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# Pathways of volatile migration in the crust beneath Harrat Lunayyir (Saudi Arabia) during the unrest in 2009 revealed by attenuation tomography

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ABSTRACT

Harrat Lunayyir is a relatively young basaltic field in Saudi Arabia located at the western margin of the Arabian Peninsula. In April–June 2009, strong seismic activity and ground deformations at this site marked the activation of the magma system beneath Harrat Lunayyir. In this study, we present new three-dimensional models of the attenuation of P and S waves during the unrest in 2009 based on the analysis of $t^*$. We measured 1658 and 3170 values of $t^*$ for P and S waves, respectively, for the same earthquakes that were previously used for travel time tomography. The resulting anomalies of the P and S wave attenuation look very similar. In the center of the study area, we observe a prominent high-attenuation pattern, which coincides with the most active seismicity at shallow depths and maximum ground deformations. This high-attenuation zone may represent a zone of accumulation and ascending of gases, which originated at depths of 5–7 km due to the decompression of ascending liquid volatiles. Based on these findings and previous tomography studies, we propose that the unrest at Harrat Lunayyir in 2009 was triggered by a sudden injection of unstable liquid volatiles from deeper magma sources. At some depths, they were transformed to gases, which caused the volume to increase, and this led to seismic activation in the areas of phase transformations. The overpressurized gases ultimately found the weakest point in the rigid basaltic cover at the junction of several tectonic faults and escaped to the surface.

## 1. Introduction

Areas of intracontinental volcanic activity are widely spread throughout the world; however, eruptions in such areas during present times have been rare. Typically, if any volcanic activity occurs within an intracontinental area, it will attract much attention from specialists since it may provide important information about the mechanisms of intraplate volcanism and the structure of deep magma sources. Harrat Lunayyir in western Arabia (Fig. 1) is a volcanic complex, which is still active and represents a real volcanic hazard. A recent seismic crisis in April–May 2009 (Pallister et al., 2010), which was accompanied by a "failed eruption of Lunayyir" (Koulakov et al., 2015), yielded rich material for studying the processes in the magma system during its activation, even though the activity did not end with a real eruption.

This event in the Harrat Lunayyir volcanic field has been thoroughly studied with different methods. Before 2009, moderate seismic activity was observed in this area, and it was mostly associated with tectonic displacements in the Red Sea and Gulf of Aqaba (e.g., El-Isa and Al-Shanti, 1989; Al-Amri, 1995). Note, however, that no seismic network was operational in the Lunayyir area at that time; thus, volcano-related seismicity with the magnitude of less than Mw 1–1.5, would have been missed because of the lack of sufficient instrumentation.

In April 2009, strong seismic activity started suddenly in the area of Harrat Lunayyir. A seismic network was deployed by the Saudi Geological Survey immediately after the beginning of the seismic crisis. The network recorded more than 30,000 seismic events from April to June 2009, including dozens of events with magnitudes higher than Mw 4.0 and the strongest event (Mw 5.4) that occurred on 19 May (Pallister et al., 2010). The seismicity in 2009 formed a dense cluster within a 1.5–2 km width planar zone roughly aligned along a vertical plain oriented NNW–SSE. The events occurred first at the SSE limit of the cluster, then propagated towards its NNW limit (Zobin et al., 2013). Most of the events were identified as high-frequency impulsive volcano-tectonic earthquakes; however, there was important evidence

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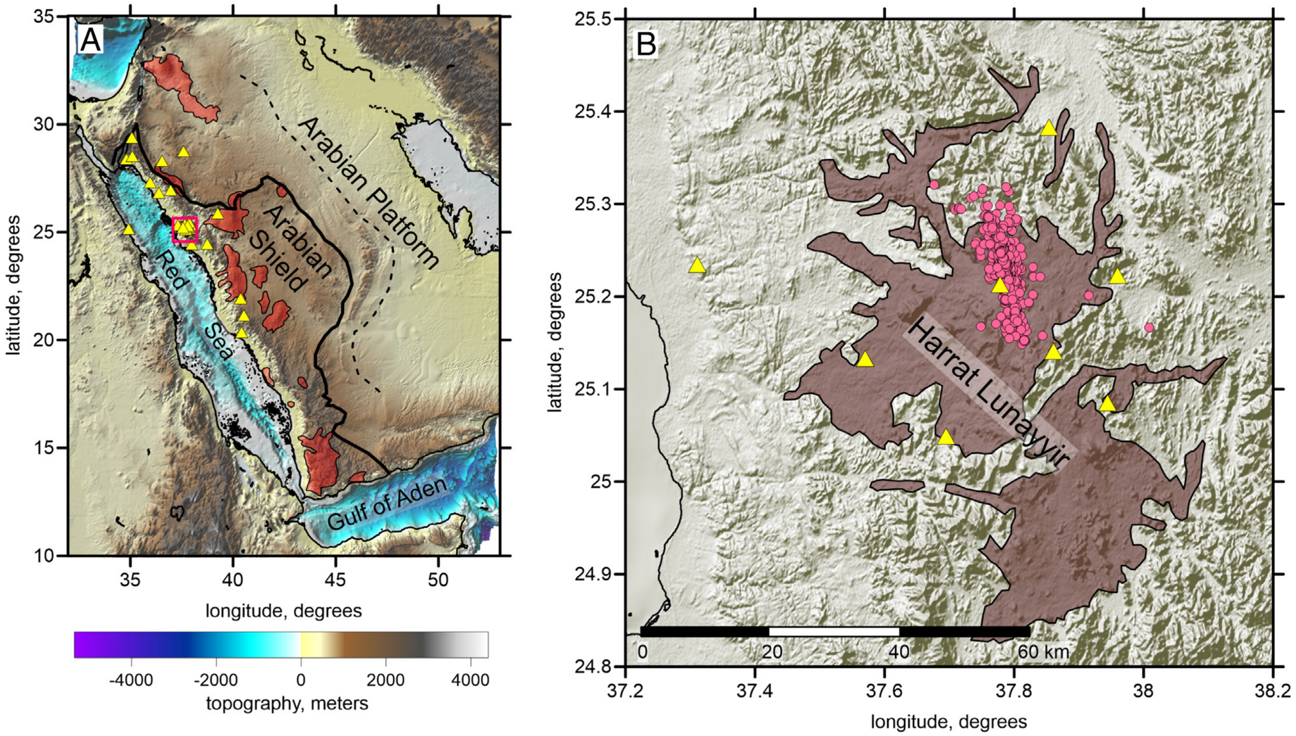

**Fig. 1.** Location of the study region. A. Map of the Arabian Peninsula and surrounding areas. The locations of the main harrats are depicted with red. Yellow triangles indicate the seismic stations used in this study. Dotted and solid lines highlights the limit of the Mesozoic orogenic belt delimiting the Arabian Platform and the Arabian Shield. Red box indicates the study area. B. Location of the stations (yellow triangles) and events (red dots) in the Harrat Lunayyir area. The basaltic cover is highlighted with brown color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of very low-frequency events that may indicate the volcanic nature of the unrest (Zobin et al., 2013). Inhabitants of the Harrat Lunayyir region reported to the media and to the Saudi Geological Survey that they observed gas emissions (unusual fog produced by steam coming out from the ground in the cold mornings) on days corresponding to the beginning of the earthquake activity during the 2009 crisis.

The seismic crisis was accompanied by strong ground deformations, which were captured by InSAR (Interferometric Synthetic Aperture Radar) measurements (Baer and Hamiel, 2010). These observations identified a rift zone with strong subsidence as opposed to the considerable uplift along the flanks (Fig. 2). Baer and Hamiel (2010) developed a numerical mechanical model with an intrusion of a vertical ~12 km long dike with the maximum thickness of 2.5 m in the area of the major seismicity swarm that generally explained the observed ground deformations.

Important information about the processes that occurred in the crust during the crisis was provided by seismic tomography studies. The first tomography model by Hansen et al. (2013), which was based on the inversion of a large amount of autopicked arrival times, reported distributions of only the P-wave velocities. They derived an image of a high-velocity body that coincided with the distribution of the major seismicity cluster, and it was interpreted as an intruded dyke. Another tomography study for the same region was performed by Koulakov et al. (2015), and it was based on manually picked P- and S-wave arrival times. They identified a prominent zone of high Vp/Vs ratios at a depth of approximately 10 km underlying the area of cinder cone distributions in Harrat Lunayyir. This anomaly with the lateral size of ~10 km and Vp/Vs ratio exceeding 1.8 was robustly resolved in the central part of the study area, where synthetic tests showed the best resolution. Koulakov et al. (2015) proposed that this anomaly represented a steady reservoir that episodically fed the eruptions during the last hundred thousand years. Another anomaly of high Vp/Vs ratios was found at the depth of ~15 km at the SSE part of the swarm, where most of events in the beginning of the crisis were recorded just after deployment of the temporary network. It was demonstrated by checkerboard tests that thanks to the dense distribution of deep events, this anomaly with the value of Vp/Vs ratio of ~1.8 was resolved robustly. It was interpreted as a conduit of overheated liquid fluids coming from deeper magma sources. According to the interpretation proposed in Koulakov et al. (2015), these fluids activated the steady crustal magma reservoir identified as anomaly of high Vp/Vs ratio at depths of 7–15 km, which coincided in the map view with the distributions of the main cinder cones in the Harrat Lunayyir. However, this fluid injection was not sufficiently enough to generate melting processes and produce a real eruption.

Another seismic model based on the inversion of coda-wave attenuation data by Koulakov et al. (2014) generally confirmed the results of the body-wave tomography results that were indicative of high attenuation in areas of the seismicity distributions below 7 km depth. In shallow areas above 7 km depth, both seismic velocity and attenuation revealed a zone with low Vp/Vs ratios and a high quality factor that was interpreted as a rigid basaltic cover.

The problem with both of these models is that they did not reveal any traces of shallow crustal processes leading to the ground deformations with more than 50 cm of subsidence in the central graben and ~40 cm of inflation in the eastern flank (Fig. 2; Baer and Hamiel, 2010). Actually, a significant part of seismicity occurred in the upper part of the crust above 7 km depth. Large ruptures along a ~ 8 km long line appeared at the surface with up to 90 cm of absolute fault motion and ~45 cm of tensional opening of the ground surface (see photos in Pallister et al., 2010), which indicate that strong mechanical deformations occurred in the uppermost crust. Why did travel time and coda-wave seismic tomographies not reveal traces of these zones in the shallow parts of the models (0–7 km depth)? Possibly, the travel time tomography is mostly sensitive to the distribution of the liquid phase, and stress/deformation patterns do not sufficiently change seismic velocities. The method used in Koulakov et al. (2014) is also not suitable for studying the local uppermost crust at structures because of fundamental limitations of the coda wave method. Actually, the coda wave

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