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Mantle structure beneath Africa and Arabia from adaptively parameterized P-wave tomography: Implications for the origin of Cenozoic Afro-Arabian tectonism

Samantha E. Hansen [a,*], Andrew A. Nyblade [b], Margaret H. Benoit [c]

[a] Geological Sciences Department, University of Alabama, Tuscaloosa, AL 35487, USA
[b] Geosciences Department, Pennsylvania State University, University Park, PA 16802, USA
[c] Physics Department, The College of New Jersey, Ewing, NJ 08628, USA

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ABSTRACT

While the Cenozoic Afro-Arabian Rift System (AARS) has been the focus of numerous studies, it has long been questioned if low-velocity anomalies in the upper mantle beneath eastern Africa and western Arabia are connected, forming one large anomaly, and if any parts of the anomalous upper mantle structure extend into the lower mantle. To address these questions, we have developed a new image of P-wave velocity variations in the Afro-Arabian mantle using an adaptively parameterized tomography approach and an expanded dataset containing travel-times from earthquakes recorded on many new temporary and permanent seismic networks. Our model shows a laterally continuous, low-velocity region in the upper mantle beneath all of eastern Africa and western Arabia, extending to depths of ~500–700 km, as well as a lower mantle anomaly beneath southern Africa that rises from the core-mantle boundary to at least ~1100 km depth and possibly connects to the upper mantle anomaly across the transition zone. Geodynamic models which invoke one or more discrete plumes to explain the origin of the AARS are difficult to reconcile with the lateral and depth extent of the upper mantle low-velocity region, as are non-plume models invoking small-scale convection passively induced by lithospheric extension or by edge-flow around thick cratonic lithosphere. Instead, the low-velocity anomaly beneath the AARS can be explained by the African superplume model, where the anomalous upper mantle structure is a continuation of a large, thermo-chemical upwelling in the lower mantle beneath southern Africa. These findings provide further support for a geodynamic connection between processes in Earth's lower mantle and continental break-up within the AARS.

1. Introduction

The Cenozoic Afro-Arabian rift system (AARS), characterized by crustal extension, volcanism, and plateau uplift across much of eastern Africa and western Arabia (Fig. 1), is arguably one of the best places to investigate geodynamic processes leading to continental break-up. Many body wave tomography models have shown that the Arabian Shield, as well as the East African and Ethiopian Plateaus, are underlain by upper mantle low-velocity anomalies that could be connected beneath the southern Red Sea and the Turkana Depression (Fig. 1) to form one, large upper mantle structure. Parts of this structure could also extend through the transition zone into the lower mantle (*e.g.* Bastow et al., 2008; Benoit et al., 2003, 2006a; Nyblade et al., 2000; Park et al., 2007, 2008; Ritsema et al., 1999). However, because these models are based on seismic networks with limited aperture, it is difficult to determine whether or not the anomalies are actually parts of the same upper mantle structure or to ascertain their depth extent. Tomography models using surface waves also show slow upper mantle velocities in this region (Debayle et al., 2001; Fishwick, 2010; Pasyanos and Nyblade, 2007; Priestley et al., 2008; Sebai et al., 2006; Sicilia et al., 2008), but the lateral resolution associated with such models is generally several hundred kilometers, which is too large to resolve separate upper mantle anomalies beneath different parts of the AARS. The corresponding vertical resolution of these models is also limited below ~300–400 km depth, making it difficult to determine if the anomalies extend through the transition zone.

The lateral and depth extent of the upper mantle low-velocity anomalies beneath East Africa, Ethiopia, and western Arabia has important implications for understanding the origin of tectonism within the AARS. Three types of geodynamic models have been proposed to explain the rifting, volcanism, and plateau uplift found in this region. The first type of model invokes small-scale convection, either resulting from lithospheric stretching (Fig. 2a; Buck, 1986; Mutter et al., 1988) or from edge-flow from beneath the Congo craton (Fig. 2b; King, 2007; King and Ritsema, 2000). The second group of models includes one or more mantle plumes beneath eastern Africa and western Arabia (Fig. 2c; *e.g.* Camp and Roobol, 1992; Chang and van der

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* Corresponding author.
E-mail address: shansen@geo.ua.edu (S.E. Hansen).

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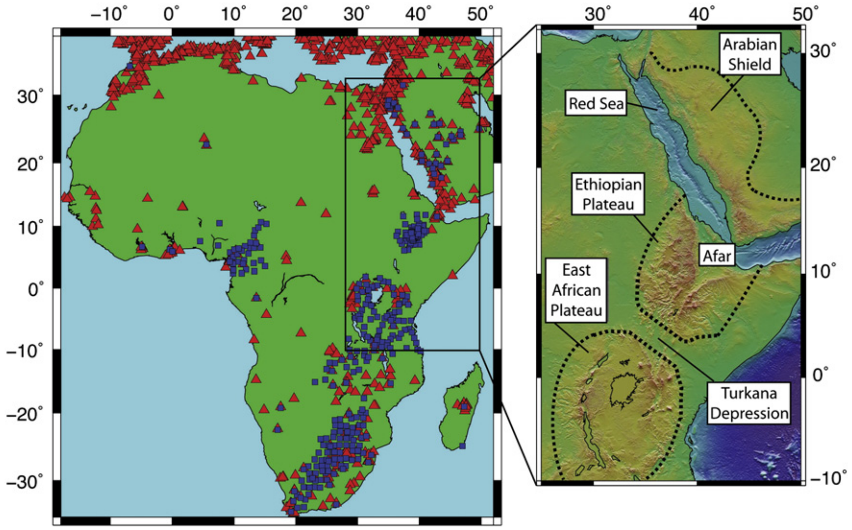

Fig. 1. Maps of study area and station distribution. (left) Distribution of stations used in our tomographic inversion. Red triangles denote stations included in the EHB database while blue squares denote stations from the augmented dataset. (right) Close-up of the Afro-Arabian region with topography from the 30 s digital elevation map in GMT (Wessel and Smith, 1998). Dashed lines show the extent of the East African and Ethiopian Plateaus as well as the Arabian Shield. Important topographic features are labeled.

Lee, 2011; Ebinger and Sleep, 1998; George et al., 1998; Montelli et al., 2006), and these models are characterized by ~100–200 km thick plume head material ponded beneath the lithosphere, fed by a narrow (~100–200 km diameter) plume tail. The final category of models attributes the origin of the AARS to a feature commonly referred to as the African superplume (Fig. 2d; *e.g.* Bastow et al., 2008; Benoit et al., 2006b; Forte et al., 2010; Furman et al., 2006; Park and Nyblade, 2006; Ritsema et al., 1999; Simmons et al., 2007, 2009), which is thought to be a large, thermo-chemical anomaly that develops near the core-mantle boundary beneath southern Africa and that tilts northeastward beneath eastern Africa at mid-mantle depths. Because the different types of geodynamic models would result in different upper mantle anomalies, the nature of the upper mantle structure across the AARS can be used to evaluate them.

To further investigate the lateral and depth extent of the upper mantle anomalies beneath the AARS, we have developed a new tomographic image of P-wave speed variations in the African and Arabian mantle using an adaptive parameterization method (Kárason, 2002; Li et al., 2008). An expanded dataset containing travel-times from earthquakes recorded on many new permanent and temporary seismic networks throughout the study region has also been employed. This approach leads to a P-wave tomography model with improved resolution of mantle structure beneath the AARS compared to many previous models, thereby enabling us to reevaluate geodynamic models for the origin of the Cenozoic tectonism in this area.

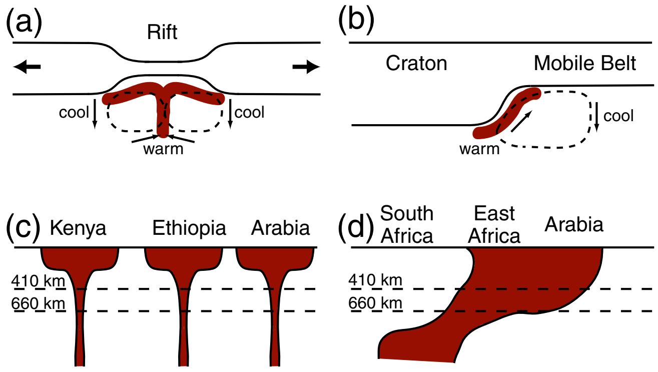

Fig. 2. Origin models for the AARS. Cartoons illustrating different geodynamic origin models that have been proposed for the AARS, including (a) small-scale convection induced by lithospheric stretching, (b) small-scale convection resulting from edge-flow, (c) plume models, and (d) the superplume model.

2. Background and previous studies

2.1. Global seismic models

Using global tomographic models, a number of authors over the past decade have commented on mantle structure beneath Africa and Arabia. Based on a 3-D shear-wave model, the study by Ritsema et al. (1999) was one of the earliest to suggest that the African superplume structure might be linked to Cenozoic tectonism in eastern Africa and Arabia. Mégnin and Romanowicz (2000) made a similar suggestion based on their model of shear-velocity heterogeneity, and a possible connection between anomalous lower and upper mantle structure beneath Africa was apparent in several other shear wave models that were published at about the same time (*e.g.* Grand, 2002; Gu et al., 2001; Masters et al., 2000). More recently, Simmons et al. (2007, 2009, 2010) developed global models using both shear-wave travel times and geodynamic observations, and in these models, the African superplume is interpreted as a low-density, thermo-chemical structure extending upwards from the core-mantle boundary to depths of at least ~1500 km. Eastern Africa is also underlain by an upper mantle low-density structure, but the authors stated that it is unclear whether this feature is connected to the deeper mantle. A recent model by Ritsema et al. (2011) highlights anomalously slow shear velocities extending through the lower mantle beneath southern Africa, but this study also mentions that the connection between the superplume and the upper mantle beneath eastern Africa might be less certain than suggested by Ritsema et al. (1999).

Using a global P-wave tomographic model, Montelli et al. (2006) examined the depth extent of various mantle plumes. Similar to Simmons et al. (2007, 2009, 2010), they imaged the superplume extending upwards from the core-mantle boundary to a depth of ~1500 km. The Montelli et al. (2006) model also shows low-velocity anomalies in the upper mantle beneath Afar and East Africa, and the authors suggest that these anomalies originate at mid-mantle depths or deeper. Using the same methodology as the current study, Li et al. (2008) developed a global model of P-wave velocity perturbations. While not discussed in detail, their model shows low velocities throughout much of the upper mantle beneath eastern Africa and