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Imaging of magma intrusions beneath Harrat Al-Madinah in Saudi Arabia

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ABSTRACT

High-resolution tomographic images of the crust and upper mantle beneath Harrat Al-Madinah, Saudi Arabia, are obtained by inverting high-quality arrival-time data of local earthquakes and teleseismic events recorded by newly installed borehole seismic stations to investigate the AD 1256 volcanic eruption and the 1999 seismic swarm in the study region. Our tomographic images show the existence of strong heterogeneities marked with low-velocity zones extending beneath the AD 1256 volcanic center and the 1999 seismic swarm area. The low-velocity zone coinciding with the hypocenters of the 1999 seismic swarm suggests the presence of a shallow magma reservoir that is apparently originated from a deeper source (60–100 km depths) and is possibly connected with another reservoir located further north underneath the NNW-aligned scoria cones of the AD 1256 eruption. We suggest that the 1999 seismic swarm may represent an aborted volcanic eruption and that the magmatism along the western margin of Arabia is largely attributed to the uplifting and thinning of its lithosphere by the Red Sea rifting.

1. Introduction

Large areas on the western margin of the Arabian plate are covered with intraplate basaltic volcanic fields that are commonly related to the upwelling of the Afar mantle plume (~30 Ma) and the consequent formation of the East African, Gulf of Aden, and Red Sea rift systems (Coleman et al., 1983; Bosworth et al., 2005; Pallister et al., 2010; Chang et al., 2011). Thirteen of these volcanic fields, known locally as the *harrat*, are located in western Saudi Arabia (Coleman et al., 1983). One of these volcanic fields is Harrat Rahat. Its importance stems from the fact that its northern extremities extend to the south-eastern and eastern suburbs of the holy city of Al-Madinah Al-Munawarah.

Harrat Rahat forms a 50–75 km-wide, 300 km-long, N20–25°W-trending plateau (Durozoy, 1970; Berthier et al., 1981; Coleman et al., 1983). It comprises four coalesced smaller volcanic fields attaining an approximate area of 19,830 km^2 and an estimated volume of 1999 km^3 (Camp and Roobol, 1989). In previous studies, the northern part of Harrat Rahat was referred to as Harrat Al-Madinah (Coleman et al., 1983; Moufti, 1985; Moufti et al., 2012). In this study, Harrat Al-Madinah is used to describe the volcanic terrains of Harrat Rahat located north of latitude 24°N. It is mainly composed of olivine basalts and hawaiites with minor silicic differentiates of mugearites, benmoreites, and trachytes (Moufti et al., 2012). The northern part of Harrat Al-Madinah (NHM), however, is covered mainly with basaltic scoria cones, tephra fall deposits, and lava flows (Camp and Roobol, 1989). On the contrary, the southern part of Harrat Al-Madinah (SHM) is uniquely marked with the development of trachytic lava domes, tuff rings, explosion craters, and pyroclastic deposits (Moufti and Németh, 2013).

The most recent volcanic eruption took place in NHM in AD 1256, when an eruption lasted for 52 days, extruded 0.5 km^3 of alkali-olivine basalt from a 2.25 km-long fissure and produced at least 7 scoria cones and a 23 km-long lava flow that came to within 8 km from Al-Madinah (Camp et al., 1987; Camp and Roobol, 1989; Ambraseys et al., 1994; El-Masry et al., 2013; Murcia et al., 2014b). In the SHM, an earthquake swarm of ~500 events occurred at the

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end of 1999. The recorded earthquakes with magnitudes ranged between M0.5 and M3.0 went without any filed reports from the locals. These events have raised the importance of understanding the relationship between volcanicity and lithospheric structures in Harrat Al-Madinah.

Although many researchers have extensively studied the lithospheric structure beneath the Arabian Plate and the Red Sea region (e.g., Benoit et al., 2003; Nyblade et al., 2006; Park et al., 2007, 2008; Chang and Van der Lee, 2011; Hansen et al., 2007), quite few have addressed this subject in the harrats (e.g., Harrat Lunayyir, Pallister et al., 2010; Hansen et al., 2013; Koulakov et al., 2015). In this work, the detailed 3-D structure beneath Harrat Al-Madinah is investigated through the collaborative project of Volcanic Risks in Saudi Arabia (VORiSA) between King Abdulaziz University, Saudi Arabia, and the University of Auckland, New Zealand. Eight short-period seismic borehole stations were installed to record local micro-seismic activity. Due to the sparsity of local seismicity in the area, we applied a tomography method (Zhao et al., 1994, 2012) to invert abundant travel-time data of local and teleseismic events simultaneously. This method has been used successfully so far to image the deep structure of the Japan subduction zone (e.g., Zhao et al., 1994, 2012; Abdelwahed and Zhao, 2007; Huang et al., 2013; Liu et al., 2013, 2014), the Yellowstone and Cape Verde volcanic fields (Tian and Zhao, 2012; Liu and Zhao, 2014), as well as many other regions in the world (see a recent review by Zhao, 2015). After one-year of data collection, and with the aid of data from the Saudi Geological Survey (SGS), about 5800 arrival-time data were collected which enabled us to image the crustal and upper mantle structures beneath Harrat Al-Madinah.

2. Data and method

Our results are mainly derived from the analysis of two sets of data. One is arrival-time data of local earthquakes and teleseismic events recorded by the newly installed VORiSA Seismic Network (VSN) (Abdelwahed, 2013; Kenedi et al., 2014). The other is the 1999 earthquake swarm data recorded by the Al-Madinah Seismic Network (SGS-MSN) operated by the SGS (Endo et al., 2007).

The VSN consists of eight short-period borehole stations deployed in the NHM area (Fig. 1). The sensors were installed in the boreholes at the depth of 120 m and consisted of three-component 2 Hz velocity seismometers with a Reftek acquisition system (DAS-130) recording the data at 250 sample/s. The technical specifications of the borehole sensor are shown in Table S1. This network has been operated by the Geohazards Research Center (GRC), King Abdulaziz University since April 2012. The SGS-MSN has been operated by SGS since 1999. It consists of 16 three-component Nanometrics broadband seismic stations recording the data at 100 sample/s. The distribution of the seismic stations used in this study is shown in Fig. 1. Table S2 shows the coordinates, sensor types, and the installation dates of the seismic stations used in this study. The waveform data in this study are analyzed using the SGRAPH software and a waveform modelling method (Abdelwahed, 2012, 2013; Abdelwahed and Zhao, 2005, 2014).

2.1. Local earthquake data

A total of 4609 P-wave arrival times from 733 local earthquakes are used in this study (Fig. 2a). This dataset was recorded by the VSN during the period from April 2012 to November 2013 and by the SGS-MSN during the period from November 1999 to December 1999. Fig. 2b shows the travel time–distance curve of the local data used in this study. The first P-wave arrival times were picked up manually by the GRC and the Saudi Geological Survey (SGS) operators, respectively. The picking errors are estimated to be ~0.1 s. Fig. S1 shows an example of the seismograms of a local earthquake recorded by the VSN. The focal depths of the local events range from 0 to 40 km, which caused some scattering in the observed travel-time curve, particularly for larger distances.

2.2. Teleseismic data

The other dataset consists of 1179 P-wave relative travel-time residuals from 151 teleseismic events recorded by the VSN. The teleseismic travel-time data were firstly picked up manually before applying the multi-channel cross-correlation technique (VanDecar and Crosson, 1990) to improve the picking accuracy. Fig. S2 shows an example of the seismograms of a teleseismic event recorded by the VSN. The epicentral distances of the teleseismic events (M 5.5–8.0) range from 30° to 90° (Fig. 2c). Most of the events occurred in the subduction zones in the northern Pacific and Tonga, and eastern and southern Asia. Although the incident angles of the teleseismic rays are generally small (within ~30° from the vertical direction), the teleseismic rays crisscross in the upper mantle beneath the study area. In the tomographic inversion, relative travel-time residuals of the teleseismic events are used to minimize the effects of the hypocentral mislocations and the structural heterogeneities outside the modelling space (Zhao et al., 1994, 2012). To calculate the relative travel-time residuals (RTTRs), we first calculated the travel-time residuals (TTRs) by subtracting the theoretical travel times (T_{cal}) that were calculated for the iasp91 Earth model (Kennett and Engdahl, 1991) from the corresponding observed travel times (T_{obs}). The RTTRs for all the teleseismic events and stations were then calculated by removing the average of the entire TTRs from the individual TTR (see Zhao et al., 1994 for more details). Furthermore, the mean RTTR at each station was calculated by averaging all the corresponding TTRs of all the teleseismic events recorded by the corresponding station. Fig. 3 shows the distribution of the RTTRs at the eight VSN stations from the teleseismic events in four geographical quadrants. Positive residuals dominate the central and western parts of the study region, suggesting the existence of significant low-velocity (low-V) anomalies beneath those parts. Whereas negative residuals are observed at stations VW02 and VW06 in the NE and SW quadrants, respectively, indicating the existence of high-velocity (high-V) anomalies beneath these stations. The patterns of the residual distribution for the four quadrants (Fig. 3a–d) are generally consistent with that obtained from the data of all quadrants (Fig. 3e) with the exception of the SW quadrant where a small number of teleseismic events exist (see Fig. 2c). This confirms the reliability of the observed features and suggests the existence of significant structural heterogeneities beneath the study region, which could explain the observed volcanic and seismic activities in the area.

2.3. Method

In this study, the joint inversion method of Zhao et al. (1994, 2012) is used to analyze the teleseismic RTTRs together with the local earthquake arrival times in tomographic inversions. This method deals with a general velocity model in which complex velocity discontinuities exist and velocity changes in three dimensions. The medium under the area is divided into layers, where three-dimensional grid nodes are arranged. Velocity perturbations at the grid nodes from a starting 1-D velocity model are taken to be unknown parameters. The velocity perturbation at any point in the model is calculated by linearly interpolating the velocity perturbations at the eight nodes surrounding that point. The 3-D ray tracing technique (Zhao et al., 1992; Zhao and Lei, 2004) is used to trace rays between hypocenters and receivers and to calculate theoretical