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Evidence for crustal low shear-wave speed in western Saudi Arabia from multi-scale fundamental-mode Rayleigh-wave group-velocity tomography

Zheng Tang[a,*], P. Martin Mai[a], Sung-Joon Chang[b], Hani Zahran[c]

[a] King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia
[b] Kangwon National University (KNU), Chuncheon, South Korea
[c] Saudi Geological Survey (SGS), Jeddah, Saudi Arabia

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ABSTRACT

We investigate the crustal and upper-mantle shear-velocity structure of Saudi Arabia by fundamental-mode Rayleigh-wave group-velocity tomography and shear-wave velocity inversion. The seismic dataset is compiled using ~140 stations of the Saudi National Seismic Network (SNSN) operated by the Saudi Geological Survey (SGS). We measure Rayleigh-wave group-velocities at periods of 8–40 s from regional earthquakes. After obtaining 1-D shear-wave velocity models by inverting group-velocities at each grid node, we construct a 3-D shear-velocity model for Saudi Arabia and adjacent regions by interpolating the 1-D models. Our 3-D model indicates significant lateral variations in crustal and lithospheric thickness, as well as in the shear-wave velocity over the study region. In particular, we identify zones of reduced shear-wave speed at crustal levels beneath the Cenozoic volcanic fields in the Arabian Shield. The inferred reductions of 2–5% in shear-wave speed may be interpreted as possibly indicating the presence of partial melts. However, their precise origin we can only speculate about. Our study also reveals an upper-mantle low velocity zone (LVZ) below the Arabian Shield, supporting the model of lateral mantle flow from the Afar plume. Further geophysical experiments are needed to confirm (or refute) the hypothesis that partial melts may exist below the Cenozoic volcanism in western Saudi Arabia, and to build a comprehensive geodynamic–geological model for the evolution and present state of the lithosphere of the Arabian Plate and the Red Sea.

1. Introduction

The Arabian Plate started to separate from Africa as the Red Sea and Aden Gulf rifting began around 30 Ma ago (e.g., Camp and Roobol, 1992; Bosworth et al., 2005; Garfunkel and Beyth, 2006). It is geologically divided into two distinct terrains: the western Arabian Shield and the eastern Arabian Platform (Fig. 1). Extensive Precambrian Proterozoic basement rocks are exposed in the Arabian Shield, although they underlie the entire Arabian Peninsula. Cenozoic volcanic rocks, known as "harrats", mainly overlie the western part of the Arabian Shield. The Arabian Platform is covered by predominant Paleozoic, Mesozoic and Cenozoic sedimentary rocks with increasing thickness eastward away from the Shield (Brown, 1972; Stoeser and Camp, 1985).

The rifting of the Red Sea strongly affected the geology and recent tectonic history of western Saudi Arabia. Some studies suggest that the Red Sea is passively rifting, driven by extensional stresses due to far-field forces such as slab pull (e.g. Wernicke, 1985; McGuire and Bohannon, 1989; Koulakov et al., 2016). Other studies (e.g. Bellahsen et al., 2003; Hansen et al., 2007) argue that the Red Sea developed as an active rift, driven by hot mantle upwelling that leads to thermal uplift and lithospheric thinning. In addition, the hypothesis of hybrid rifting has been proposed in which the Red Sea opening is thought to be initiated passively, but is then followed by a period of active processes (Camp and Roobol, 1992; Ebinger and Sleep, 1998; Daradich et al., 2003). The stage of rifting is non-uniform along the Red Sea. The southern Red Sea already indicates seafloor spreading and prominent volcanic activity (Ebinger and Sleep, 1998; Daradich et al., 2003; Xu and Jónsson, 2014), while the northern Red Sea is still at a passive rifting stage (Kaban et al., 2016), and/or an active rift at the end of its continental stage beginning to transit into oceanic seafloor spreading (Cochran and Martinez, 1988).

* Correspondence to: P.O. Box 4700-3770, Thuwal, Jeddah, 23955-6900, Saudi Arabia.
E-mail address: Zheng.Tang@kaust.edu.sa (Z. Tang).

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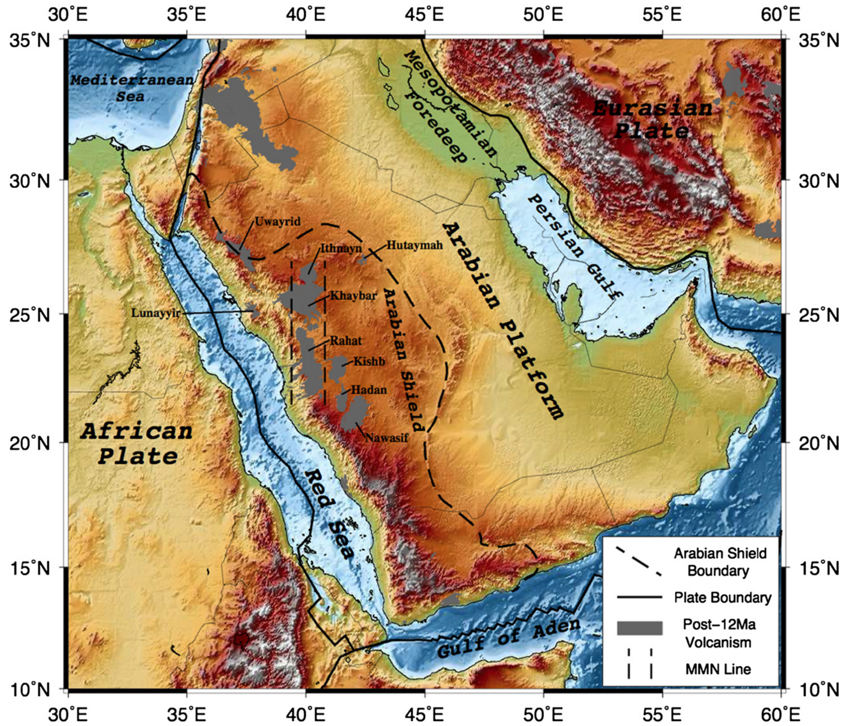

Fig. 1. Geographic map of the Arabian Plate and its surrounding regions, showing the main geologic features, the Cenozoic volcanism during the past 12 Ma (gray-shaded regions), and the so-called Makkah–Madinah–Nafud (MMN) volcanic line. Main volcanic regions (called harrats locally) are indicated by their names to which we refer in the text.

Western Arabia is dotted with areas of Cenozoic volcanism that formed during the past 30 Ma, showing a bimodal chemical character that indicates two distinct phases of volcanism (Camp and Roobol, 1992). Older lavas (30–20 Ma) are tholeiitic to transitional in composition. These are oriented approximately parallel to the Red Sea and have been attributed to the early rifting stage of the Red Sea. In contrast, younger lavas (12 Ma to recent) are transitional to alkalic, and can be found mainly along the north–south oriented Makkah–Madinah–Nafud (MMN) line. Chang and Van der Lee (2011) suggests that the pronounced Cenozoic volcanism originates from lateral mantle flow from the Afar and, perhaps, a hypothesized Jordan hotspot. Other studies argue that a local mantle plume (Camp and Roobol, 1992) and/or a local hot mantle upwelling (Koulakov et al., 2016) under the Arabian Plate may play a key role in the formation of the Cenozoic lava fields.

Several geophysical studies of crustal and upper-mantle structure of the Arabian Plate provide evidence for lateral variations of lithospheric properties (e.g., Mooney et al., 1985; Gettings et al., 1986; Mokhtar and Al-Saeed, 1994; Sandvol et al., 1998; Rodgers et al., 1999; Mokhtar et al., 2001; Kumar et al., 2002; Julià et al., 2003; Al-Damegh et al., 2005; Tkalčić et al., 2006; Hansen et al., 2007; Chang and Van der Lee, 2011; Tang et al., 2016; Yao et al., 2017). Generally, the crustal thickness in the Arabian Shield varies between 27 and 45 km (Hansen et al., 2007; Tang et al., 2016), while the crustal shear-velocity ranges from 3.48 to 3.95 km/s with an average bulk V_p/V_s ratio of 1.73 ± 0.07 (Tang et al., 2016). Thinner crust (25–32.5 km thick) with strong lateral variations is present along the Red Sea margin (Al-Damegh et al., 2005; Tkalčić et al., 2006; Tang et al., 2016). The Arabian Platform has crustal shear-velocities between 3.44 and 3.68 km/s and an average bulk V_p/V_s of 1.77 ± 0.09 (Tang et al., 2016).

In addition, it has been inferred that the depth of the lithosphere–asthenosphere boundary (LAB) varies considerably across the Arabian Peninsula, showing thin lithosphere under western Arabia that thickens toward the Arabian interior (Hansen et al., 2007). Tkalčić et al. (2006) observes anomalously low upper-mantle velocities and strong polarization anisotropy in the lithospheric upper-mantle below the Arabian Shield. Chang and Van der Lee (2011) and Chang et al. (2011) find slow shear-wave velocities at ~150 km depth, stretching from the Afar through the southern Red Sea and into the western Arabia, as well as a quasi-vertical low velocity anomaly under Jordan. Yao et al. (2017) confirms the upper-mantle low velocity zone (LVZ) of ~300 km width, roughly 60–190 km depths, and trending approximately north–south below the MMN volcanic line.

However, most of the above-mentioned studies are limited by poor station coverage and sparse datasets. Thus, there is still considerable ambiguity regarding the lateral variations of crustal and upper-mantle structure below the Arabian Shield, the regions of Cenozoic volcanism (harrats), and the Arabian Platform. In this study, we aim to revise previous models by conducting a fundamental-mode Rayleigh-wave group-velocity tomography and inverting for 3-D shear-wave velocity structure underneath Saudi Arabia, based on a new seismic datasets obtained from the Saudi Geological Survey (SGS). The new observations include seismic data recorded by a dense station network (unavailable for previous studies) in the years of 2007–2014, which greatly improves the spatial coverage and helps illuminating intraplate regions. Our study therefore extends previous efforts to map crustal and upper-mantle structure of Saudi Arabia, and achieves higher local resolution.

In the following, we first describe the seismic data and our Rayleigh-wave group-velocity measurements. The next section presents the Rayleigh-wave tomography method and resulting maps of Rayleigh-wave group-velocities, followed by the description of the shear-wave velocity inversion and the estimated 3-D velocity model for the entire study region. Finally, we examine in detail the local velocity structure below the regions of Cenozoic volcanism in the Arabian Shield and discuss possible interpretations for the observed spatial patterns of shear-wave velocity variations.