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Evidence for anomalous mantle upwelling beneath the Arabian Platform from travel time tomography inversion

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ABSTRACT

We present a new model of P-velocity anomalies in the upper mantle beneath the Arabian Peninsula, Red Sea, and surrounding regions. This model was computed with the use of travel time data from the global catalogue of the International Seismological Center (ISC) for the years of 1980–2011. The reliability of the model was tested with several synthetic tests. In the resulting seismic model, the Red Sea is clearly associated with a higher P-velocity anomaly in the upper mantle at least down to 300 km depth. This anomaly might be caused by upward deviation of the main mantle interfaces caused by extension and thinning of the lithosphere due to passive rifting. Thick lithosphere of the Arabian Platform is imaged as a high-velocity anomaly down to 200–250 km depth. Below this plate, we observe a low-velocity structure that is interpreted as a hot mantle upwelling. Based on the tomography results, we propose that this upper mantle anomaly may represent hot material that migrates westward and play a major role in the formation of Cenozoic basaltic lava fields in western Arabia. On the north-eastern side of the Arabian Plate, we clearly observe a dipping high-velocity zone beneath Zagros and Makran, which is interpreted as a trace of subduction or delamination of the Arabian Plate lithosphere.

1. Introduction

The western part of the Arabian Peninsula along the Red Sea Rift is characterized by widespread Cenozoic basaltic lava fields (Fig. 1), also called harrats, which cover large areas of more than 180,000 km^2 in total. Some of these volcanic centers appear to have been active in recent past and even currently. Camp et al. (1987) identified more than twenty large eruptions in Saudi Arabia and Yemen during the last 1500 years. For example, the existence of ongoing magmatic activity was supported by recent unrest in the Harrat Lunayyir in April–June 2009 (e.g., Pallister et al., 2010). More than 30,000 earthquakes, with some of them reaching a magnitude of M5.4, were recorded during this period. Many geophysical observations (e.g., Al-Amri et al., 2012; Baer and Hamiel, 2010; Hansen et al., 2013; Pallister et al., 2010) indicated that this crisis was caused by the ongoing activation of magmatic activity, even though the magma did not reach the surface and a volcanic eruption did not occur. The structural cause of this "missed" eruption in the Lunayyir basaltic field is discussed by Koulakov et al. (2015).

The lava composition from recent eruptions in western Arabia appears to indicate deep origins, probably arising from a mantle plume (Duncan and Al-Amri, 2013). Duncan and Al-Amri (2013) provide an overview of geochemical analyses of lavas from different harrats in western Arabia. They point out that the lava composition includes basanite to alkali olivine basalts of Hawaiian type, which mostly characterize plume-related hotspots, considerably different from the tholeiitic basalts observed in the Red Sea spreading center. Camp and Roobol (1992) found that the basalt properties in the western Arabian harrats were closer to the spreading-type in the older volcanic fields but became more alkalic in younger volcanoes.

The distribution of volcanic activity appears to be asymmetric with respect to the Red Sea. Most of the basaltic fields are located along the eastern side of the rift. Along the African Red Sea coast, there are no recent volcanic manifestations, except for the Afar region, which is located at the southernmost edge of the Red Sea and is presumed to be associated with a mantle plume (e.g., Ebinger and Sleep, 1998). The origin of Cenozoic volcanism in western Arabia and its possible links with the

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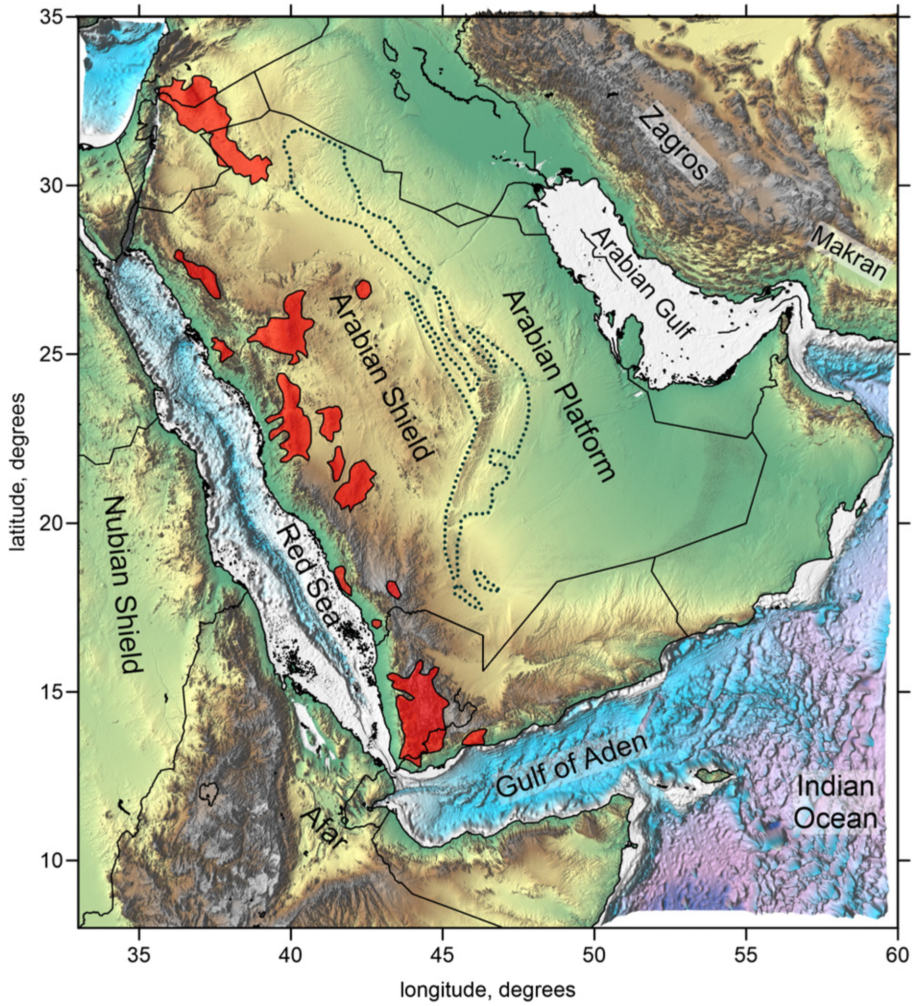

Fig. 1. Topography/bathymetry and major geographic units across the study area (downloaded from www.marine-geo.org). Red areas indicate the locations of Cenozoic basaltic fields (harrats). Green dotted line highlights Mesozoic rocks lineating the boundary between the Arabian Shield and Platform.

Red Sea rifting and Afar plume are subject to active debate. Some authors (e.g., Altherr et al., 1990) suggest that the opening of the Red Sea is caused by ascending hot mantle material (i.e., an active rifting mechanism), which is spread over a large region surrounding the rift leading to anomalous heating of the overlying crust and volcanic activity. Another model invokes passive extension of the Red Sea due to relative displacement of the lithospheric plates. Thinning of the lithosphere during the rifting causes an asymmetric mantle upwelling (e.g., Bohannon et al., 1989; Watremez et al., 2013) that mostly affects the eastern side of the rift and results in volcanic activity. An alternative scenario links the volcanic manifestations in western Arabia with the Afar plume (e.g., Courtillot et al., 1984; Debayle et al., 2001). This concept is supported by geochemical similarity of lavas in the East African Rift and western Arabia (e.g., Bertrand et al., 2003) as well as by geophysical observations of seismic anisotropy described in the next paragraph, which might indicate a path of northward plume migration (e.g. Chang et al., 2011; Lazar et al., 2012). Another mechanism for explaining the volcanism in western Arabia invokes the presence of a mantle plume directly beneath the Arabian Platform (e.g., Chang and van der Lee, 2011). This hypothesis is supported by receiver function studies (Vinnik et al., 2003), detecting anomalously low S-velocities below the cratonic lithosphere of the Arabian Plate.

Many geophysical studies of the deep structure beneath the Red Sea, Arabian Plate, and surrounding regions have been recently conducted to further examine the source of volcanic activity in western Arabia. For example, the analysis of SKS splitting (Elsheikh et al., 2014; Hansen et al., 2006) shows E–W oriented fast directions to the south of the Arabian Plate in Yemen. However, in the western part of Arabia, the anisotropy is generally oriented S–N which is interpreted as northward migration of the material from the Afar plume. A receiver function study by Hansen et al. (2007) highlights the variations of crustal thickness and depth to the lithosphere–asthenosphere boundary in the Arabian Peninsula. Another receiver function study by Vinnik et al. (2003) provides evidence for anomalously low velocities below the thick lithosphere in central Arabia.

Most of the information on mantle structure comes from several regional and global surface and body wave tomography models. For example, a number of global and regional studies covering large regions of Africa and Arabia e.g. (Ritsema et al., 1999; Ritsema and van Heijst, 2000; Sebai et al., 2006; Montagner et al., 2007: Ekström, 2011) provide evidence for mantle origins of volcanism in Afar and Arabia. Another model by Pasyanos and Nyblade (2007) revealed consistent low-velocity patterns below the volcanic fields in western Arabia but also detected a neutral velocity anomaly beneath the Red Sea. Similar patterns were found by higher resolution surface wave tomography models by Park et al. (2008) and Chang and Van der Lee (2011).

Body wave tomography is also used for studying the Arabian region, but it faces the problem of sparsely distributed stations and very uneven distribution of seismicity that causes lower resolution in the crust and uppermost mantle. Usually most details on mantle structure come