Investigation of Seismic Velocity Structure Beneath Harrat Lunayyir Using Travel-Time Tomography

تركيب السرع السيزمية تحت حرة لونير باستخدام التصوير المقطعي ثلاثي الابعاد للمسار الزمني

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Abstract

Assessing the seismic-volcanic hazard beneath Harrat Lunayyir in northwestern Saudi Arabia has proven to be difficult given the lack of information about the crustal and upper mantle structure in this region. The harrat has experienced multiple seismic swarms since 2007 and is associated with considerable volcanic and geothermal activity. Using data from numerous broadband and short-period seismic stations that have been deployed throughout the region, we propose to investigate the velocity structure beneath Harrat Lunayyir using seismic travel-time tomography. The resulting models will highlight both magmatic and seismic structures within the harrat, allowing for more accurate hazard assessment. It is estimated that work on this project will begin in May or June 2011, and the final model should be completed by June 2012.

Introduction

The Cenozoic lava field of Harrat Lunayyir in northwestern Saudi Arabia has experienced multiple seismic swarms since 2007. Most recently, in April-June 2009, a swarm of more than 30,000 earthquakes occurred beneath the harrat, leading to damage in the nearby town of Al Ays. Recent studies (e.g. Pallister et al., 2010) have indicated that these swarms are associated with magma that has risen to shallow levels beneath Harrat Lunayyir, potentially increasing the likelihood of a volcanic eruption.

Little is known about the crustal and upper mantle structure of this region, making characterization of the seismic-volcanic hazard more difficult. We propose to investigate the velocity structure beneath Harrat Lunayyir using seismic travel-time tomography. In this method, absolute and relative travel-times from local and regional earthquakes are inverted for improved event relocations and models of seismic velocity structure. These details will allow us to delineate magmatic features and seismic structures within the harrat, thereby giving us considerable information about the three-dimensional structure.

Much of the data for this analysis will come from the network of broadband seismic stations installed in the Lunayyir region by the Saudi Geological Survey (SGS) in early May 2009. These data will be supplemented by that from additional broadband and short-period stations throughout the region. It is estimated that the seismic velocity models will be completed by spring or early summer 2012, ultimately providing important information necessary to assess the volcanic and seismic hazards within Harrat Lunayyir.

Literature Review and Objectives

Rifting of the Red Sea began about 30 Ma, separating the western edge of the Arabian Plate from Africa (Camp and Roobol, 1992). Several studies have shown that the Red Sea initiated as a passive rift, resulting from large-scale extensional stresses (Wernicke, 1985; Voggenreiter et al., 1988; McGuire and Bohannon, 1989). However, more recent work (Camp and Roobol, 1992; Ebinger and Sleep, 1998; Daradich et al, 2003; Hansen et al., 2006; 2007) has illustrated that the Red Sea has been undergoing active rifting processes within the last 15-20

Ma, where the lithosphere is being thinned by both extension and thermal erosion associated with asthenospheric flow (Fig. 1). Sea-floor spreading is much more developed in the southern Red Sea, while the northern Red Sea appears to be highly extended and intruded continental crust (Girdler and Styles, 1974; Cochran, 1983; Steckler, 1985)

Cenozoic tectonic activity associated with active, mantle flow has led to uplift and volcanism throughout western Arabia, resulting in extensive harrat lava fields that cover an area of about 180,000 km^2 (Fig. 1; Coleman et al., 1983). Volcanism along the Makkah-Medinah-Nafud (MMN) volcanic line, including Harrats Rahat, Khaybar, and Ithnayn, is thought to result from flow directed along a pre-existing flexure in the continental lithosphere, the so-called West Arabian Swell (Camp and Roobol, 1992; Al-Saud, 2008). The NW-orientation of dykes (Zahran et al., 2002; Johnson, 2006), the N-S and NW-SE alignment of vents in the volcanic fields (Coleman et al., 1983; Camp and Roobol, 1989; 1992; Roobol, 2009), and patterns of seismic anisotropy (Hansen et al., 2007) are also consistent with this interpretation, indicating that the modern stress field in the crust of northwestern Arabia primarily reflects mantle flow dynamics.

Beneath Harrat Lunayyir (Figs. 1-2), asthenospheric flow has also led to considerable volcanic and geothermal activity. It is estimated that at least twenty-one different eruptions have occurred in western Arabia over the past 1500 years (Camp et al., 1987), including one near Harrat Lunayyir about 1000 years ago. More recently, groundwater temperatures up to 32ºC were measured in this region, and local farmers have reported rising steam in many locations on cold winter mornings.

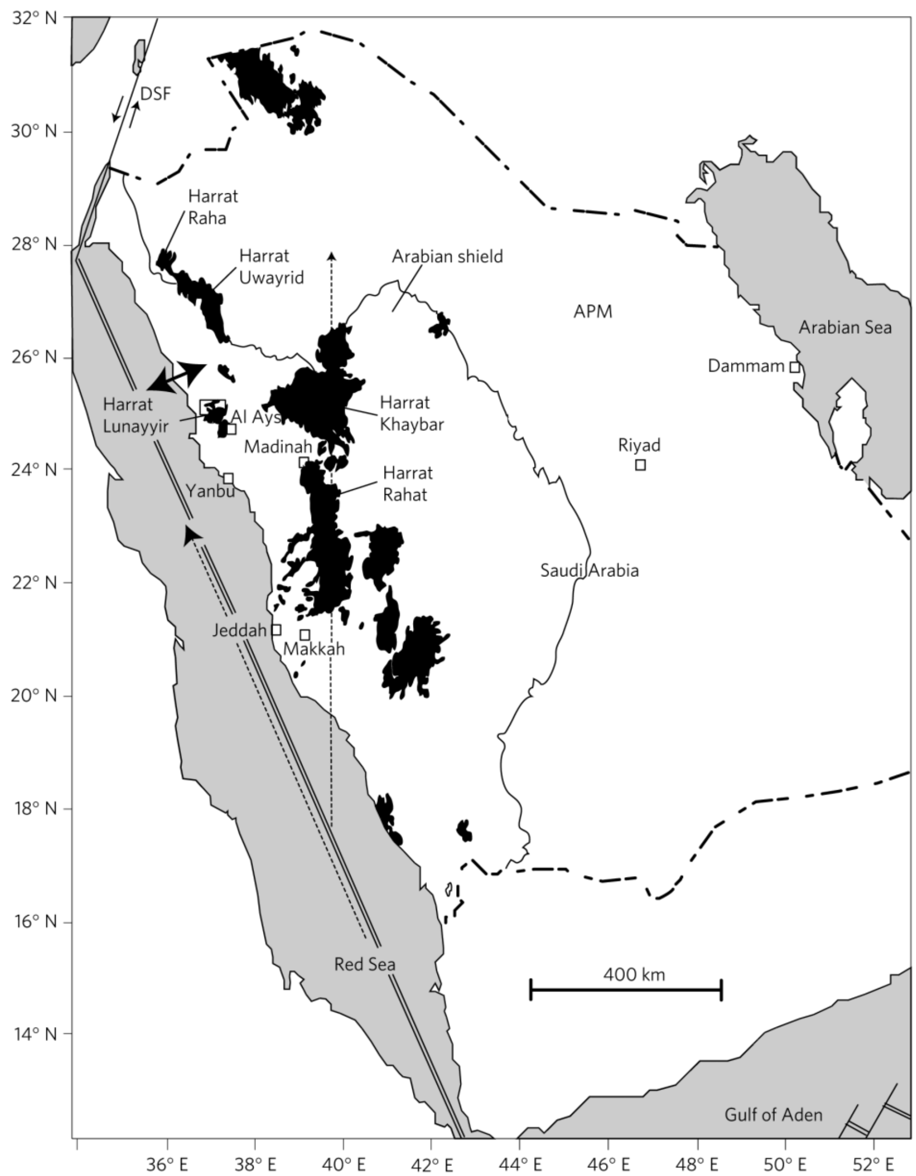

Figure 1. Map of harrat lava fields (black) within Saudi Arabia. Double lines indicate spreading axes in the southern Red Sea and Gulf of Aden (and the axis of crustal extension in the northern Red Sea). Dotted vectors show inferred asthenospheric flow directions. Harrat Lunayyir is denoted with the small rectangle. DSF: Dead Sea Fault. Taken from Pallister et al. (2010).

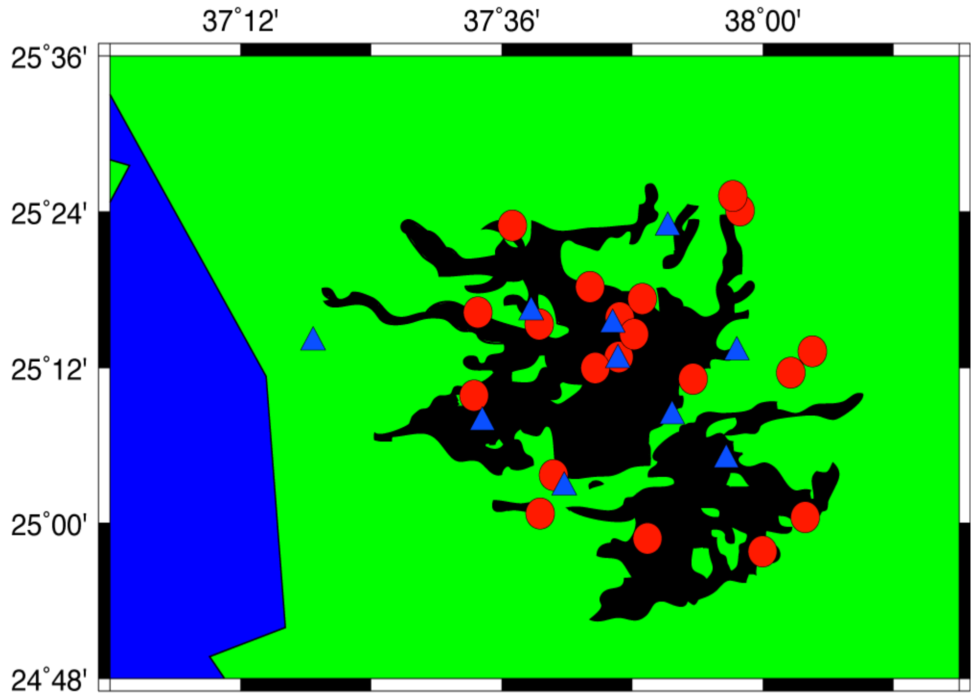

Figure 2. Map of Harrat Lunayyir (black) with regional broadband (blue triangles) and short-period (red circles) seismic stations (Table 1). Regional stations YNBS and YOBS are outside the plotted area of the map.

The Harrat Lunayyir region is also associated with significant seismic activity. In October 2007, a swarm of earthquakes began on the eastern edge of the harrat, north of Yanbu. The epicenters formed two adjacent clusters oriented NE-SW, similar to the trend of transform faults that cross the Red Sea (Fig. 3). In April-June 2009, another swarm of more than 30,000 earthquakes occurred beneath Harrat Lunayyir, leading to minor damage in the town of Al Ays. A mixture of both high-frequency and very low-frequency earthquakes was observed (Pallister et al., 2010), consistent with volcanic intrusion. Low-frequency earthquakes are generally associated with the movement of fluids (magma, water, or gas) while high-frequency earthquakes are associated with brittle fracture of the rigid, surrounding rocks. The 2009 earthquake swarm was also accompanied by an 8-km-long, NW-trending surface rupture that propagated across the northern section of the harrat. Pallister et al. (2010) concluded that the orientation of this fault rupture, along with their InSAR-modelled dyke intrusion, indicate that crustal stress in the region is controlled by asthenospheric flow away from the Red Sea rift axis as opposed to channelized flow along the West Arabian Swell. This may reflect different, complex rifting mechanisms associated with the northern section of the Red Sea.

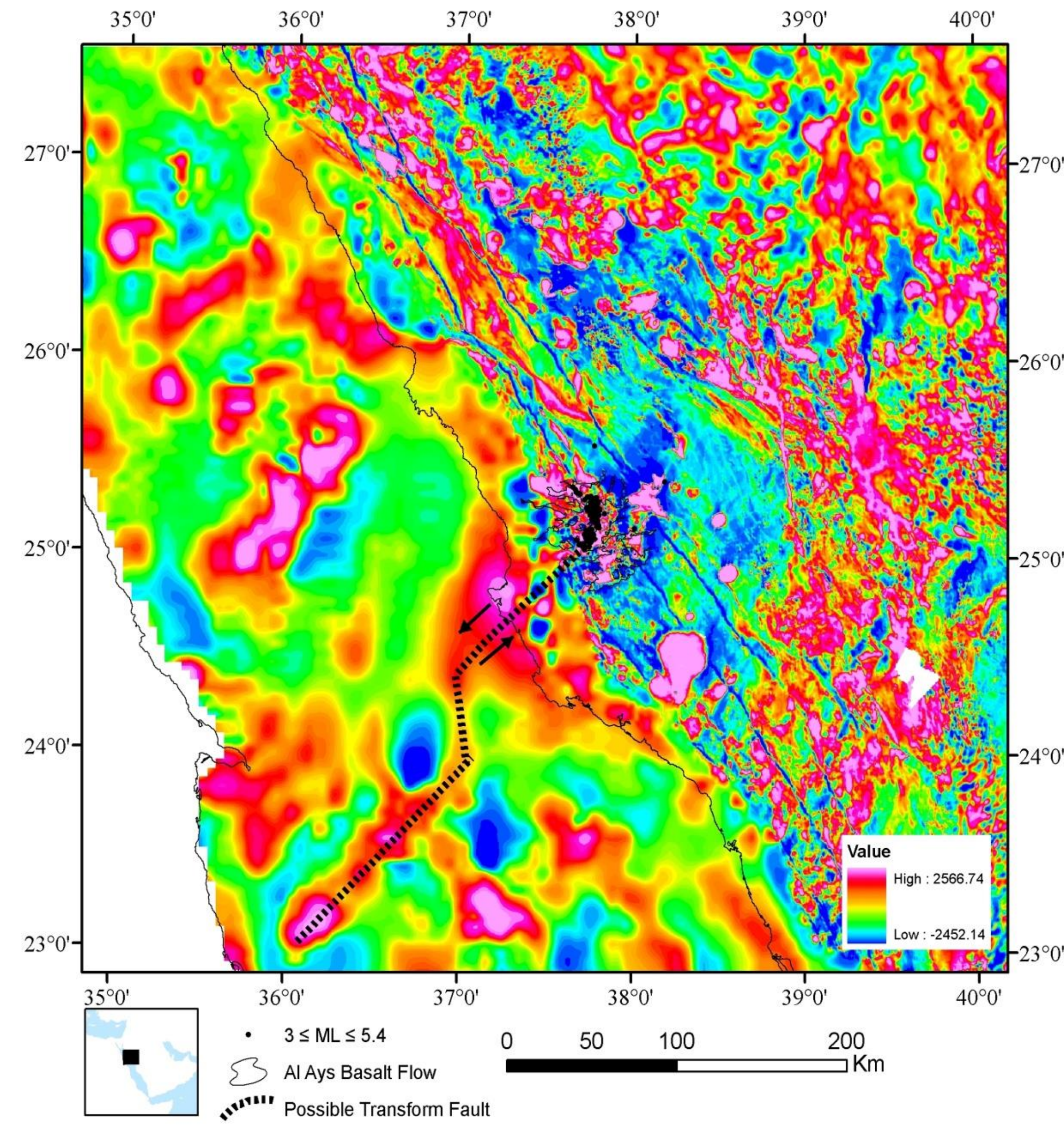

Fig. 3 Aeromagnetic map showing the relation between the epicentral distribution , tectonic features, and locations of the faults inferred from the offset of magnetic. Alignment of epicenters and the northeast trending faults near latitudes 24.5° N could indicate that this fault extends northeastward on land.

It has been suggested that magma has risen to shallow levels beneath Harrat Lunayyir (Pallister et al., 2010), potentially increasing the likelihood of a volcanic eruption. Past eruptions here are generally characterized as "Hawaiian-style" eruptions, with slow-moving lava and only moderate amounts of ash (Camp and Roobol, 1989; Camp et al., 1991). Additionally, no significant hydrologic basin is present near the vent area; therefore, the associated risk of volcanic hazard is considered to be fairly low. However, seismic activity associated with the movement of magma through the subsurface poses a significant threat to surrounding areas. Volcanic-seismic swarms in the future may lead to additional damaging earthquakes. Better characterization of the Harrat Lunayyir region is necessary to improve our understanding of the tectonic characteristics associated with rifting in the northern Red Sea and to provide necessary details to assess the hazard implications in this area.

Methodology

We propose to investigate the crustal and upper mantle velocity structure beneath Harrat Lunayyir using body wave travel-time tomography. A number of different earthquake tomography packages are available, such as SIMULPS (Thurber, 1983; Thurber and Eberhart-Phillips, 1999; Hansen et al., 2004) and tomoDD (Zhang and Thurber, 2003; Pesicek et al., 2010), which invert absolute and relative travel-times from local and regional earthquakes for improved event relocations and models of seismic velocity structure. Seismic velocity in a given region depends on the rock characteristics, such as porosity, fracturing, and fluid saturation, and its physical condition, such as temperature and pressure. In volcanic environments, such as Harrat Lunayyir, the presents of fluids, cracks, and gas can also change the elastic properties

(Mavko, 1980; Sato et al., 1989; Sanders et al., 1995). Figure 4 shows an example from Kilauea Volcano in Hawaii, where Hansen et al. (2004) used the travel-time tomography approach to relocate seismic events and determine the velocity structure beneath the South Flank of the volcano. In Harrat Lunayyir, tomographic velocity variations determined with this approach will allow us to differentiate between the slow seismic velocities associated with magmatic features and the fast seismic velocities in the surrounding regions, thereby giving us considerable information about the three-dimensional structure. Additionally, the accurate earthquake locations determined as part of the tomographic analysis will help delineate the seismic structures within the harrat.

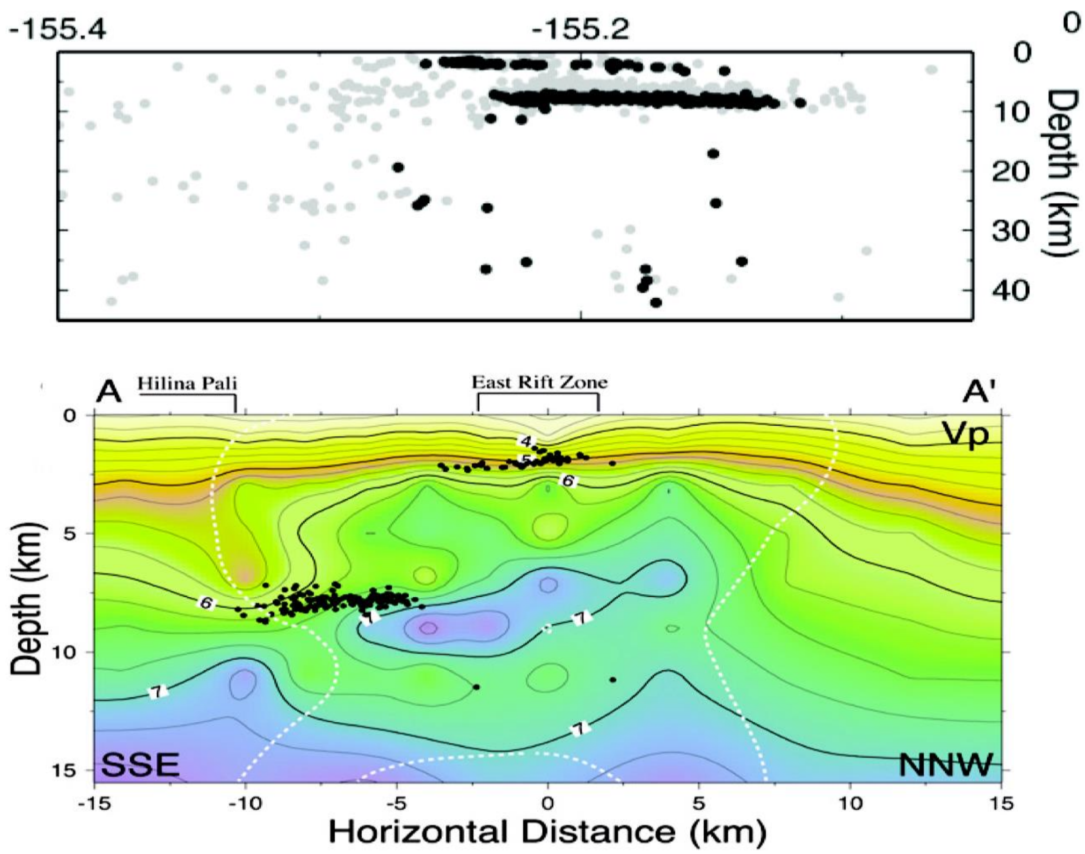

Figure 4. (Top) Initial (gray dots) and final (black dots) earthquake locations and (bottom) P-wave velocity structure beneath the South Flank of Kilauea Volcano, Hawaii, determined using the SIMULPS tomographic inversion method. Taken from Hansen et al. (2004).

Data for the harrat analysis will be collected from three regional broadband stations (YOBS, YNBS, and UMJS) as well as seven permanent broadband seismometers that were deployed by the SGS in the Lunayyir region immediately following the start of the 2009 seismic swarm. Additionally, data from two temporary networks operated by the King Abdulaziz City of Science and Technology (KACST) and King Saud University (KSU) will also be included (Fig. 2 and Table 1). The KACST network consists of 10 short-period, single component seismic stations and one broadband station while the KSU network consists of eight short-period seismic stations. Broadband stations were equipped with either Streckeisen STS-2 or Trillium 120 seismometers while short-period stations were equipped with SS-1 Ranger seismometers. All stations acquired data with a sampling rate of 300 sps.

Preliminary analysis of almost 5000 earthquakes, ranging in magnitude from 0.43 to 5.4, has been performed to acquire initial hypocentral locations. Figure 5 shows 1050 aftershocks that occurred between May 20 and June 19, 2009, following a large mainshock event on May 19, 2009. It appears that the aftershocks originally extended along a NE-SW trend, but later changed to a NW-SE orientation. Most events seem to be constrained to depths between 5-25 km.

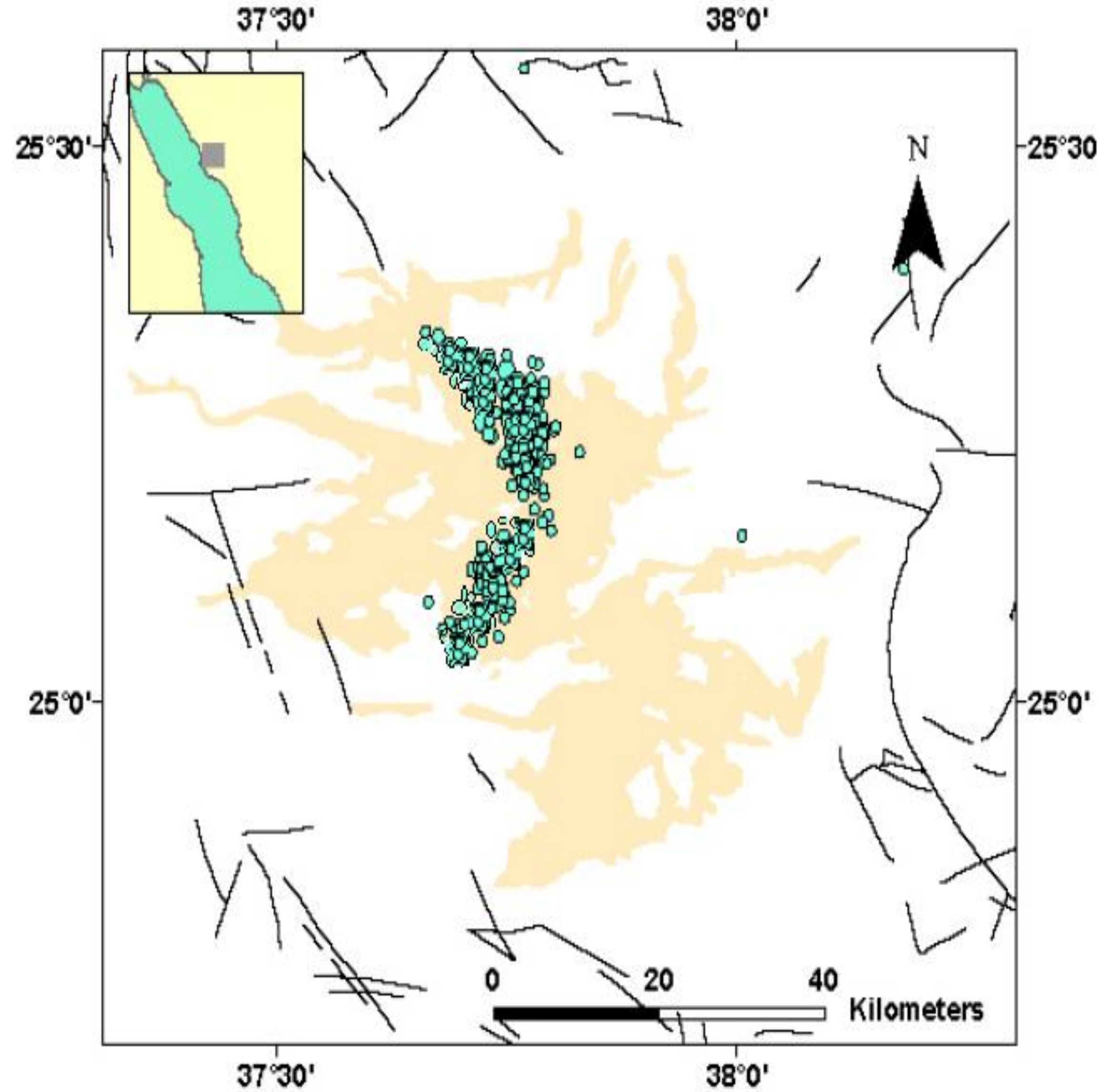

Figure 5. Aftershocks from May 20 to June 19, 2009, within Harrat Lunayyir.

Table 1. Station coordinates and sensor types.

Station Code	**Latitude**	**Longitude**	**Sensor Type**
LNYS	25.0815	37.9439	Trillium 120
LNY1	25.22	37.96	Trillium 120
LNY2	25.1378	37.861	Trillium 120
LNY3	25.3799	37.8543	Trillium 120
LNY4	25.2716	37.645	Trillium 120
LNY5	25.046	37.6953	Trillium 120
LNY6	25.2098	37.7781	Trillium 120
LNY7	25.1296	37.5699	Trillium 120
YOBS	24.3578	38.7424	Trillium 120
YNBS	24.33956	37.99391	STS-2
UMJS	25.23229	37.31092	Trillium 120
STN01	25.2554	37.7698	STS-2
STN02	25.0618	37.6792	SS-1
STN03	25.1851	37.8929	SS-1
STN04	25.2640	37.7805	SS-1
STN05	25.1637	37.5574	SS-1
STN06	25.1934	38.0424	SS-1
STN07	25.4015	37.9651	SS-1
STN08	25.3823	37.6161	SS-1
STN09	24.9631	37.9994	SS-1
STN10	25.0120	37.6592	SS-1
STN11	25.2877	37.8155	SS-1
STN12	25.2708	37.5637	SS-1
STN13	25.0072	38.0650	SS-1
STN14	24.9802	37.8231	SS-1
STN15	25.2204	38.0755	SS-1
STN16	25.4202	37.9542	SS-1
KSU01	25.2134	37.7794	SS-1
KSU02	25.2423	37.8026	SS-1
KSU03	25.3030	37.7355	SS-1
KSU04	25.255	37.6571	SS-1
KSU05	25.1989	37.6743	SS-1

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