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Full waveform tomography of the upper mantle in the South Atlantic region: Imaging a westward fluxing shallow asthenosphere?

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ABSTRACT

A prominent feature of the South Atlantic region is its strongly asymmetric residual bathymetry across the ocean basin. It has been suggested that the residual bathymetry is dynamic in nature, arising from the large slow velocity seismic anomaly located in the lower mantle beneath the African plate. Unfortunately, the pattern of mantle heterogeneity particularly in the upper mantle is not well known owing to the sparsity of seismic stations and the existence of large aseismic regions on the African and South American plates. Here we present a new seismic tomographic study of the South Atlantic upper mantle. Our model is based on a full seismic waveform inversion of ≈4000 high-quality seismograms for isotropic 3-D seismic structure using a powerful adjoint methodology capable of extracting maximum information from each seismogram. The theory requires simulation of seismic wave propagation in 3-D heterogeneous earth models computed with a spectral-element method where the differences between observed and synthetic seismograms are quantified using phase misfits obtained through a time–frequency transform. The model images a continuous channel of pronounced slow seismic velocity in the shallow sublithospheric mantle between ≈150 and ≈300 km depth that branches in between the cratonic roots under the African and South American continents. At greater depth, below 300–350 km, the slow anomalies are less pronounced and a change in the convective planform is indicated by isolated, round shaped patches in an overall faster mantle. It is possible that the depthwise change of the convective planform from vertical to horizontal advection of hot buoyant material in a low viscosity asthenosphere can reconcile the anomalous residual bathymetry in the region, and we present a simple fluid dynamic model of pressure driven flow to assess the feasibility of this scenario.

1. Introduction

The South Atlantic region is characterized by major structural elements that include the conjugate margins of South America and Africa with their adjacent cratonic cores, the Parana and Etendeka continental flood basalts and their hotspot tracks along the Walvis Ridge and Rio Grande Rise, as well as the Tristan da Cunha, St. Helena and Ascension hotspots (Fig. 1). The presence of well preserved magnetic isochrons (Fig. 2a), moreover, allows one to constrain the opening history of the basin, so that residual ocean floor topography can be assessed after removing thermal cooling effects within the oceanic lithosphere. An outstanding observation from the residual topography maps (Fig. 2b) is the existence of strongly anomalous bathymetry cutting across the structural elements. Elevated topography, termed the African superswell by Nyblade and Robinson (1994), consists of uplifted portions of the African continent and areas of abnormally high bathymetry in the south-eastern Atlantic, while much of the south-western Atlantic especially in the Argentine Basin is abnormally deep.

Pronounced residual bathymetry in the South Atlantic implies that significant topography must be supported by heterogeneity beneath the tectonic plates. Whether this topography originates from upper mantle flow directly beneath the lithosphere, or whether it reflects dynamic support of deeply seated buoyancy in the lower mantle, remains unclear. Global tomography models (e.g., Grand, 2002; Grand et al., 1997; Ritsema et al., 2011; Simmons et al., 2007) persistently image slow seismic velocities in the lower mantle beneath the African plate, and a substantial portion of this wave speed reduction is probably due to highly elevated temperature (Schuberth et al., 2009a, 2009b) so that the region may act as a source of considerable thermal instabilities.

Anderson (1982) noted that the sub-African mantle had long been shielded from subduction by the former supercontinent Pangea.

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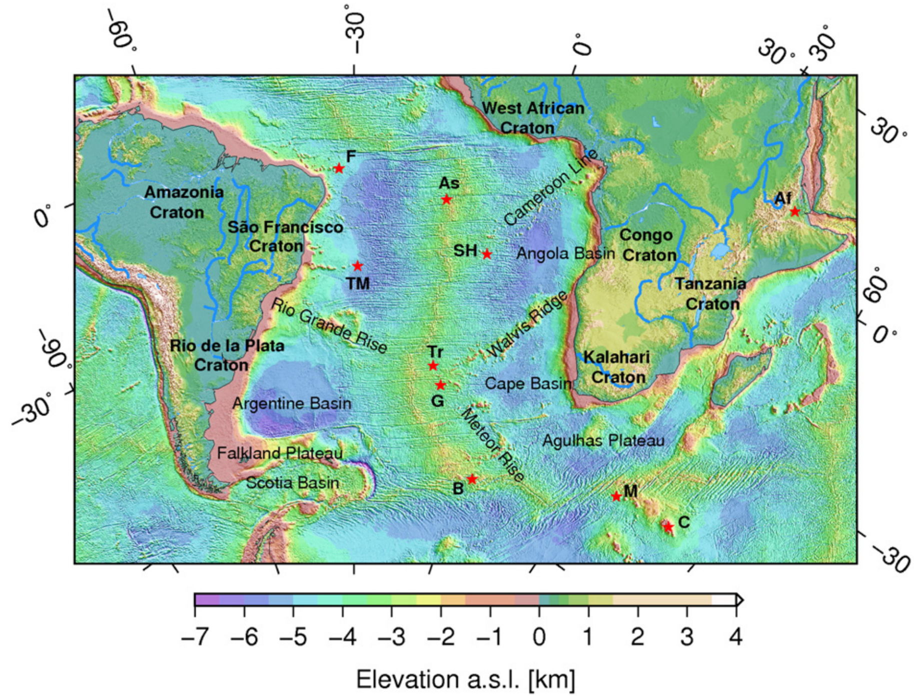

Fig. 1. Topographic map of the South Atlantic and adjacent continents from EOTPO1 (Amante and Eakins, 2009), annotated with major structural elements cited in the text. Oblique Mercator projection: central parallel passes through the points (30°S, 30°W) and (0°S, 60°E), projection centred on (28.024°S, 7.204°W). Craton names are boldface, while stars denote prominent hotspots (F: Fernando de Noronha; As: Ascension; Af: Afar; SH: Saint Helena; TM: Trinidade and Martim Vaz; Tr: Tristan da Cunha; G: Gough Island; B: Bouvet Island; M: Marion; C: Crozet Islands).

Significant hot thermal upwellings are thus expected in the region, in agreement with inferences that Africa experienced greater uplift in the Tertiary than other continents (e.g., Burke and Gunnell, 2008). A variety of geodynamic models (e.g., Forte et al., 2010; Gurnis et al., 2000; Lithgow-Bertelloni and Silver, 1998; Moucha and Forte, 2011) suggest deep mantle heterogeneity as a plausible cause for high topography in Africa and the South Atlantic, and that the entire region is influenced by a major mantle convection cell (Husson et al., 2012).

The African plate contains many volcanic centres that may be interpreted as the surface expression of mantle plumes rising from the lower mantle, but the path of deep material taken on its passage from the lower into the upper mantle, and its advective redistribution within the asthenosphere and toward the Mid-Atlantic ridge system is not well known. It must be inferred from seismic studies.

Upper mantle structure in the South Atlantic region remains poorly studied owing to the sparse distribution of seismic stations and the existence of large aseismic areas on the African and South American plates. Temporary deployments of seismometers were carried out at some localities, for example across the shields in southern Africa, to provide detailed seismic images of the crust and upper mantle (e.g., Chevrot and Zhao, 2007; Freybourger et al., 2001). Tomographic studies have revealed thick, seismically fast

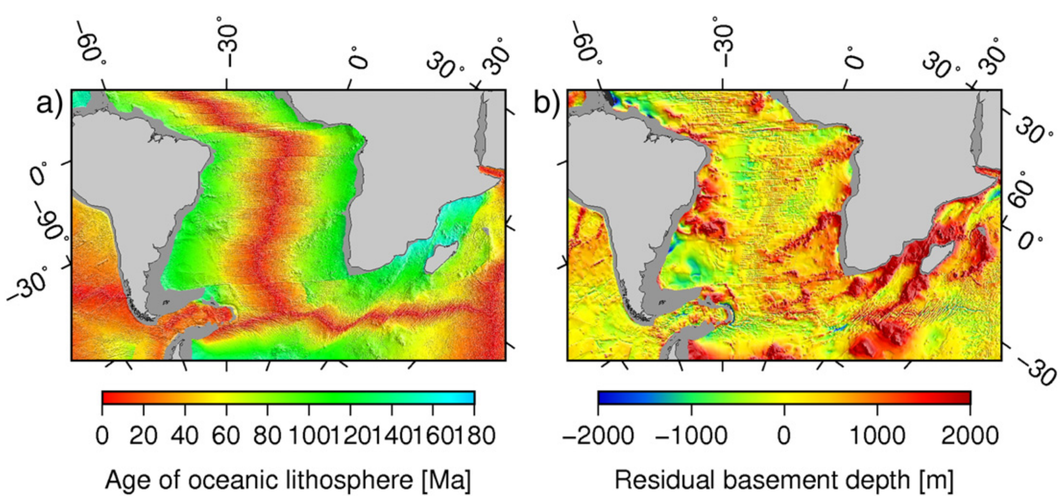

Fig. 2. Left: age-area distribution of the ocean floor from Müller et al. (2008); right: residual basement depth grid computed by calculating the difference between the predicted basement depth and the sediment unloaded basement depth. Predicted basement depth is obtained by applying Crosby et al.'s (2006) North Pacific thermal boundary layer model to the age-area distribution from Müller et al. (2008). Oblique Mercator projection. Note the anomalous bathymetry cutting across the regional structural elements, with excess topography in correspondence with the African superswell and anomalously high bathymetry in the south-eastern Atlantic.