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The lithospheric shear-wave velocity structure of Saudi Arabia: Young volcanism in an old shield

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ABSTRACT

We investigate the lithospheric shear-wave velocity structure of Saudi Arabia by conducting H-κ stacking analysis and jointly inverting teleseismic P-receiver functions and fundamental-mode Rayleigh wave group velocities at 56 broadband stations deployed by the Saudi Geological Survey (SGS). The study region, the Arabian plate, is traditionally divided into the western Arabian shield and the eastern Arabian platform: The Arabian shield itself is a complicated mélange of crustal material, composed of several Proterozoic terrains separated by ophiolite-bearing suture zones and dotted by outcropping Cenozoic volcanic rocks (locally known as harrats). The Arabian platform is primarily covered by 8 to 10 km of Paleozoic, Mesozoic and Cenozoic sedimentary rocks. Our results reveal high Vp/Vs ratios in the region of Harrat Lunayyir, which are interpreted as solidified magma intrusions from old magmatic episodes in the shield. Our results also indicate slow velocities and large upper mantle lid temperatures below the southern and northern tips of the Arabian shield, when compared with the values obtained for the central shield. We argue that our inferred patterns of lid velocity and temperature are due to heating by thermal conduction from the Afar plume (and, possibly, the Jordan plume), and that volcanism in western Arabia may result from small-scale adiabatic ascent of magma diapirs.

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1. Introduction

A number of previous geophysical studies (e.g., Sandvol et al., 1998; Kumar et al., 2002; Julià et al., 2003; Al-Damegh et al., 2005; Tkalčić et al., 2006; Hansen et al., 2007) have provided important insight into the large-scale structure of the lithosphere of Saudi Arabia. The complex geology of the Arabian plate together with the sparse nature of previous datasets, however, have limited the information and prevented a detailed characterization of the lithospheric structure and its spatial relationship to surface geology. In particular, lateral variations in crustal thickness and shear-wave velocity across the Arabian plate are not well resolved. Although variations from west to east seem generally consistent among those studies, detailed differences of the velocity structure between the Arabian shield and the Arabian platform remain elusive. There is also considerable ambiguity regarding the lateral variations in crustal thickness along the western margin of Saudi Arabia, close to the Red Sea, and within the regions of recent volcanism.

More interestingly, the precise origin and detailed plumbing of the pronounced Cenozoic volcanism in western Saudi Arabia – locally known as harrats –are still unresolved. These volcanic outcrops are expected to originate from localized deep sources within the crust (Camp and Roobol, 1992), but unambiguous seismic imaging of such sources is still lacking. While slow P- and S-wave velocities and large Vp/Vs ratios are expected under the harrats due to the likely presence of partial melt, recent local tomography studies (Hansen et al., 2013) reported a pronounced fast P-velocity anomaly between 10 and 20 km depths in Harrat Lunayyir. Also, the Cenozoic volcanism may be ultimately originating from either lateral mantle flow from the Afar and, perhaps, Jordan hotspots (Chang and Van der Lee, 2011), or a local mantle plume beneath the Arabian shield (Camp and Roobol, 1992). Chang et al. (2011) inferred a region of deep (~150 km) low shear velocities under the southern Red Sea and the western Arabian plate, which they consider as an indication for lateral mantle flow from the Afar plume to western Arabia. Moreover, a quasi-vertical low S-velocity anomaly under Jordan had been imaged (Chang and Van der Lee, 2011). Previous petrological work (e.g., McGuire, 1988) on xenolith samples from various harrats provides point estimates of crustal and upper-mantle temperature–pressure conditions that can be reconciled with seismological observations. It is thus particularly critical to interpret the lithospheric properties and their relation to the possible lateral flows of plume materials by investigating crustal and upper-mantle shear velocity structures under the areas of active volcanism on the Arabian shield.

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In this study, we make use of a newly acquired seismic dataset, recorded on a modern (broadband), permanent seismic network operated by Saudi Geological Survey (SGS), to investigate the detailed lithospheric structure of Saudi Arabia. We determine crustal and upper-mantle S-wave velocity structure by jointly inverting receiver functions and surface-wave dispersion curves (Julià et al., 2000, 2003). The receiver functions were computed from teleseismic P-waveforms recorded by the broadband network, while the dispersion curves were extracted from the independent tomographic study of Pasyanos (2005). We also estimated bulk Vp/Vs ratios and crustal thicknesses under each station using the H-κ stacking technique of Zhu and Kanamori (2000). Our study extends previous efforts to map crustal and upper-mantle structures of the Arabian plate (e.g. Julià et al., 2003; Tkalčić et al., 2006; Hansen et al., 2007), providing a more comprehensive analysis of the velocity structure of Saudi Arabia.

2. Geological and geophysical background

2.1. Geology and tectonic setting

The Arabian plate consists of the western Arabian shield and the eastern Arabian platform (Fig. 1). The Arabian shield is mainly composed by six Proterozoic terrains, separated by four major ophiolite-bearing suture zones (Schmidt et al., 1979). The six major terrains include four western intra-oceanic island-arc terranes (Midyan, Hijaz, Jeddah and Asir) and two eastern continental terrains (Afif and Ar Rayn). These micro-plates were accreted 600–900 million years ago (Stoeser and Camp, 1985), eventually making part of a larger Pan-African orogen that crossed supercontinent Gondwana (e.g. Kröner and Stern, 2004). Much of the Arabian shield is thus formed by Precambrian rocks, although Cenozoic volcanic rocks related to the opening of the Red Sea are present along the western part. In contrast, the Arabian platform is covered by predominant Paleozoic, Mesozoic and Cenozoic sedimentary rocks. The thickness of these Phanerozoic sediments increases from the west to the east, reaching up to about 8–10 km thickness near the Arabian Gulf (Brown, 1972; Stoeser and Camp, 1985).

The Red Sea started forming when modern Arabia began to separate from Africa, approximately 30 Ma (Camp and Roobol, 1992; Bosworth et al., 2005; Garfunkel and Beyth, 2006). During this process, periods of both passive and active rifting occurred. Passive rifting is initiated by extensional stresses caused by plate motions that stretch and thin the lithosphere, which in turn generates an upwelling of hot asthenospheric material and volcanism below the rift. Active rifting is due to upwelling of hot mantle material that leads to thermal uplift and lithospheric erosion, thus thinning the overlying lithosphere. One model of Red Sea evolution invokes a two-stage rifting process in which rifting is initiated passively and followed by a period of active rifting (Camp and Roobol, 1992; Ebinger and Sleep, 1998; Daradich et al., 2003). The southern Red Sea (south of ~21°N) has already evolved into a rifting stage involving seafloor spreading and volcanic activity (Ebinger and Sleep, 1998; Daradich et al., 2003; Chang et al., 2011; Xu and Jónsson, 2014), while the northern Red Sea (north of ~21°N) is interpreted as an active rift at the end of its continental stage that is starting to transition into oceanic seafloor spreading (Cochran and Martinez, 1988).

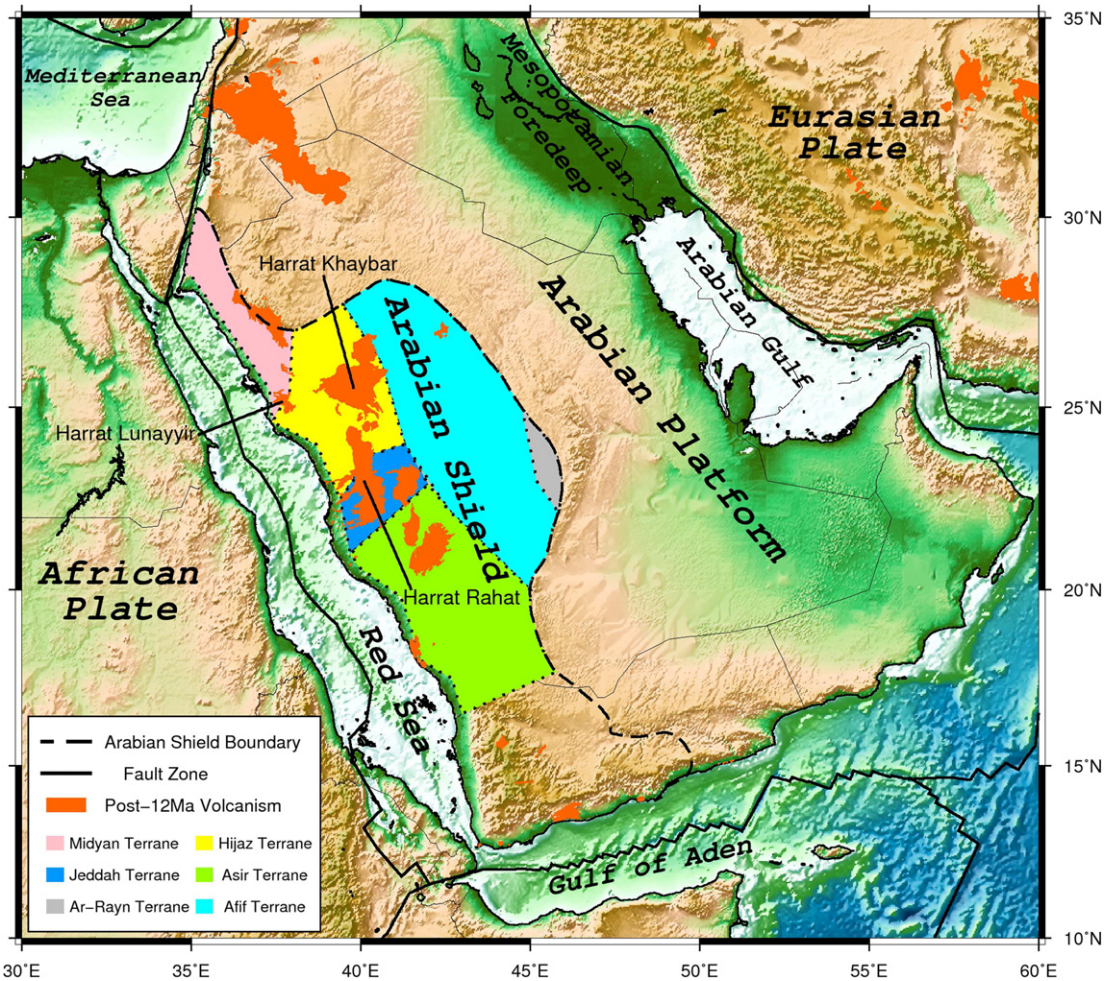

Fig. 1. Geographic map of the Arabian plate and surrounding regions, showing also the major geologic features of six accreted terranes (Miyan terrane, Hijiaz terrane, Jeddah terrane, Asir terrane, Afif terrane and Ar Rayn terrane), and areas of volcanic activity in the last 12 million years.

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