images. Deen et al. (2006) and Afonso et al. (2008) showed the importance of considering compositional effects, as well as temperature differences, when interpreting seismic tomography at lithospheric depths. Strong lateral gradients in seismic velocity were shown to be due to compositional effects, whereas thermal gradients, unless due to recent thermal events, generally produce more diffuse gradients in seismic velocity.

2. What is the sub-continental lithospheric mantle?

The sub-continental lithospheric mantle (SCLM) forms the lowermost part of the lithospheric plate complex that is considered to move horizontally in a relatively rigid way over the hotter, rheologically weaker and convecting asthenosphere. Lithosphere is by definition non-convecting, and thus characterised by conductive (or locally advective) geotherms (e.g. McKenzie and Bickle, 1988). The SCLM is geochemically depleted compared with the convecting asthenospheric mantle (i.e. relatively low in basaltic components such as CaO, FeO and Al_2O_3, and high in MgO).

The base of the SCLM is the lithosphere–asthenosphere boundary (LAB), which has been recognised geochemically, seismically, electrically and rheologically (e.g. Pavlenkova, 1997; Anderson, 1989; Jones et al., 2003; Eaton et al., 2008; Wyllie, 1980; McKenzie and Bickle, 1988; O'Reilly and Griffin, 1996). Geochemically, the LAB is marked by the change from relatively depleted to refertilised geochemical signatures in lithospheric peridotite, indicating the effects of infiltrating melts of asthenospheric composition (e.g. Malkovets et al., 2007; see summary in O'Reilly and Griffin, 2006). Seismically, the LAB in tectonically young regions may be marked by a low-velocity zone, and is commonly ascribed to changes in rheology and the presence of low degrees of partial melting in that region. This low-velocity zone commonly is not detectable beneath older regions, although the Lehman discontinuity (e.g. Anderson, 1989; Gung et al., 2003) coincides with the geochemical LAB in some cratonic regions (Griffin et al., 1999). As discussed below (Section 5.2), the significance of this discontinuity beneath cratons is not clearcut; it may not represent the boundary between cratonic lithosphere and the convecting mantle. Rheologically, the LAB has been interpreted as the base of the SCLM where it acts as a mechanical boundary layer (McKenzie and Bickle, 1988). The temperature at the LAB is typically about 1200–1300 °C (although perturbations occur due to advection of melts and fluids and melt production from transient thermal instabilities, e.g. Wyllie, 1980; Finnerty and Boyd, 1987). At the lithosphere–asthenosphere boundary, the temperatures of the lowest lithosphere and the uppermost asthenosphere must coincide, so the greater rigidity of the depleted lithosphere is an important factor in maintaining its mechanical integrity during plate movement; however, this may only be relevant in oceanic and young continental tectonic regimes.

2.1. Sampling the mantle

A brief overview of the most relevant aspects of mantle sampling is given below for context: a comprehensive account is given in O'Reilly and Griffin (2006).

2.1.1. Solid samples of the mantle

2.1.1.1. Xenoliths and xenocrysts. Most solid samples of actual mantle material are fragments of lithospheric mantle.

Samples of the lithospheric mantle are brought to the surface as rock fragments (xenoliths) or disaggregated minerals (xenocrysts of e.g. garnet, olivine, chromite, pyroxene, diamond) by magmas that ascend rapidly enough to the surface to retain these high-density

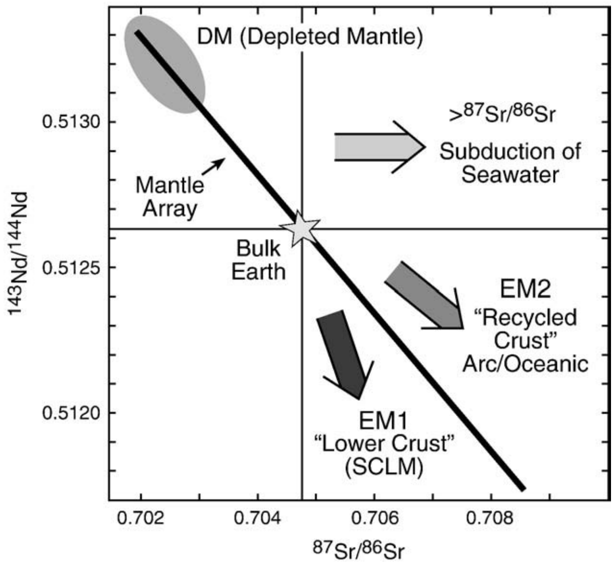

Fig. 1. Isotopic components commonly observed in basaltic magmas and their fields in Nd and Sr isotopic space. Explanations of the acronyms are given in the text.

fragments in suspension, and that cool quickly enough to preserve their original geochemical characteristics. Fragments of the lowermost lithosphere from zones of rifting or strong lithospheric thinning (e.g. eastern Australia, Gaul et al., 2003; eastern China, Xu et al., 2000) appear to represent cooled asthenosphere with a fertile composition (high in basaltic components CaO, FeO and Al_2O_3, and low in MgO).

Ultra-high pressure xenoliths (e.g. Haggerty and Sautter, 1990) and transition-zone and lower-mantle mineral inclusions in diamonds (e.g. Harte et al., 1999) represent sublithospheric samples, some considered to be parts of deep mantle plumes (which may be partially re-equilibrated to lower pressure conditions) underplated beneath older lithosphere (e.g. Griffin et al., 1999; Davies et al., 1999).

2.1.1.2. Orogenic mantle outcrops. Outcrops of mantle sequences on the scale of tens of km occur in regions such as the Ivrea Zone (e.g. Fountain and Salisbury, 1981), southern France (e.g. Lherz, Woodland et al., 1996; Le Roux et al., 2007) and Western Norway (e.g. Brueckner and Medaris, 1998; Beyer et al., 2006). Quarries in Western Norway expose tens of square km of mantle material and reveal large- and meso-scale rock-type relationships and structures including deformation styles and geometry, shear zones, metasomatic zones and fronts, and fabric variations, including original grainsizes exceeding 1 m. Mantle outcrops at Otrøy (Norway) contain breakdown products of ultra-high pressure majoritic garnet indicating an original depth greater than 200 km (e.g. Van Roermund and Drury, 1998; Drury et al., 2001; Spengler et al., 2006; Scambelluri et al., 2007).

2.1.1.3. Mafic magmas as probes of the deep Earth. Basaltic, kimberlitic and related magmas are generally considered to represent melting products of the convecting mantle, although small-volume lithospheric melts may be important as "contaminants" that provide unique geochemical fingerprints for different basaltic provinces (e.g. Thompson et al., 1990; Foley, 1992; Zhang et al., 2001, 2008) or the even as the major source for some kimberlitic magmas (Becker and Le Roex, 2006 and references therein).

Mafic magmas form across the range of tectonic environments where thermal anomalies provide energy and can result in mantle melting of <1 to >25%. Such magmas provide a geochemical average of a restricted mantle volume. The primitive magmas may change compositionally by magmatic processes such as fractionation and may interact with mantle and crust as they ascend. Magmas carrying mantle xenoliths are inferred to have travelled very rapidly to the surface (less than 60 h maximum and probably about 20 h (e.g. O'Reilly, 1989 and references therein; Kavanagh and Sparks, 2009) and thus transit contamination is likely to be restricted to rapid interactions with the conduit walls, and addition of low-volume flash-melted lithospheric material. Such magmas may sample regions including the convecting mantle, plumes, mantle wedges, subducted slabs, and the low-temperature melting fraction of the lithospheric mantle (Zhang et al., 2001).

2.1.1.4. Mantle reservoirs and the geochemists' alphabet. Geochemists have constructed a system of acronyms to describe particular basaltic isotopic signatures and their inferred mantle reservoirs, shown in Fig. 1. An early observation was that mantle-derived basaltic magmas generally define a coherent trend in Nd–Sr isotopic space, the "mantle array". Hart et al. (1992) studied radiogenic isotopic variations (mostly Sr–Nd–Pb–He) of oceanic island basalts (OIBs) at the global scale and found that in the 3-dimensional (Sr–Nd–Pb) space, almost all the trends represented by individual provinces converge toward a narrow "focal zone" (FOZO) at the base of a tetrahedron limited by four previously defined mantle components. These geochemical components, shown in Fig. 1 are: DMM (depleted MORB (Mid-Ocean Ridge Basalt), HIMU (an old high-U/Pb mantle source with time-integrated high $^{206}Pb/^{204}Pb$; in oceanic settings this may be related to subducted oceanic crust), EM1 (interpreted as old lower crust or "lithospheric contamination"), and EM2 (interpreted in terms of recycled arc and oceanic material). Zindler and Hart (1986) proposed that FOZO may represent the composition of the lower mantle, and that this dominates mantle plumes.

The presence of continental mantle–lithosphere domains with EM1, EM2 and/or HIMU signatures has long been recognised (e.g. Leeman, 1982; Menzies et al., 1983; Menzies and Wass, 1983; Griffin et al., 1988; O'Reilly et al., 1988; Zhang et al., 2001). Griffin et al. (2000) used the Hf-isotope compositions of mantle zircons, and the trace-element chemistry of mantle peridotites to argue that ancient SCLM must have low $^{143}Nd/^{144}Nd$ and low $^{187}Hf/^{186}Hf$; Choukroun et al. (2005) substantiated this with a study of metasomatised volumes (MARID xenoliths) from the Kimberley area, South Africa.

2.1.1.5. Geophysical data. Geophysical data provide remotely sensed information about the physical properties of the deep Earth. Seismic tomography models at both global and regional scales (e.g. James et al., 2001; Grand, 2002; Ritsema et al., 2007; Li et al., 2008) are providing increasingly higher-resolution images of contrasting velocity domains. Magnetic (Purucker, 2007), electric (e.g. Jones et al., 2003) and gravity inversions (Poudjom Djomani et al., 2003, 2005) are all contributing new data that are changing our knowledge base and thus, conventional views.

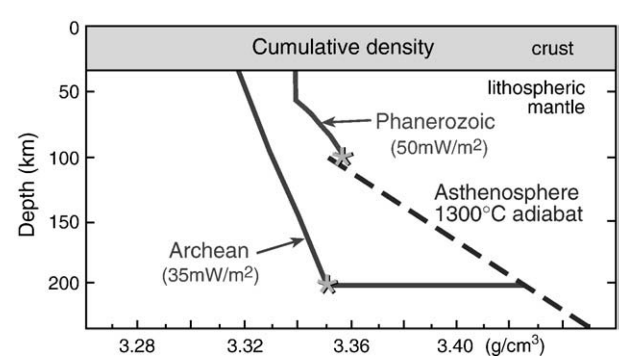

Fig. 2. Cumulative density relationships for Archean and Phanerozoic average lithospheric compositions relative to asthenosphere (adapted from Poudjom Djomani et al. (2001) and O'Reilly et al. (2001)).

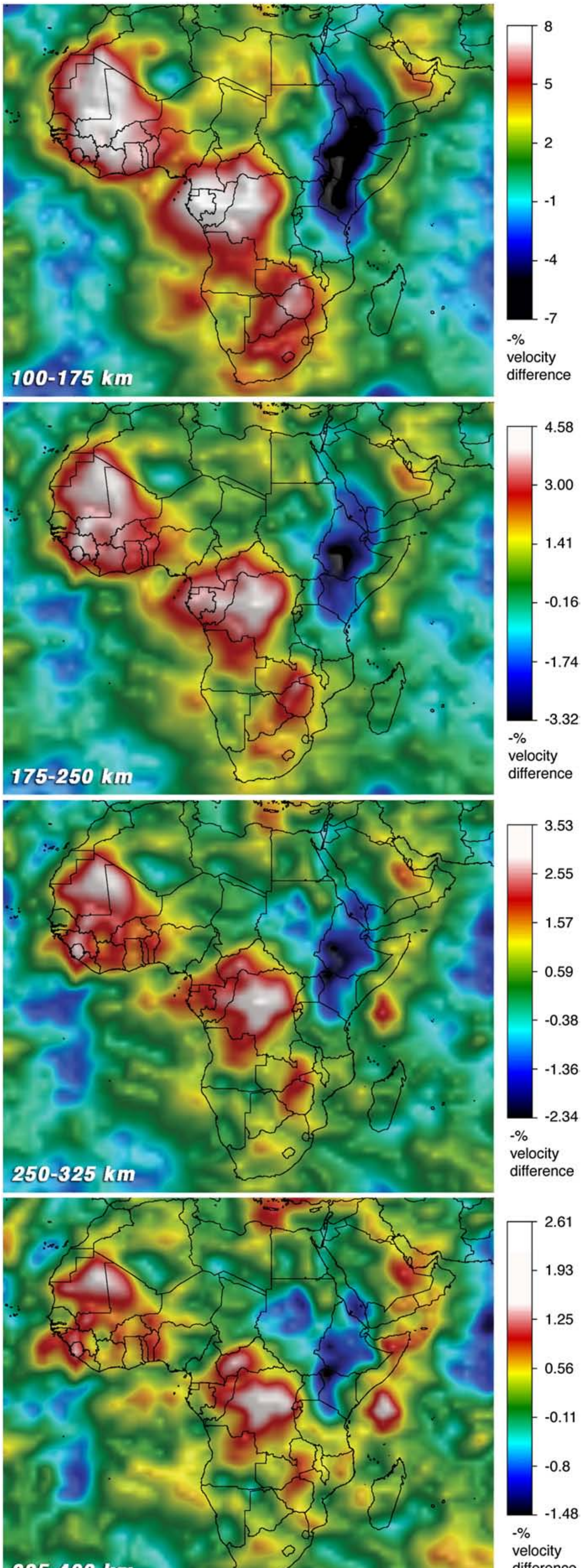

Fig. 3. Tomographic model images (Vs models) for four depth slices through the lithospheric mantle an upper mantle beneath Africa. See text for explanation and discussion. Note that red colours indicate higher velocities and cool colours lower velocities. Colour scales are given for velocities in each depth slice; reference velocity is 4.5 km/s.

2.2. Are mantle lithospheres homogeneous?

Lithosphere composition, thickness and seismic velocity vary with tectonothermal age, so that most Archean lithosphere is thicker and cooler (today) than Phanerozoic lithosphere. Possible mechanisms of formation are summarised by O'Reilly and Griffin (2006) and Griffin et al. (2008).

Archean lithosphere is significantly less dense than asthenosphere at any depth (Fig. 2); whereas young (Phanerozoic) lithosphere is initially less dense due to thermal buoyancy, but on cooling becomes denser and thus gravitationally unstable. Original (unmetasomatised) Archean lithosphere is depleted (Mg-rich and low in basaltic components such as Al, Ca, Fe), consists dominantly of dunite and Ca-poor harzburgite (see Bell et al., 2005; Bernstein et al., 2006; Griffin et al., 2008) and has high seismic wave velocities mainly due to the high proportion of Mg-rich olivine (Fo 92–94). Young lithosphere is fertile (higher in Al, Ca and Fe) with more Fe-rich olivine (Fo 88 average) and higher modal pyroxene, resulting in lower seismic velocity (O'Reilly et al., 2001). These compositional variations alone can account for about 25% of the observed seismic velocity differences between cratonic and tectonically active regions. However, the combined effects of composition and tectonic environment are intrinsically additive; the Mg-rich cratonic SCLM is also the coolest, and the young tectonic SCLM with its Fe-rich olivine and high pyroxene content is warmer. Thus the separate effects of composition and temperature on seismic wave speed are reinforced in Earth's different tectonic regimes (Griffin et al., 1999; Poudjom Djomani et al., 2001; O'Reilly et al., 2001; Deen et al., 2006).

3. Evidence for deep mantle roots beneath Africa and ancient continental lithosphere domains in the Atlantic oceanic region

3.1. Summary of the global tomography model parameters

We use a high-resolution global tomography model derived from SH body wave travel times based on the approach of Grand (2002) and fully described by Begg et al. (2009). The velocity model is parameterised in blocks 75–150 km thick and 275 km across and shows deviations in velocity from a defined Earth model (based on a 1-D reference structure for the mantle discussed in Grand (2002), and the 2D Crust 5.1 model of Mooney et al. (1998)). As lateral variations in seismic velocity are more significant near the surface than at greater depths, the tomographic inversions were performed in steps with an initial inversion allowing only the upper 300 km of the mantle to vary in velocity and then proceeding to allow deeper heterogeneity. The raw model was constructed on an irregular 3D grid and is thus not suitable for most display purposes. It therefore was interpolated using a modified 3D version of Shepard's method (Renka, 1988) and regridded to a 100-km cell size (Begg et al., 2009).

The resolution of the model depends on data distribution and on the original block size, and was assessed using checkerboard tests run for anomalies in each of the upper four layers. The lateral limits of the anomalies are well determined and most of the error in the inversion is due to vertical smearing of anomalies, which is most marked in the immediately adjacent layers and weakens dramatically in successive layers. The vertical resolution is estimated as 75–150 km in either direction. Overall, the inversion should represent good spatial mapping of average upper mantle shear velocity.

Traditionally, tomographic images use a colour spectrum with high velocities represented by “cool” colours (green to blue), and low velocities by “hot” colours (red to white). This reflects the implicit assumption that low seismic velocities correlate with high temperatures in the mantle, and high seismic velocities with relatively cold mantle. However, as discussed above, compositional variations in the lithospheric mantle account for at least 25% of the variation in Vs shown in these images and we wish to emphasise the compositional aspects here. Therefore, the tomographic images presented here have a reversed colour palette to simply reflect seismic velocity relative to the starting model. This is consistent with the standard presentation of other geophysical datasets, in which “hot” colours represent high values of the imaged parameter.

3.2. Tomographic images of Africa and deep cratonic roots

Fig. 3 shows a series of tomographic slices through the African continent from 100 to 175 km, 175 to 250 km, 250 to 325 km and 325 to 400 km.

The cratonic regions are clearly visible in the 100–175 km layer with the (white to red) highest-velocity cores surrounded by slightly lower-velocity regions. There is considerable internal velocity variation within the Kaapvaal Craton, both in this global dataset and the regional dataset of the Kaapvaal geophysical traverse (e.g. James et al., 2001; Fouch et al., 2004; Larson et al., 2006) and particularly visible with this colour image. This variability is attributed to metasomatic refertilisation of original depleted Archean lithospheric mantle, leading to more fertile compositions in the lower-velocity regions (Griffin et al., 2008). The straight edges of the cratons are notable. These craton-boundary “lineaments” represent episodically reactivated rift regions (Begg et al., 2009); many are characterised by linear arrays of repeated volcanic activity, and are interpreted as markers of disruption and re-assembly of these cratonic regions (e.g. Kaapvaal Craton; Griffin et al., 2004). The East Africa Rift Zone is obvious as a very low velocity region, and the Hoggar uplift, an area of significant basaltic volcanism, is clearly seen as a low-velocity “bulls-eye” coinciding with the Hoggar plume of Beccaluva et al. (2007). Of particular significance in this layer is the extension of the Congo Craton significantly west of the Africa coastline, and the presence of a very high-velocity region to the southwest of this craton at the margin of the Atlantic Ocean Basin, a feature also clearly seen in the magnetic anomaly data (Figs. 3, 4 and 5). This feature is also apparent in the more recent tomography models for Africa by Fishwick (personal communication, July 2008).

The clear demarcation of cratonic domains persists in the 175–250 km layer that extends to the lower level accepted for most subcontinental lithospheric mantle, and the Hoggar region is still clearly lower in velocity than the surrounding material. At 250–325 km, the cratons maintain coherence and relative velocity contrast at depths below Archean SCLM regions. The Hoggar hot spot and the East Africa Rift are still distinct with contrasting, relatively low velocities. At 325–400 km, domains beneath the cratons still show higher Vs than the Earth model. Even allowing for considerable vertical smearing of velocity, the higher-velocity roots beneath the cratons extend almost to the transition zone (410 km discontinuity). This has important consequences for geodynamic circulation as discussed below.

Such deep continental roots (to near 400 km) have also been interpreted from previous seismic models (e.g. Masters et al., 1996; Ritsema et al., 1999; Mégnin and Romanowicz, 2000). Gung et al. (2003) suggested these deep roots could show fast wave speeds because of olivine anisotropy at depths greater than 200–250 km beneath continents, and their base may represent the Lehmann discontinuity and mark a “transition to flow-induced asthenospheric anisotropy”. SKS wave-splitting treatments of seismic data show that olivine anisotropy due to the traditional assumption of olivine deformation by dominant [100](100) dislocation slip, could account for high Vs beneath cratonic roots (e.g. Barruol et al., 2004)). However,

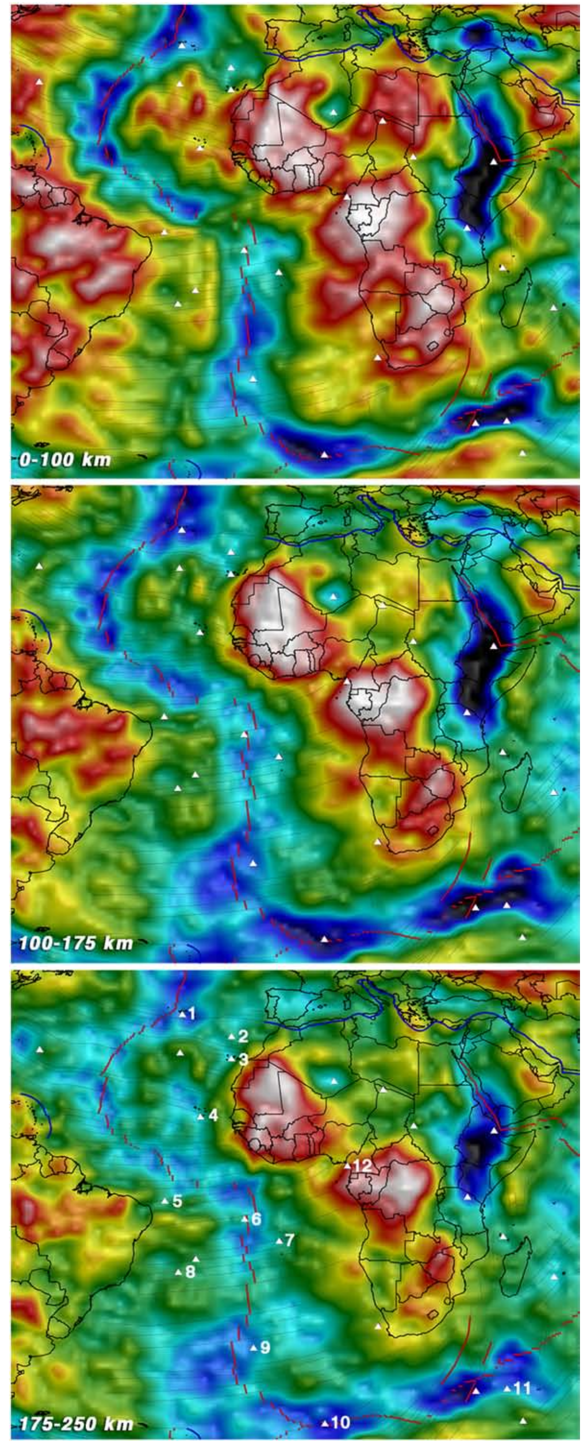

Fig. 4. Tomographic model images at three depth slices for the Atlantic Ocean Basin (see text for details of the model). Note that “hot” (red–white) colours indicate higher velocities and cool colours lower velocities. Relevant OIB Provinces are shown and numbered locations are: 1, Azores; 2, Madeira; 3, Canary Islands; 4, Cape Verde; 5, Fernando de Noronha; 6, Ascension Islands; 7, St. Helena; 8, Trindade; 9, Tristan da Cunha (Walvis Ridge at ~130 Ma; Richardson et al., 1984); 10, Bouvet; 11, Crozet Archipelago (Afanasy–Nikitin Rise in the Indian Ocean at Late Cretaceous, ~115–80 Ma; Mahoney et al., 1996); 12, Cameroon Line. Colour scale for velocity differences is the same as for Fig. 3, except for 0–100 km where the colour scale extends from 5 to −8 km/s.

there is no constraint on the depth location for this phenomenon and no unambiguous way to focus this effect at 200–400 km depth. Mainprice et al. (2005) demonstrated that dislocation creep in olivine also dominates in the lower part of the upper mantle, but the slip direction is different ([001](*hk*0)), producing lattice-preferred

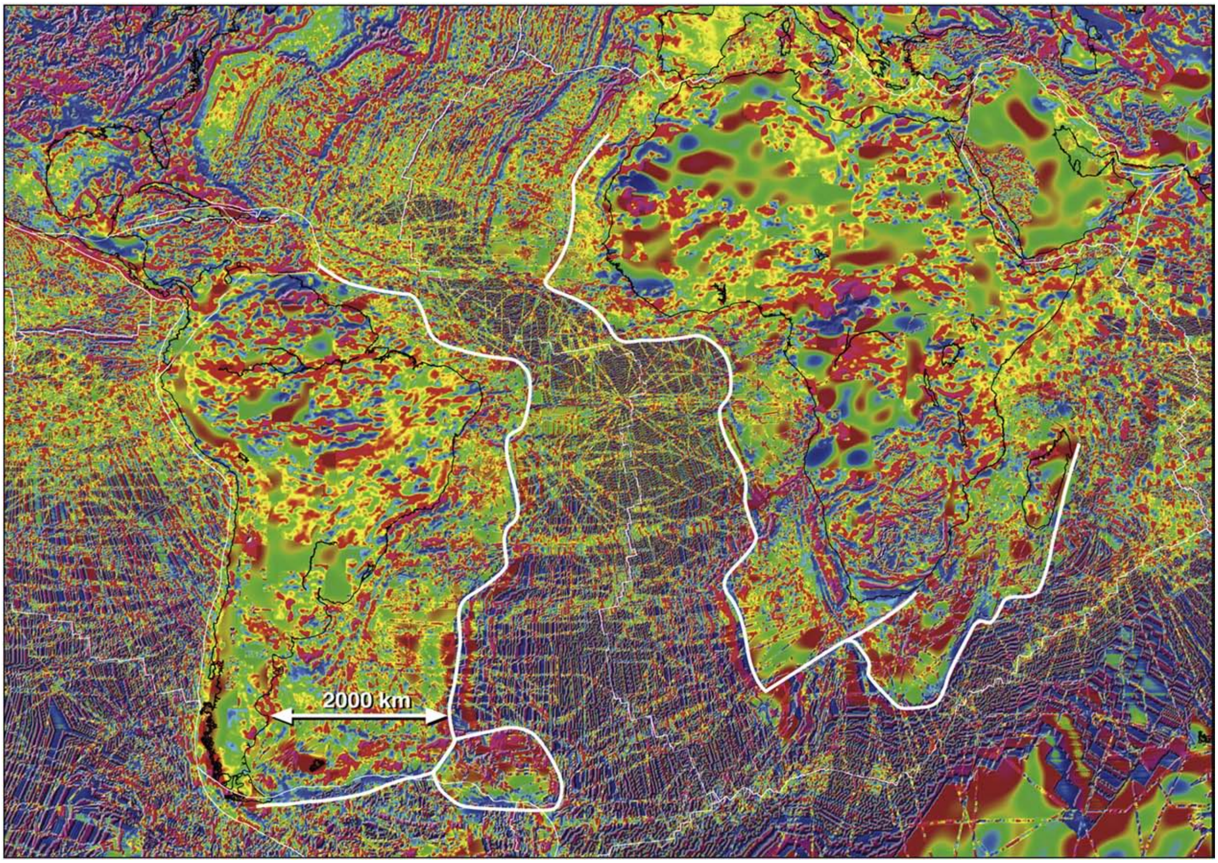

Fig. 5. Modified extract from the global magnetic anomaly map (Korhonen et al., 2007) showing the Atlantic Ocean Basin and Atlantic coasts of South Africa and South America. White lines outline the regions with crustal rather than oceanic magnetic characteristics.

orientations that result in "extremely low seismic anisotropy". Wang (2008) confirmed this effect and demonstrated that it persists in peridotite bodies tectonically emplaced from depths greater than about 200 km, such as Alpe Arami and Cima di Gagnone in the Central Alps, the Norwegian Caledonides and the Sulu terrane (China). Thus the high S-wave velocities observed in the deep continental roots are unlikely to be explained simply by anisotropy.

3.3. Tomographic images of the Atlantic Ocean lithosphere and upper mantle

Fig. 4 shows tomographic slices through the oceanic lithosphere and upper mantle of the Atlantic Ocean Basin at 0–100 km, 100–175 km and 175–250 km.

In the 0–100 km section, high-velocity regions are obvious. Some are apparently continuous with continental regions (especially off the southwestern African and southeastern South American coasts) and some occur as discrete "blobs" extending towards the mid-ocean ridge from the continental margins such as those between the mid-Atlantic Ridge and the northwest African coast. In the layer from 100 to 175 km, these fast domains persist, and some also show velocity contrasts in the 175–250 km layer.

A traditional interpretation for high-velocity regions at the margins of ocean basins is the effect of cooling of the oceanic lithosphere with time and distance from the ridge. However, this cannot be the explanation for the discrete blobs that lie within the ocean basin, away from the original rift margins and some near the present-day ridge, with some extending to depths of at least 250 km.

We suggest that these high-velocity volumes represent remnants of depleted (buoyant) ancient continental lithosphere, fragmented and stranded during the rifting process at the opening of the ocean basin. The high-velocity domains extending out from the coastlines are not uniformly distributed along the basin edge. The most marked high-velocity regions off SE South America and northwest and southwest Africa, appear continuous with their respective continental deep structure as seen in the tomographic models. The new global magnetic-anomaly map (Fig. 5) shows that these regions have a complex magnetic signature that is consistent with extended continental crust, and distinct from that of oceanic lithosphere, which is characterised by the regular magnetic striping produced at spreading centres. The seismic data suggest that this thinned continental crust is underlain by Archean to Proterozoic SCLM that has been mechanically disrupted and thinned during the formation of the ocean basins. The listric detachment of continental crust from the underlying continental SCLM has previously been inferred from studies of ophiolite complexes ranging in age from Proterozoic to Phanerozoic, and by analysis of seismic data in the North Atlantic basin (e.g. Peltonen et al., 2003; Shillington et al., 2004; Van Avendonk et al., 2005; Rampone et al., 2005; Griffin et al., 2008; Begg et al., 2009).

This interpretation implies that ocean basins do not form by clean breaks at now-observed continental boundaries, but that significant volumes of buoyant old mantle are embedded within the newly generated oceanic lithosphere. Old Re–Os ages for mantle sulfides in depleted mantle rock types beneath rift zones (e.g. Brandon et al., 2000; Wang et al., 2003), mid-ocean ridges (e.g. Liu et al., 2008; Alard et al., 2005) and ocean islands (Coltorti et al., submitted for publication) are consistent with the interpretation of these high-velocity blobs as relict original Archean to Proterozoic SCLM. The sequence of events recorded in Re–Os studies of mantle xenoliths beneath the Cape Verde Island of Sal (Point 4, Fig. 4), close to an underlying high-velocity mantle domain, mirrors the tectonic history of the West African craton (Coltorti et al., submitted for publication and references therein).

In the Pacific Ocean, similar high-velocity regions are irregularly and densely distributed. However, the velocity structure at least to the transition zone reflects the complexity of widespread subduction in that region. Therefore an analogous approach to analysing mantle structure using tomographic models is more difficult for the Pacific Ocean Basin, whereas the Atlantic Basin has undergone no significant subduction since it opened.

4. Atlantic basaltic provinces, their geochemical fingerprints, and high-Vs mantle domains

4.1. Distribution of some Atlantic basaltic provinces relative to the high-Vs mantle domains

Fig. 4 shows the location of some basaltic islands in the Atlantic Ocean, superimposed on the tomographic model for the depth slice 175–250 km. Isotopic data for these basalts are shown in Figs. 6–8. Some of these provinces (including Ascension and Bouvet) are distant from the high-Vs mantle domains; where data are available, these have "primitive" (FOZO-type) geochemical signatures, indicating that they have not been affected by interaction with material carrying EM1, EM2 or HIMU signatures.

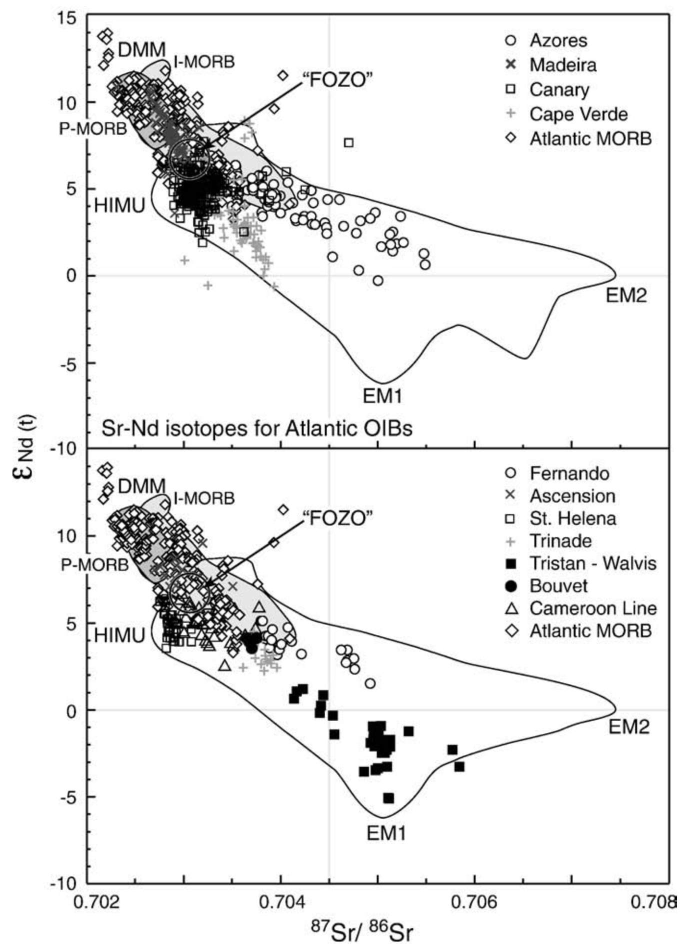

Fig. 6. $^{87}Sr/^{86}Sr$–ε_{Nd} isotopic systematics of the Central and Southern Atlantic OIBs. Data for the Atlantic OIBs are from the GEOROC Database (2008) and data for MORBs are from Hofmann (1997) and references therein. OIB locations are shown in Fig. 4. (1, Azores; 2, Madeira; 3, Canary Islands; 4, Cape Verde; 5, Fernando de Noronha; 6, Ascension Islands; 7, St. Helena; 8, Trindade; 9, Tristan da Cunha; 10, Bouvet; 12, Cameroon Line.)

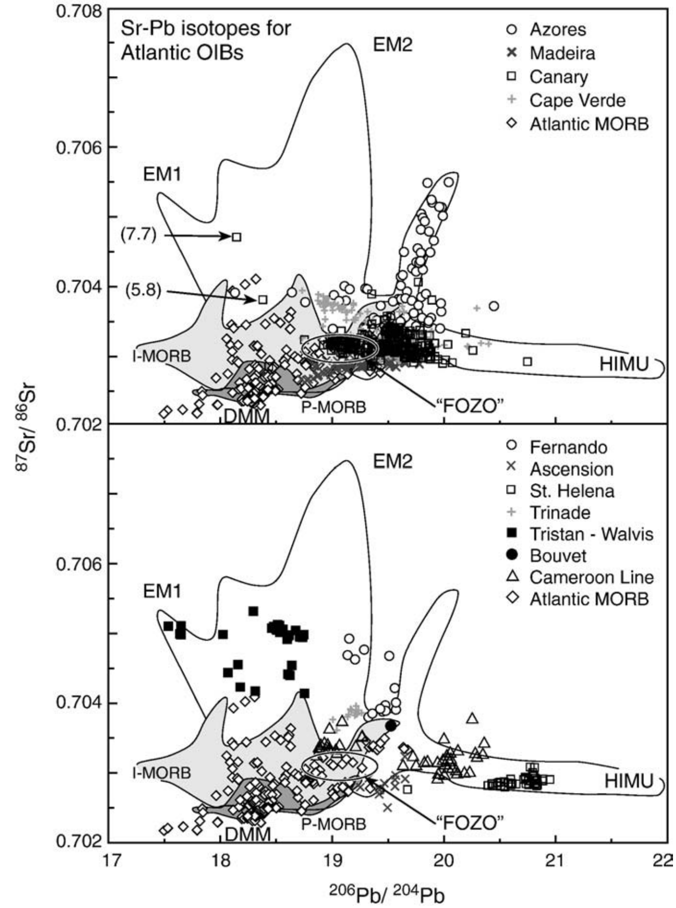

Fig. 7. $^{206}Pb/^{204}Pb$–$^{87}Sr/^{86}Sr$ isotopic systematics of the Central and Southern Atlantic OIBs. Data sources and OIB locations are the same as in Fig. 6.

However, some basaltic provinces such as Fernando de Noronha, Trindade and parts of Cape Verde (e.g. Gerlach et al., 1987; Siebel et al., 2000; Holm et al., 2006) have geochemical fingerprints that clearly indicate components similar to EM1 and EM2, possibly indicating interaction with old lithospheric material. These are located over or near the high-Vs mantle domains, within the ± 75 km horizontal resolution of the model.

Tristan da Cunha and Crozet basalts show a change over time from compositions indicating an old lithospheric component, to those typical of primitive mantle. The Crozet basalts erupted over a long time interval (~115 Ma to present; Mahoney et al., 1996) with the oldest lavas now located at the Afanasy–Nikitin Rise in the northern part of the Indian Ocean. When the older basalts were erupting, Crozet was located near high-Vs mantle, but by the time the younger basalts were generated it had moved to a position over low-velocity oceanic-type lithosphere. Accordingly, the oldest Crozet basalts (at the Afanasy–Nikitin Ridge) have a significant EM1 signature, covering a wide range of Sr–Nd–Pb isotopic compositions with very low $^{206}Pb/^{204}Pb$ (16.77) and $\varepsilon_{Nd}(t)$ (-8), but relatively high $^{87}Sr/^{86}Sr$ (0.7066), attributed by Mahoney et al. (1996) to derivation from a shallow SCLM source prior to and during the breakup of Gondwana.

The Tristan plume also shows a long eruptive period from 134 Ma at the Walvis Ridge (Richardson et al., 1984) to the present location close to the Atlantic Ridge (Richardson et al., 1984; Gibson et al., 2005). The older basalts have been considered as representing the EM1 end-member of the OIBs worldwide ((Fig. 1) e.g. Zindler and Hart, 1986) and associated with the opening of the Atlantic Ocean. However, their enriched isotopic signatures may simply reflect the

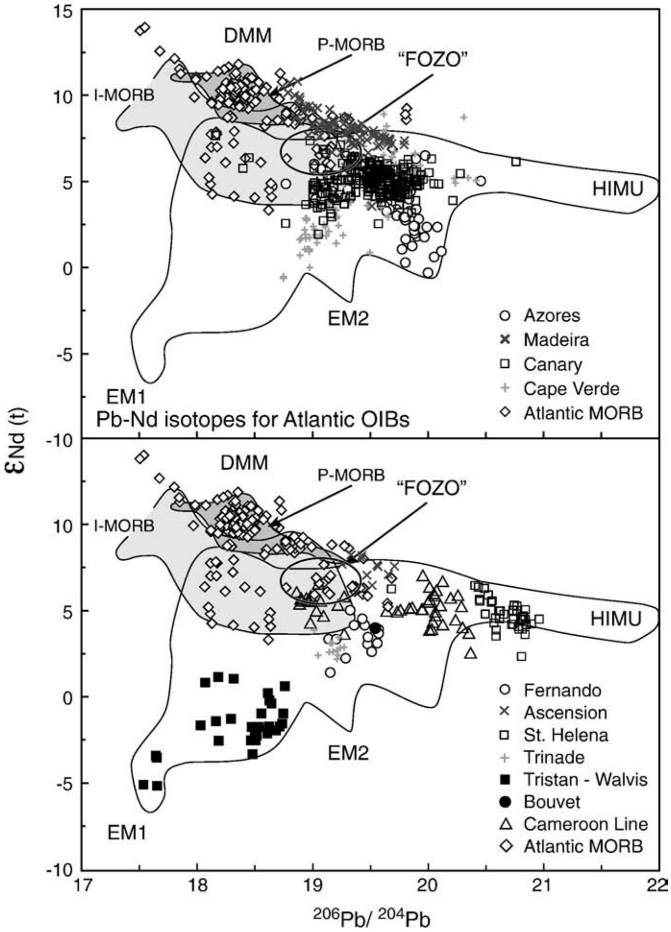

Fig. 8. $^{206}Pb/^{204}Pb–\varepsilon_{Nd}$ isotopic systematics of the Central and Southern Atlantic OIBs. Data sources and OIB locations are the same as in Fig. 6.

thick, cratonic SCLM that existed beneath Southern America and Southern Africa before the rifting, and the associated eruption of the Parana–Etendeka continental flood basalts.

Basalts from the Cape Verde Islands, located near the western margin of a high-Vs region (Fig. 5) show a range of isotopic signatures. Although most primitive lavas from the Cape Verde Islands are HIMU-type OIB and do not show strong enrichment toward EM1 or EM2 mantle components, a minor EM1 component had been identified from Pogo and Santiago Islands in the southeastern part of the volcanic province (Holm et al., 2006). The EM1 component has been interpreted as representing unspecified old continental-derived material contained in the oceanic lithosphere (Kokfelt et al., 1998) or a zoned plume (Holm et al., 2006). However, *in-situ* Re–Os analyses of individual sulfide grains in mantle xenoliths from Sal, in the eastern part of the Cape Verde Islands, produced depleted mantle model ages of 2.7–3.5 Ga (Coltorti et al., submitted for publication), suggesting that these xenoliths are disrupted fragments of the West African cratonic SCLM. Therefore, an Archean SCLM is also likely to have provided the EM1 component in the Cape Verde basalts.

The Azores basalts appear to be an anomaly as they have a distinct EM2 signature, but there is no obvious nearby high-velocity domain. However, the Azores lie adjacent to the mid-Atlantic Ridge and above a hot plume, and the temperature factor would dominate the seismic velocity in this region, obscuring any compositional effects. Schaefer et al. (2002) interpreted whole-rock Re–Os model ages of ≥2.5 Ga from the Azores basalts as reflecting a deep origin involving recycled Archean lithospheric mantle. However, thallium-isotope data on the Azores basalts (Nielsen et al., 2007) demonstrate that the mantle source of the Azores OIBs contained no detectable contribution from Fe–Mn sediments or altered upper oceanic crust. These data suggest that a recycled component is unlikely and that a contribution from a domain such as the Iberian SCLM could explain the enriched (probably EM2) component in the Azores basalts.

The empirical relationship between recycled signatures in ocean island basalts that have erupted near high-Vs mantle domains, and the primitive isotopic characteristics of those distant from such domains are consistent with studies that demonstrate provinciality in continental basaltic magmas due to interaction with underlying SCLM (e.g. Menzies et al., 1983; Wilson and Downes, 1991; Zhang et al., 2001; Thompson et al., 2005; Zhang et al., 2008). We therefore suggest that "recycled" isotopic signatures in ocean–island basalts may be due to magma interaction with disrupted remnant high-Vs subcontinental lithospheric domains.

4.2. Summary of geochemical parameters of the Atlantic Ocean Islands

Analysis of the existing database for the Atlantic OIBs (Figs. 6, 7 and 8; GEOROC Database, 2008) demonstrates that Walvis Ridge–Tristan da Cunha–Gough Islands chain contains a significant proportion of EM1-type OIBs. Basalts from Cape Verde and Trindade have minor EM1 components, whereas some of the Azores, Fernando de Noronha and the Cameroon Line basalts (Fig. 4) carry an EM2 component. The enriched geochemical signatures from the Walvis Ridge, Cape Verde, Fernando de Noronha and Trindade are compatible with interaction with high-velocity mantle domains in the seismic tomography model (Fig. 4), and the inference that these represent fragments of old disrupted continental roots. On the other hand, basaltic lavas from the St. Helena chain, Ascension Island, Bouvet Islands, and possibly the Canary Islands are relatively homogeneous without recognizable contributions from enriched mantle components though some of them are dominated by typical HIMU-type OIBs. The Madeira Archipelago basalts show clear trends between FOZO and the Atlantic MORB, indicating interaction between a plume and a depleted asthenospheric MORB source. The lack of enriched components in these OIBs is also in general compatible with the absence of seismically defined thick lithospheric roots in the regions. This may be also true for the youngest basalts from Crozet and Marion islands in the SW Indian Ocean where the lack of a thick lithospheric root is obvious although isotopic data for these basalts are limited.

Simon et al. (2008) reported the presence of ultra-refractory mantle domains as sampled by mantle xenoliths at ocean islands such as the Azores, Cape Verde, and Canary Islands. They interpreted these primary cpx-free harzburgites as fragments that had existed within the convecting mantle over long time and were preferentially incorporated into newly formed oceanic lithosphere. Alternatively, these ultra-refractory (and thus buoyant) peridotites from the Atlantic Ocean may represent fragments of continental lithospheric roots extended or stranded in the oceanic settings, consistent with the Archean model ages of mantle sulfides (Coltorti et al., submitted for publication) and the seismic data. The hypothesis of zoned mantle plumes, involving heterogeneous incorporation of crustal materials, is not required to explain the observed chemical heterogeneity of OIBs, even where these involve large deviations from the FOZO composition. It should be noted that our model does not exclude the possibility of lower mantle involvement through "recycled" plumes, however it presents a mechanism to explain the "crustal" signatures in OIBs that is consistent with recent geophysical and geochemical datasets.

Our model also has important implications for the interpretation of the isotopic characteristics of Atlantic MORB. Studies of the Re–Os isotopic systematics of both bulk rocks (Harvey et al., 2006) and sulfides (Alard et al., 2005) in abyssal peridotites from the slow-spreading Mid-Atlantic Ridge (MAR, 15°N) reveal the presence of depleted Archean (≥2.6 Ga) mantle materials compositionally (including isotopically) similar to cratonic mantle. Therefore, interaction of the asthenosphere-derived basalts with fragments of ancient

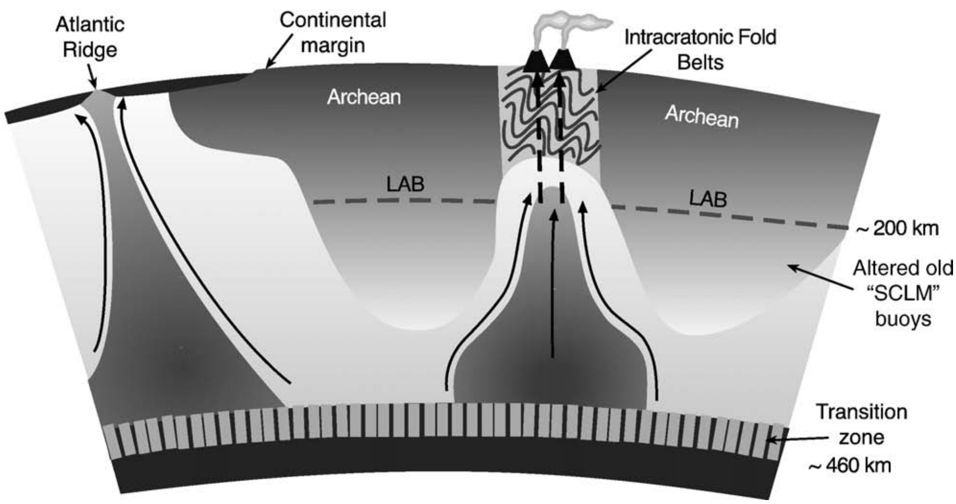

Fig. 9. Cartoon indicating the dominantly vertical convection required around deep continental roots in the upper mantle.

lithospheric mantle residue (Harvey et al., 2006), rather than asthenosphere–mantle plume interaction, may be responsible for the large Sr–Nd isotopic variations exhibited by the Atlantic MORBs (i.e. with ranges to both higher and lower $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ and lower $^{206}Pb/^{204}Pb$) when compared with the homogeneous Pacific MORBs (Figs. 6–8; and 5 of Hofmann, 1997). This argument is also supported by recent studies of both abyssal peridotites and basalts from the isolated ultraslow-spreading Gakkel ridge in the Arctic region. Liu et al. (2008) reported Re–Os model ages of >2.0 Ga from the refractory abyssal peridotites. They argued that these "old" samples "represent the ambient heterogeneity of depleted harzburgite domains in the oceanic mantle rather than definite evidence of delaminated subcontinental lithospheric mantle." On the other hand, Goldstein et al. (2008) concluded that the geochemical signatures of Arctic MORBs from the western Gakkel ridge were derived from "subcontinental lithospheric mantle that delaminated [i.e. not subducted and recycled — current authors' addition] and became integrated into the convecting Arctic asthenosphere."

Therefore, evidence from oceanic basalts, mantle xenoliths and abyssal peridotites suggests a much wider distribution of the old (including Archean) SCLM materials in the oceanic lithosphere, even in mid-ocean ridge settings.

5. The geodynamic significance of deep lithospheric roots under continents and in ocean basins

5.1. Deep lithospheric roots beneath continents

If the interpretation of seismic tomography models, (including e.g. Fishwick, personal communication, July 2008; Kustowski et al., 2008; the Grand model used here) is valid, then coherent "lithospheric material" extends to at least ~300 and possibly to ~400 km beneath Archean cratonic regions. The persistence of such extensive remnant Archean mantle roots has important implications for the nature of global convection, the timing and mechanism of formation of Archean lithosphere and its evolution.

These deep roots are seismically consistent with the downward persistence of original depleted ancient lithosphere, geochemically refertilised by interaction with mantle fluids and melts, but retaining their geochemical and physical coherence since early formation. They contrast chemically and in physical properties (rheology, seismic wave speed, mechanical behaviour) with adjacent asthenospheric mantle, although they would have equilibrated to the ambient upper mantle temperature. Geodynamic models involving large-scale horizontal convection would be difficult to reconcile with the observation of high-Vs (relatively low-density), vertically coherent regions extending almost to the transition zone (410 km). Such deep roots would control convection pathways. Upwelling magma would tend to be diverted along the outside edges of these roots and channel movement of hot upwellings, analogous to that seen as the Hoggar branch of the East Africa Rift system.

Therefore convection in these regions may be dominantly in the form of upwelling vertical conduits, a shallow analogue of the lava-lamp model of Albarede and van der Hilst (1999; Fig. 9). The locus of convection may be controlled by the geometry of the margins and the coherence of the ancient lithospheric deep keels. The convective plate motions would represent "eddies" between these old domains and their directions are preserved in some continental assemblies as the observed plate stress directions and anisotropy (e.g. Simons and van der Hilst, 2003). Mobile belts between cratons would represent lithosphere accretion between these deep roots during tectonic cycles. Horizontal flow in the upper convecting mantle would be confined to regions where the deep ancient roots do not occur, and to shallow regions where such roots may be disrupted, as suggested by the detailed tomographic ("mushroom cloud") model of Yuan (1996) for the North China Craton.

Phanerozoic lithosphere does not show such deep attached lithospheric mantle domains, but there is increasing evidence from Re–Os isotopic data in mantle xenoliths that there are significant ancient components within the SCLM beneath young tectonic regions (e.g. south and central eastern Australia, Handler et al., 1997 and Powell and O'Reilly, 2007; the incipient rift of the Taiwan Straits, Wang et al., 2003; Cape Verde, Coltorti et al., submitted for publication).

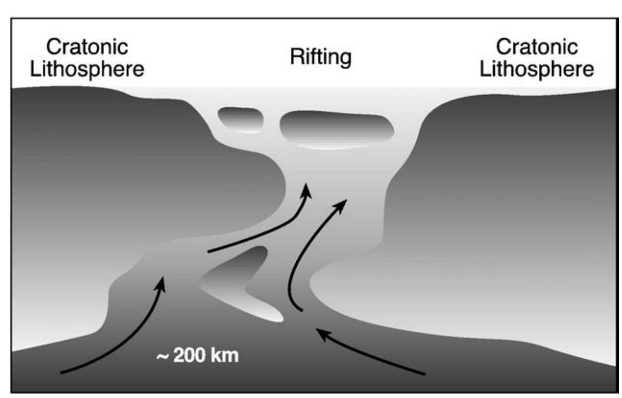

Fig. 10. Cartoon showing possible scenario for rifting mechanisms with listric faulting at cratonic margins and stranding of buoyant old sub-continental lithosphere remnants within the oceanic domain.

5.2. What and where is the lithosphere–asthenosphere boundary beneath cratons?

If cratonic lithospheric roots can persist to depths over 300 km, then there is a conflict with current perceptions of the location and nature of the continental lithosphere–asthenosphere boundary; as traditionally defined (as described in Section 2 above) it is generally considered to occur at about 200 km, placing it well within these high-Vs domains. If the sub-cratonic high-Vs domains are indeed ancient lithospheric mantle, originally highly depleted but now refertilised to varying degrees, then the ~200 km level cannot represent the change from a conducting to a convecting regime. However, it is seen as a chemical discontinuity in the trace-element compositions of garnet, by characteristic kinks in garnet-derived geotherms, and an increase in the Fe content of olivine, all indicative of interaction with "asthenospheric" fluids (O'Reilly and Griffin, 2006). This discontinuity is rarely clearly imaged geophysically beneath the cratonic regions, although a shallow discontinuity, inferred to be the lithosphere–asthenosphere boundary, is clear from magneteotelluric and seismic data beneath tectonically young continental terranes (e.g. Yuan, 1999).

There are several possible explanations for the chemical and physical changes detected at about 200 km beneath the cratons, which may coincide with the Lehmann discontinuity (e.g. Mainprice et al., 2005) and the upper boundary of the tectosphere (Jordan, 1988), although there are currently too few data to be definitive. This region may be the locus of formation and accumulation of low-degree melts as shown experimentally (e.g. Wyllie, 1980; Gudfinnsson and Presnall, 1996) at these pressure and temperature conditions. Jones et al. (2003) have suggested that it may represent a region of higher electrical conductivity; this is intriguing as the cause of conductivity in the lithospheric mantle is far from being well established. If this depth does coincide with the Lehmann discontinuity and/or Jordan's tectosphere, then it must represent an increase in the shear wave speed that could be due to a change in anisotropy, rheology and/or compositional parameters. As discussed in Section 3.2, Mainprice et al. (2005) have shown that a change in the deformation mechanism of olivine occurs at about this depth and would have the effect of changing the rheological properties of the peridotitic mantle below this level.

6. Conclusions and consequences

The roots of ancient cratons may extend to near the transition zone, representing persistence of parts of these buoyant domains since their formation in the Archean. Throughout this time, rifting and reassembly may modify the original boundaries and the deep roots may be progressively modified, especially along domain margins, by interaction with ascending melts during tectonic events, and by percolation of fluids.

Opening of ocean basins may be largely by listric faulting, leaving significant continental lithospheric wedges at rifted margins, and stranding buoyant domains of ancient lithosphere in the upper part of the new oceanic crust–mantle system (Fig. 10) where they would "surf the convecting mantle" (Alard et al., 2005).

Basaltic magmas rising through the oceanic mantle may encounter such ancient domains, enriched in components that give isotopic- and trace-element signatures (such as EMI and EMII) traditionally interpreted as due to recycled crustal material, and the basalts may acquire these imprints by interaction and incorporation of low-degree melts.

Traditional convection models involving dominantly horizontal circulation in the upper mantle either as part of a one- or two-layered mantle circulation are not consistent with such dominating coherent domains extending nearly to the transition zone. Consequent vertical convective currents would provide ample opportunity for ascending magmas to interact with the modified, extensive ancient roots.

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