Investigating Potential Geothermal Resources in Western Saudi Arabia

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Abstract. Saudi Arabia offers a strong potential for geothermal energy, but only a limited amount of exploration efforts have taken place. We are conducting a preliminary, low-cost, reconnaissance level evaluation of the volcanic area based on mapped geology and existing passive seismic data. Particular focus is on identifying areas with possible shallow magma chambers by looking for micro-seismicity, anomalous attenuation, and low velocities. The emphasis is on the Harrat Rahat volcanic area in western Saudi Arabia. The goal is to test the procedure and identify areas for future, more intensive study.

We have processed a year of data from four stations of the Saudi Geological Survey within the Harrat Rahat using an autonomous correlation detection framework developed by LLNL and Deschutes Signal Processing LLC. This process has discovered around 20 groups of repeating events in the neighborhood of the Harrat. It appears that most of the events are surface explosions. However, we performed a more detailed correlation operation on one group of events that appears to be natural. This secondary detection analysis resulted in discovery of a brief swarm of 13 events near the northern edge of the Harrat, but probably outside the Harrat.

Method

We will conduct a two-part strategy: first, identify geologic regions with high geothermal potential, and second, use low-cost regional geophysical exploration to attempt to refine the mapping and develop maps. This type of evaluation is important in evaluating ‘district’ level prospects, such as Harrat Rahat, especially where surface expression of geothermal energy is limited. Traditional geothermal exploration often uses intensive focus on specific areas using heat flow measurements and techniques such as MT to identify high-conductivity zones typical of geothermal prospects. This type of exploration is useful, but impractical on a large-scale without extensive time and resources. Therefore, we begin with low-cost exploration using existing available data sets: geologic mapping and seismic data. Sites of known geothermal significance, such as fumeroles, will also be included in the analysis.

Geologic & Geophysical Maps

The first dataset are detailed maps of Harrat Rahat and other Harrats compiled by Camp [e.g. *Camp et al*., 1987; *Camp and Roobol*, 1991]. These maps show the vents and distinct basaltic flows as well as structural features. By using these maps we will identify the most recent vents and areas of possible fracturing for enhanced permeability.

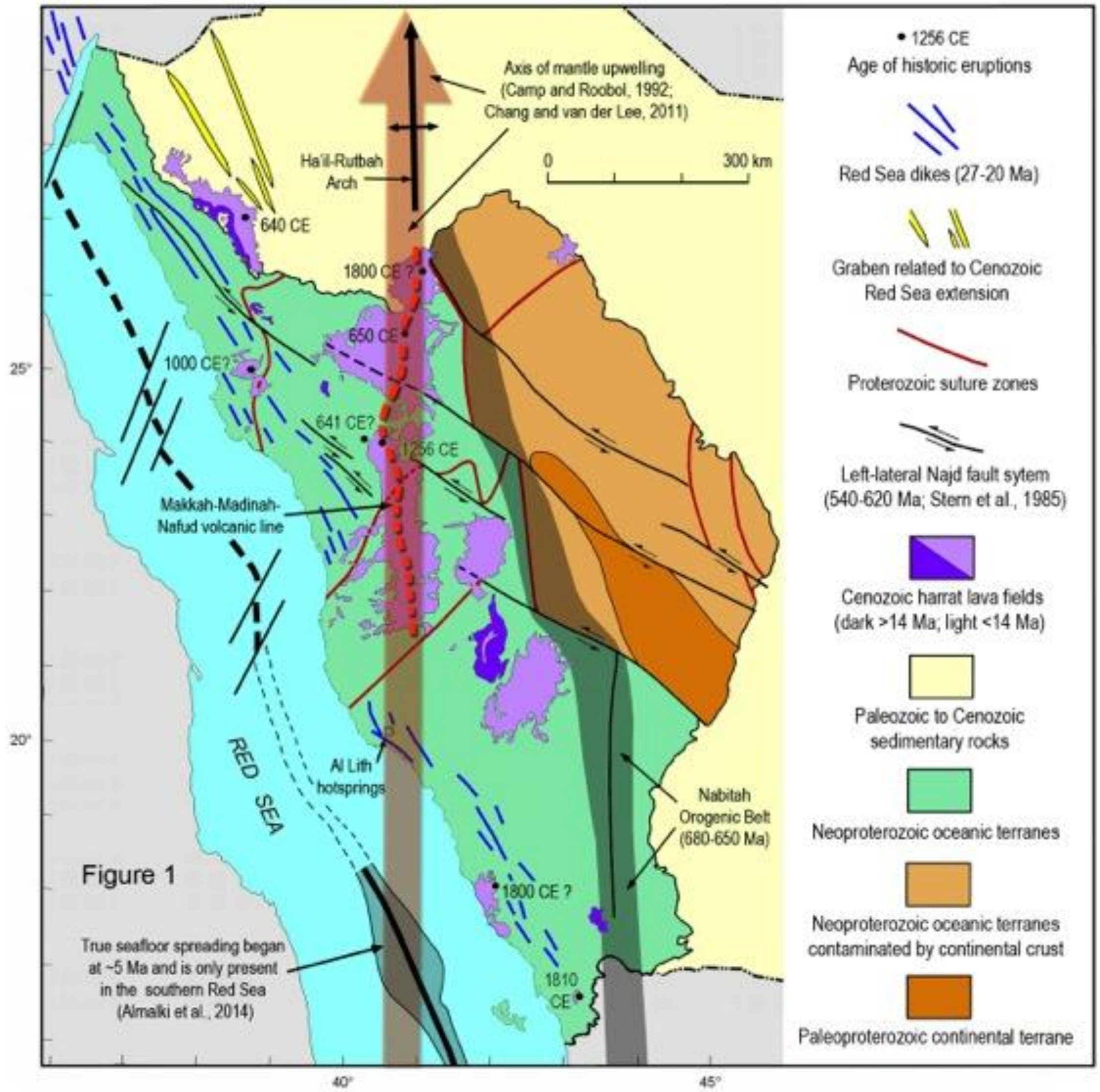


Figure 1. Regional map of tectonic, lithostratigraphic, and magmatic features of western Saudi Arabia. Note axis of volcanic activity that diverges from the trend of the Red Sea. The axis intersects a series of north-west trending faults and presumed zones of weakness that may control magmatic activity and enhance shallow permeability below the volcanic cover.

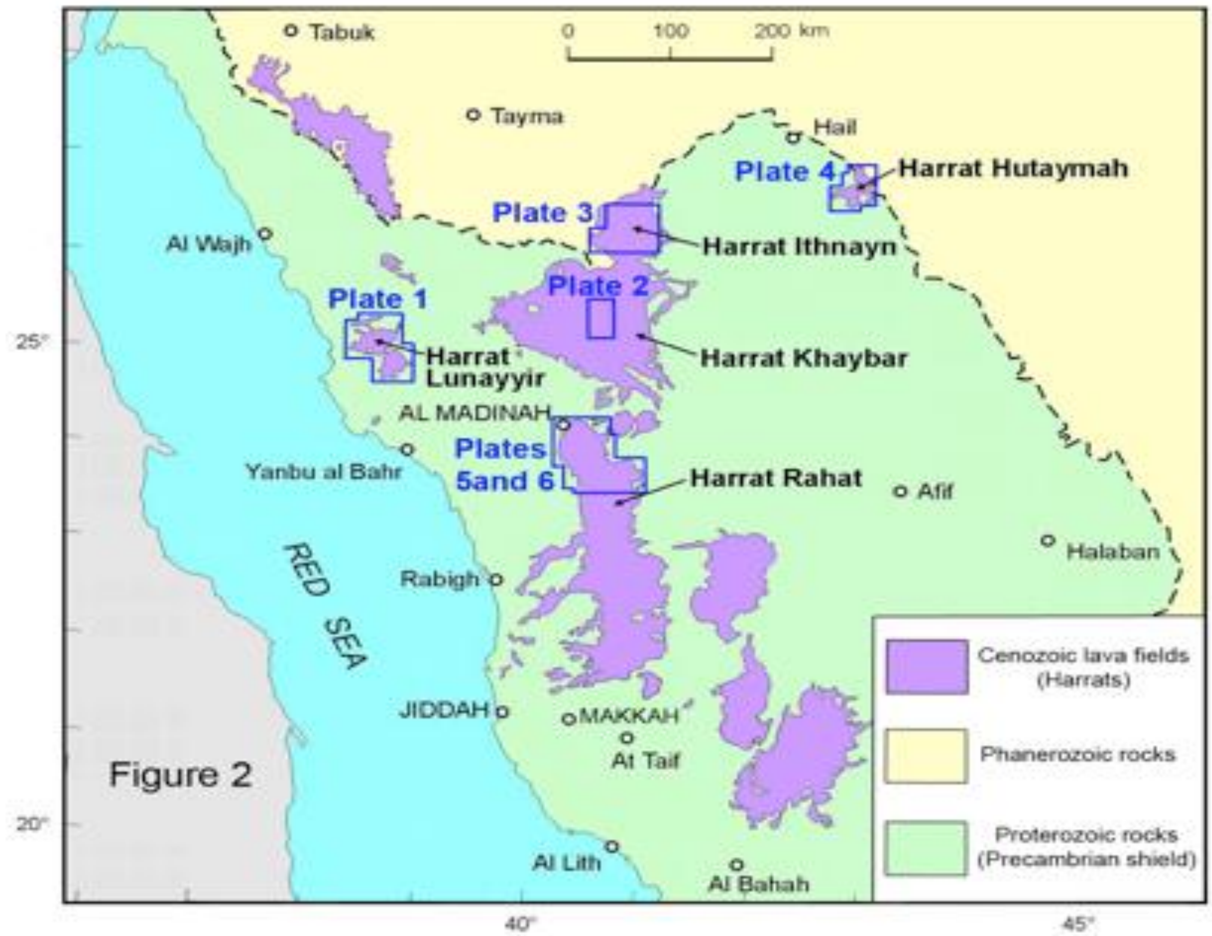


Figure 2. Index map showing harrat study areas that have geothermal potential, and the location of detailed plates 1-6, which are map compilations of volcanic features associated with their central vent systems.

Plate 1

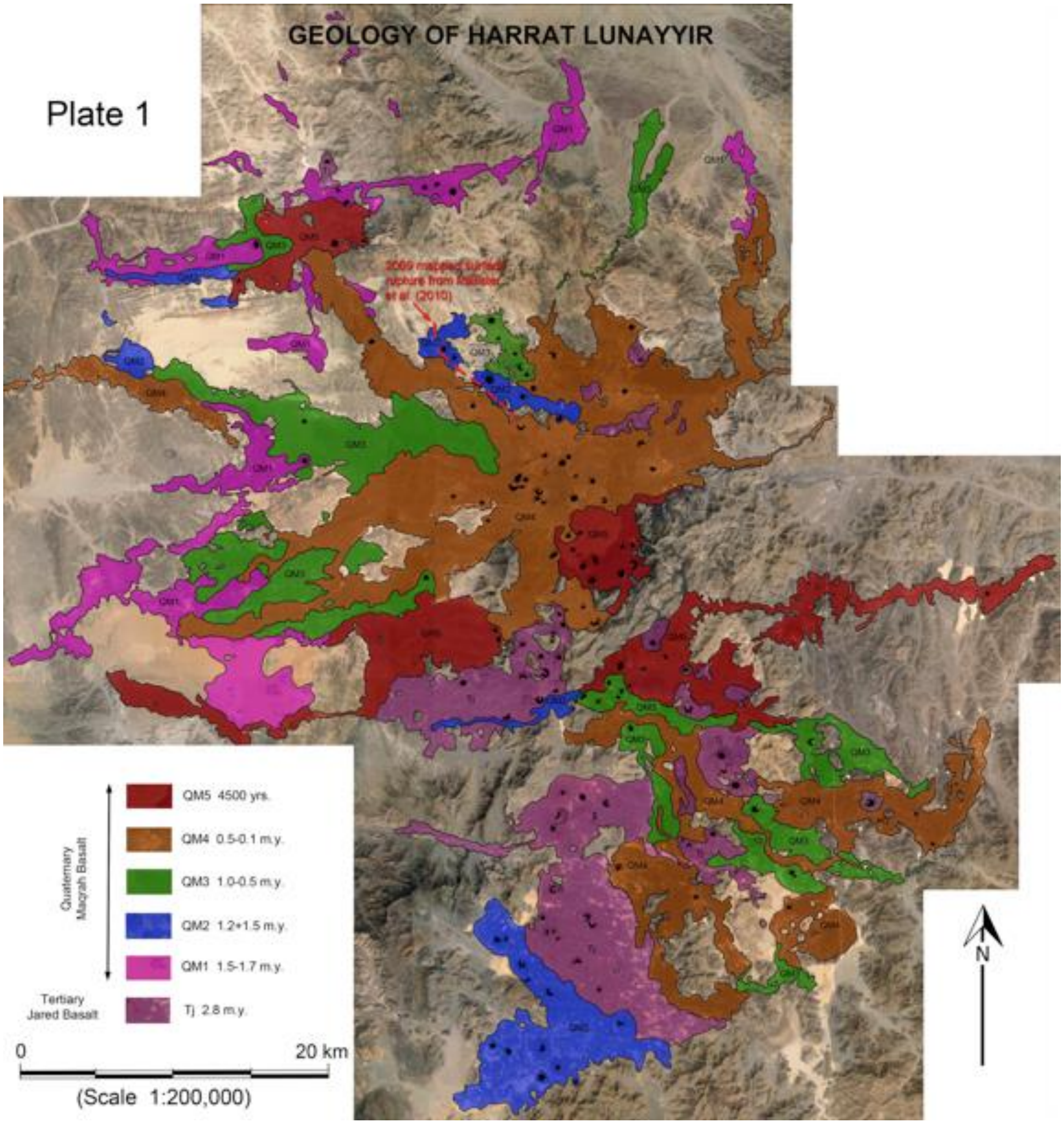

GEOLOGY OF HARRAT LUNAYYIR
QM5 4500 yrs.
QM4 0.5-0.1 m.y.
QM3 1.0-0.5 m.y.
QM2 1.2+1.5 m.y.
QM1 1.5-1.7 m.y.
Tj 2.8 m.y.
Quaternary Maqrah Basalt
Tertiary Jared Basalt
0
20 km
(Scale 1:200,000)
N

Plate 2

GEOLOGY OF THE CENTRAL VENT AREA OF HARRAT KHAYBAR

Upper Abyad Basalt

- Qb7/Qb7t, historic lavas (Qb7) and airfall tuff (Qb7t)
- Qb6, ~4500 B.P.
- Qb5
- Qb4

Lower Abyad Basalt

- Qb3
- Qb2
- Qb1

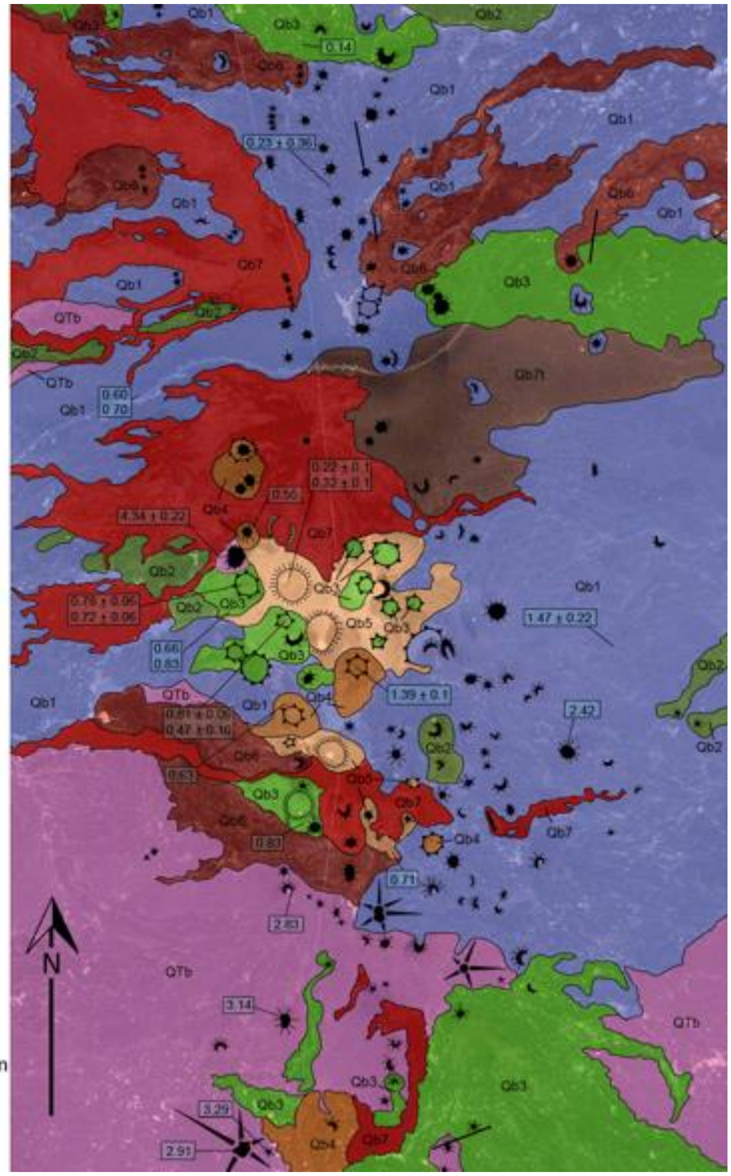
- QTb, Mukrash and Jared basalt of Roobol and Camp (1991); > 1 Ma

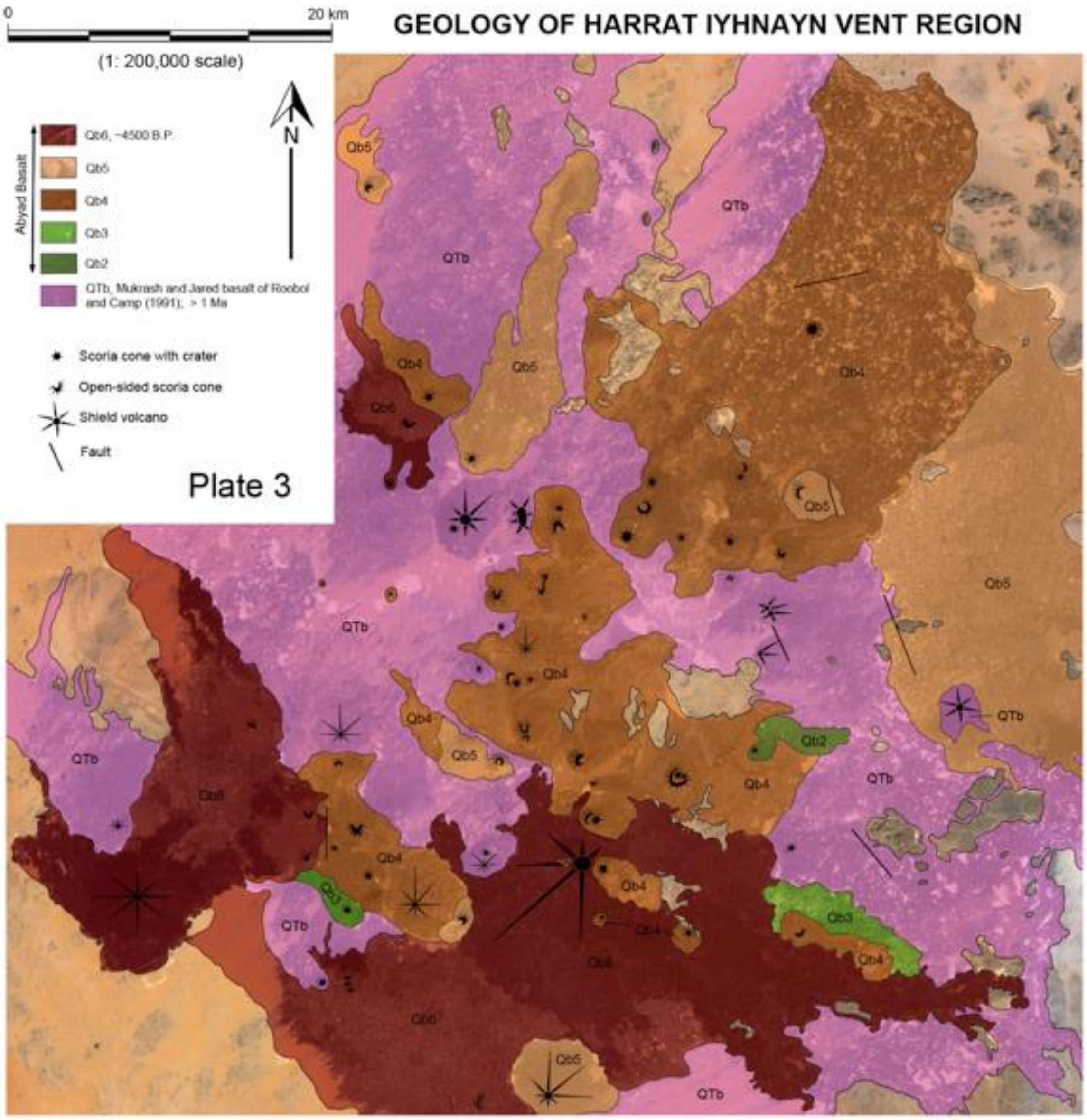
- Scoria cone with crater
- Open-sided scoria cone
- Lava dome
- Tuff ring
- Fault

4.34 ± 0.22 K-Ar age compiled from a variety of sources in Roobol and Camp (1991)

0 — 20 km

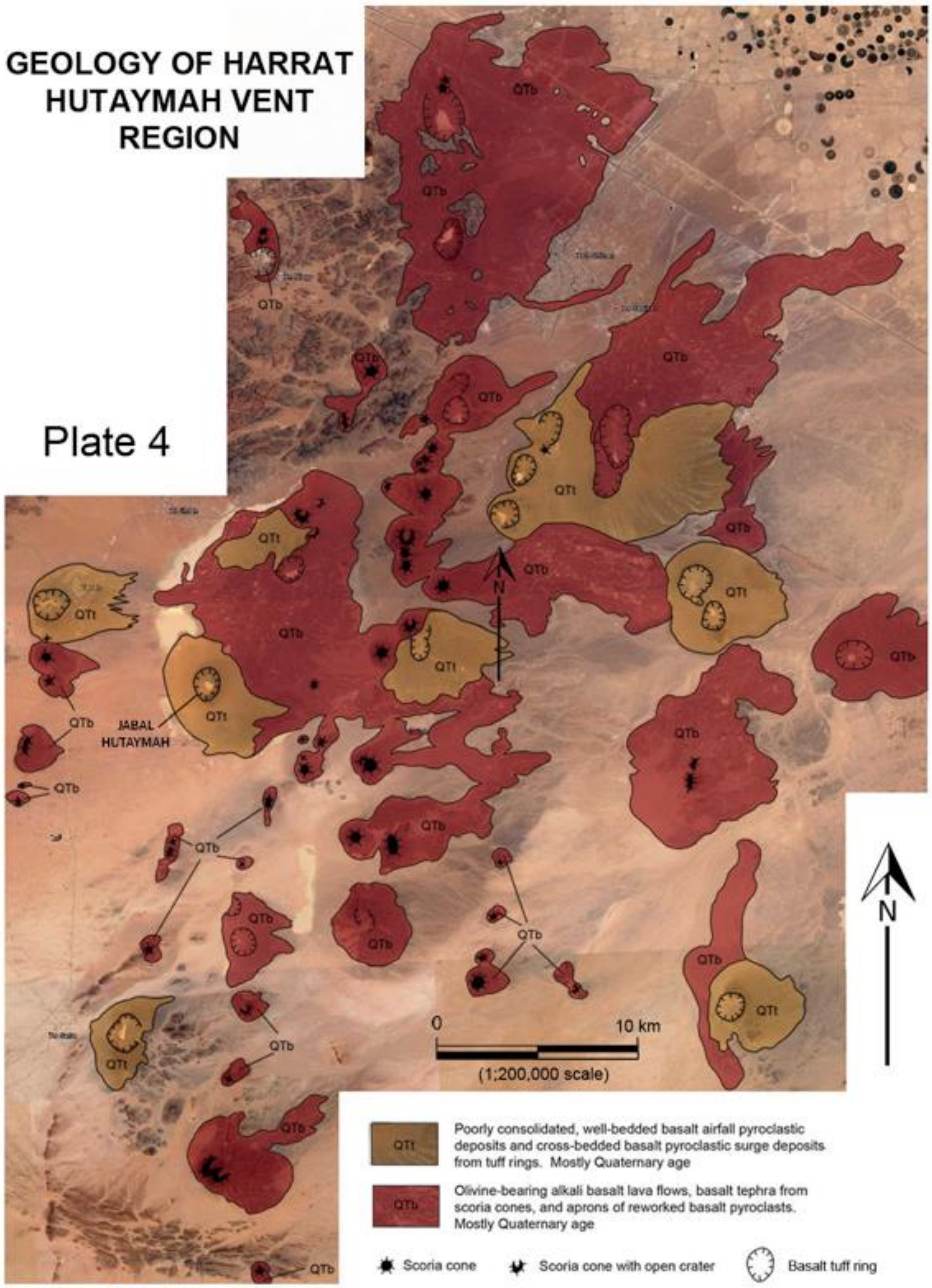
(1: 200,000 scale)



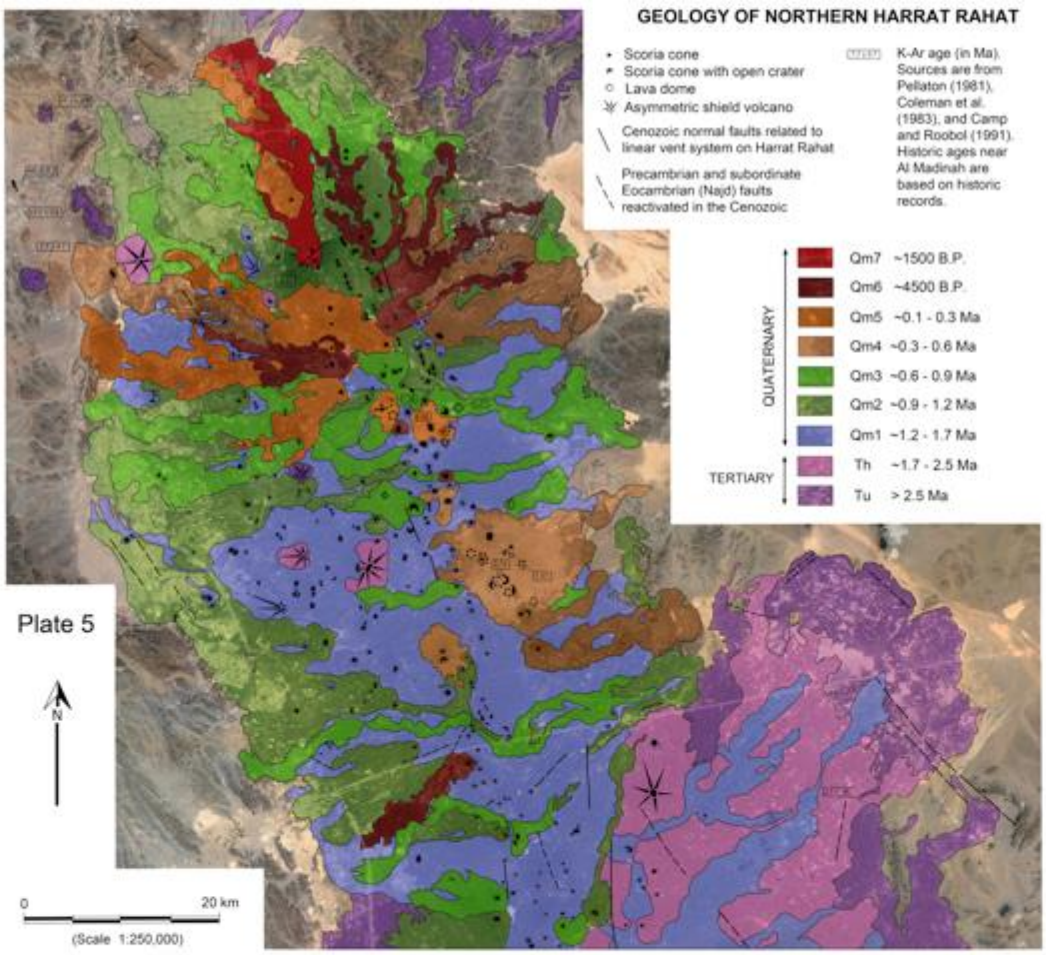

GEOLOGY OF HARRAT IYHNAYN VENT REGION
0
20 km
(1: 200,000 scale)
N
Abyad Basalt
Qb6, ~4500 B.P.
Qb5
Qb4
Qb3
Qb2
QTb, Mukrash and Jared basalt of Roobol and Camp (1991); > 1 Ma
Scoria cone with crater
Open-sided scoria cone
Shield volcano
Fault
Plate 3

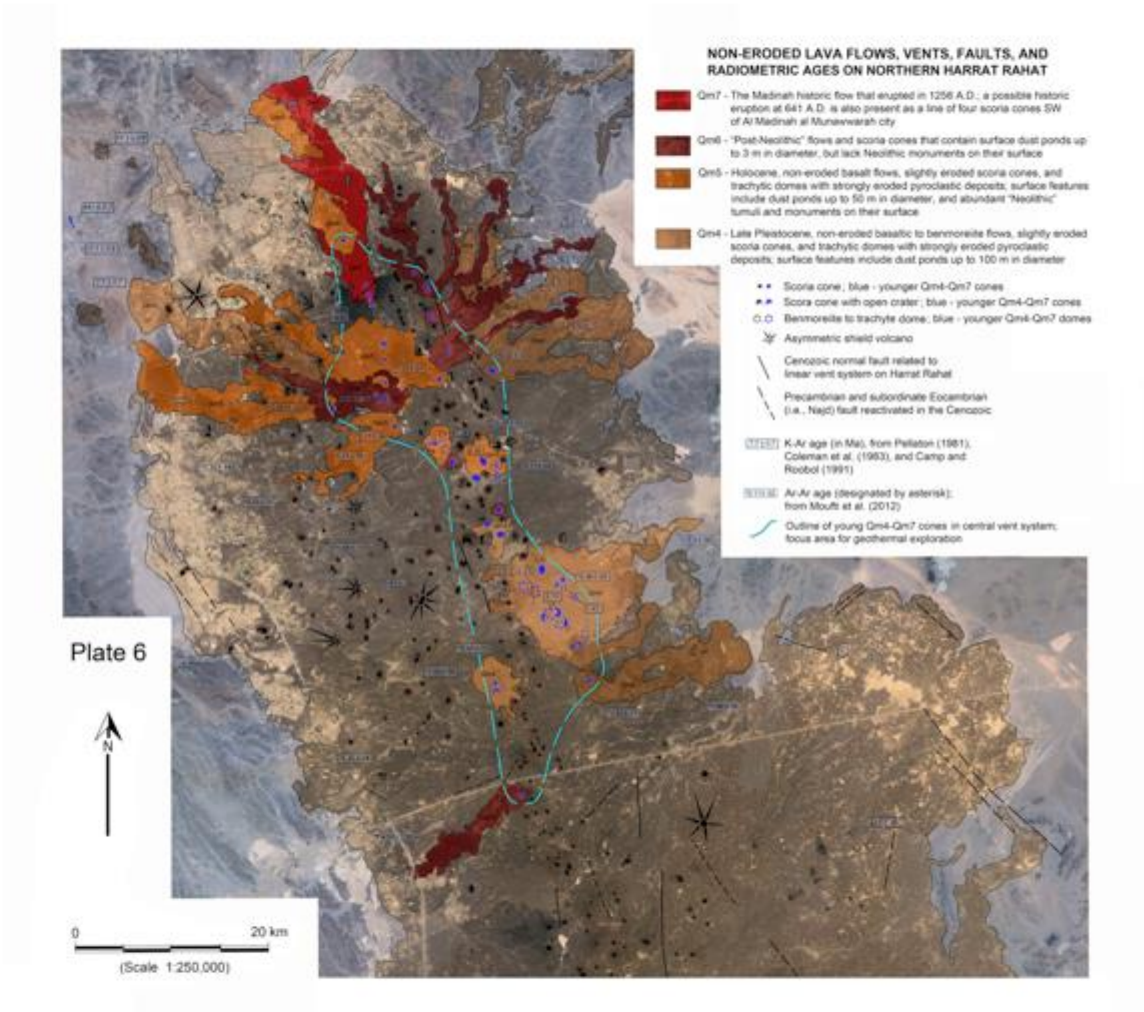
GEOLOGY OF HARRAT HUTAYMAH VENT REGION

Plate 4



Plates 1-4. These plates examine the volcanic geology of vent regions from Harrat Lunayyir (Plate 1; modified after Al-Amri et al., 2012), Harrat Khaybar (Plate 2; modified after Roobol and Camp 1991), Harrat Ithnayn (Plate 3; modified after Roobol and Camp, 1991), and Harrat Hutaymah (Plate 4; modified after Thornber, 1990). All of these harrats contain common Quaternary lava flows, many of which are Holocene in age. Two of these harrats (Khaybar and Hutaymah) are notable in containing abundant, young phreatomagmatic tuff rings, indicating the availability of water from sub-surface sources. Shallow sub-surface water bodies in such areas of known Holocene eruptions indicate a strong potential for the central vent regions of Harrats Khaybar and Hutaymah to host viable geothermal sources. There is no indication that such sources underlie Harrats Lunayyir or Ithnayn; however, both of these harrats show evidence of very young Holocene activity. In fact, the entire volcanic history at Harrat Lunayyir may be less than 600 ka (Duncan and Al-Amri, 2013), with the most recent event being a near eruption between April and June, 2009 (Pallister et al., 2010). Although Harrats Lunayyir and Ithnayn lack any clear evidence for presence of significant subsurface meteoric water, the very young age of volcanism on these harrats suggest that their central vent systems may be areas of high heat flow but low fluid flow that could be rendered geothermally viable through the creation of exploitation of enhanced geothermal systems (EGS).


GEOLOGY OF NORTHERN HARRAT RAHAT
Scoria cone
Scoria cone with open crater
Lava dome
Asymmetric shield volcano
Cenozoic normal faults related to linear vent system on Harrat Rahat
Precambrian and subordinate Eocambrian (Najd) faults reactivated in the Cenozoic
K-Ar age (in Ma). Sources are from Pellaton (1981), Coleman et al. (1983), and Camp and Roobol (1991). Historic ages near Al Madinah are based on historic records.
QUATERNARY
Qm7 ~1500 B.P.
Qm6 ~4500 B.P.
Qm5 ~0.1 - 0.3 Ma
Qm4 ~0.3 - 0.6 Ma
Qm3 ~0.6 - 0.9 Ma
Qm2 ~0.9 - 1.2 Ma
Qm1 ~1.2 - 1.7 Ma
TERTIARY
Th ~1.7 - 2.5 Ma
Tu > 2.5 Ma
Plate 5
N
0
20 km
(Scale 1:250,000)



Plates 5-6. These plates examine the volcanic geology of northern Harrat Rahat, the main focus of geothermal investigation. Plate 5 is a compilation map of the main lithostratigraphic units comprising the harrat, the location of geochronological data, vent locations, and vent types in this portion of the harrat, modified from Camp and Roobol (1991), with additional geochronological data from Moufti et al. (2012). Plate 6 displays the same vent locations and vent types, but highlights only the youngest, non-eroded flows of upper Madinah Basalt (Qm4-Qm7) defined by Camp and Roobol (1991). The youngest unit (Qm7) is historic in age and includes the only two historic eruptions in Saudi Arabia for which eyewitness accounts exist: the 1256 AD eruption southeast of Al Madinah (Camp et al., 1987; El-Masry et al, 2013), and a small eruption in 641 AD expressed as four small pyroclastic cones located in the southwest corner of Al-Madinah City (Murcia et al., 2014). Subunit Qm6 is considered post-Neolithic in age because the lavas lack abundant Neolithic burial mounds that characterize the upper surface of other flows. These burial mounds appear to have a ^{14}C ages between 7,000 and 4,500 years B.P (Kaiser et al., 1973). However, McClure (1978) notes that the Neolithic pluvial period ceased on the Arabian Peninsula at ~6000 years B.P with the onset of a hyper-arid climate. We therefore believe that all of the units of Qm6 are at least as young as 6000

years B.P., and possibly younger than 4500 years B.P. Since this time, there have been 13 post-Neolithic and historic eruptions on northern Harrat Rahat. If we assume that all are younger than 4,500 years, the average eruption rate since that time has been one per 346 years.

Eroded vents older than Qm4 are spread across a wide region of northern Harrat Rahat. However, all of the young non-eroded vents (Qm4-Qm7), denoted in blue in Plate 6, lie within a distinct northwest-trending linear axis in the central part of the harrat, the only exception being the 641 A.D eruption SW of Al-Madinah. The geologic data suggest that this central area should be the focus of geothermal exploration.

Conceptual Model Development

We will base our conceptual model on an analog geothermal field based on geologic setting. A close analog of possible geothermal prospects of the western Saudi harrats is the geothermal plant at Las Tres Virgenes in Baja California, which produces about 10 Mw from granitic fractured rocks below volcanic cover [*Hernandez et al.*, 1995]. The tectonic setting is very similar, as both Las Tres Virgines and the Saudi Harrats lie on the edges of an extension rift system. For Las Tres Virgines, it is the Gulf of California rift which is roughly analogous to the Red Sea rift. Tres Virgines is a Holocene set of volcanoes that occur at the intersection of faults in a granitic basement.

The heat source for Tres Virgines is likely derived from a magma chamber. The surface expression was primarily fumeroles but the location was the site of micro-seismicity prior to geothermal development and showed anomalies in attenuation and Vp/Vs ratio [*Wong et al.*, 2001; *Wong and Munguia*, 2007]. Permeability appears related to the intersection of faults in the basement and characterized by active seismicity, even prior to the installation of the geothermal plant. Also, like western Saudi Arabia, Baja California is arid, with low rainfall. Therefore, for the potential Saudi resource we seek a shallow magma chamber that is near mapped faults and with active micro-seismicity.

The geothermal plant itself consists of two 5 Mw flash units and power is supplied to nearby cities. For Harrat Rahat, potential use is in the nearby cities of Medina (to the north) and Mecca and Taif (to the south). This reduces the need for extensive power lines. The major uncertainty is the availability of sufficient water. However, it might be possible to use recycled water from the cities as injection water, as it done at the Geysers geothermal field in California using recycled water from the city of Santa Rosa, which is sent to the Geysers field via a 50 km long pipeline.

Table 1. Historical eruptions of some Harrats in Western Arabia

Harrat	Recent eruptions	Sub-surface water	Proximity to cities
Lunayyir	2009* AD	?	50-100 km
Khaybar	Holocene	Yes	50-100 km
Hutaymah	Holocene	Yes	50-100 km
Ithnayn	Holocene	?	100-150 km
Rahat	641, 1256 AD	?	Close

Passive Seismic Data

The second dataset is passive seismic data collected by local and regional seismic networks. Previously, passive seismic data has been used to identify geothermal resources [e.g. *Foulger*, 1982]. Several geothermal areas have been characterized using this method. *Wilson and Jones* [2003; 2004] used passive seismic data to identify magma chambers under the Coso geothermal field in California, USA. *Zucca et al*, 1994 used attenuation to examine the Geysers field, also in California. *Wong et al*., [2001; 2006] also used attenuation at the Tres Vırgenes Volcanic Area, which, as mentioned previously, is a volcanic area that is similar in setting to the harrats and which now has a 10 MW geothermal plant. More recent studies use novel techniques such as ambient noise tomography to map the Lake Toba magma chamber in Indonesia [*Stankiewicz et al*., 2010] and *Muksin et al*., [2013], also in Indonesia, identified variations in Vp/Vs using local earthquakes associated with a geothermal field. Similar investigations [*Koulakov et al*., 2015; *Hansen et al*., 2013) in Saudi Arabia have identified anomalies associated with possible magma chambers at Harrat Lunnayir, although not for the purpose of finding geothermal energy.

While passive seismic data can be used to infer velocity or attenuation structures through tomography with seismic event travel-time or phase amplitude measurements or ambient noise correlation measurements, it also can be used to search for microseismicity possibly associated with fluid motion in volcanic centers. We have begun our exploration of the data obtained from the Saudi Geologic Survey network surrounding the Harrat Rahat with a search for microseismicity. Our working assumption is that microseismicity associated with a volcanic field will be repetitive, possibly being driven by fluid flow within a relatively static system of conduits. Consequently, we use an autonomous correlation detection framework [Harris and Dodge, 2011; Dodge and Harris, 2015] designed to discover the occurrence of repetitive transients in a continuous data stream from a network of stations.

We performed an initial search of one year of data (July 2013 – July 2014) at the four central stations of the network (RHT14, RHT01, RHT15, RHT04; Figure 3) in a fairly low frequency band (2-10 Hz) intending to detect somewhat larger events over the whole study region. This step results in a number (around 20) of groups of related events in the study region. We attempt to screen out groups of explosions, which are common in this region, to focus on natural seismicity.

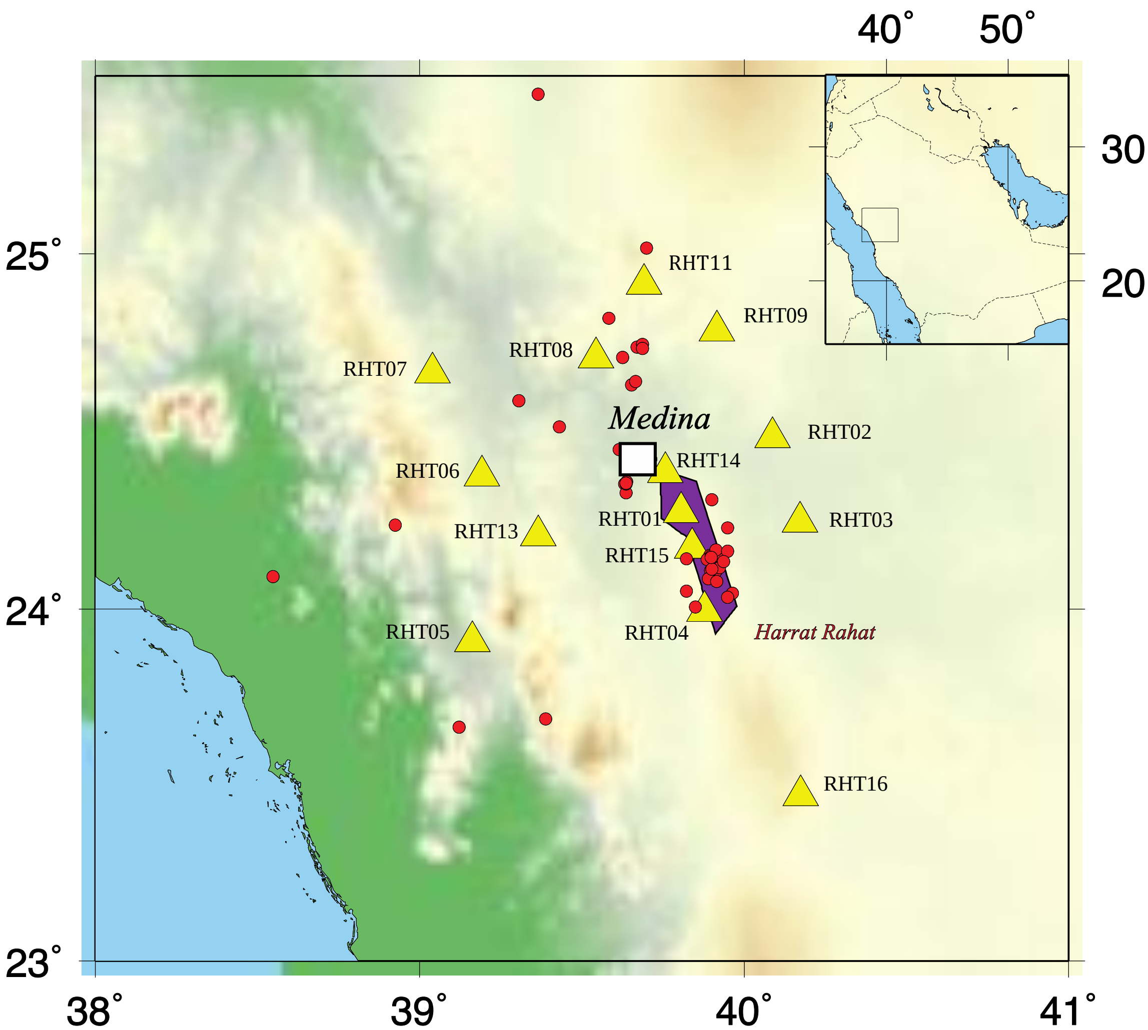


Figure 3. Map of seismic stations (yellow triangles), earthquakes from the period 2004-2005 (red circles), the central area of Harrat Rahat deemed most prospective (purple), and the city of Medina.

For those event groups which appear to arise from natural sources, we perform a second correlation detection step, processing the data at the best-observing station in a higher frequency band (4-20 Hz). The objective of this step is to reduce the detection threshold to find a larger number of repetitive natural events.

Detection Framework

A simplified diagram of the autonomous system is shown in Figure 4.

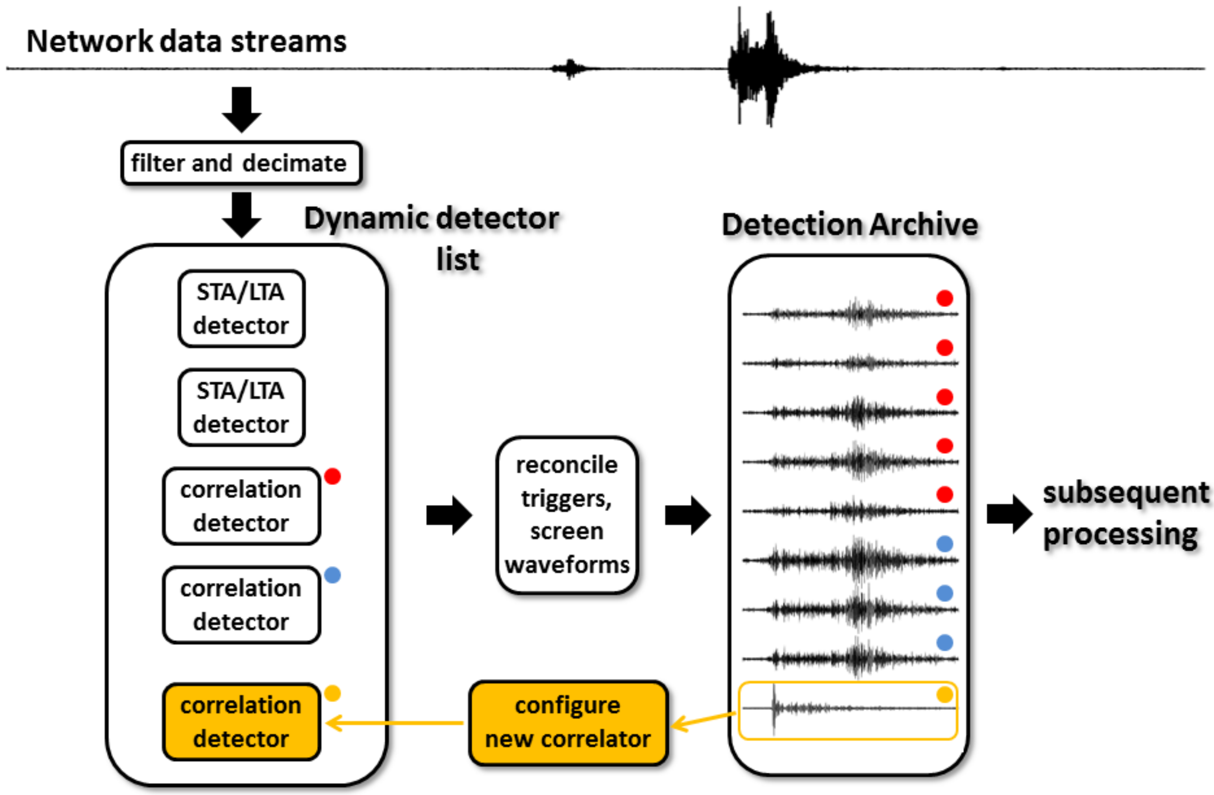


Figure 4. Simplified block diagram of autonomous correlation detection framework used to process the RHT data.

The system operates by maintaining a dynamic list of detectors, which process network stream data in consecutive, contiguous blocks. For each block, each detector in the list calculates a detection statistic, which is scanned for excursions above a pre-set threshold. Upon initiation of a run, the detector list is populated just by one or several power detectors. As the system processes the data, the power detectors trigger on waveforms which are screened by a set of measurements and rules intended to cast out triggers on noise bursts, dropouts and spikes. Waveforms which pass these tests are used as templates for correlation detectors. The correlation detectors are created and added to the detector list, then immediately begin detection operations along with the power detectors.

When several detectors trigger simultaneously on the same signal, as often happens, a set of rules determines which trigger will be considered to be the system-wide detection. The rules are simple: correlation detector triggers always take precedence over power detector triggers, and for triggers on two or more detectors of the same type, the detector with the largest detection statistic takes precedence over the other detectors. Detections are logged to an archive, retaining information on the originating detector, the value of the detection statistic, the detection time, and measurements of waveform characteristics. The system naturally sorts events into groups determined by a common correlation detector. It is for this reason that the autonomous detection framework is ideally suited to search for repetitive events in swarms associated with volcanic sources.

Results of Framework Processing

The table below summarizes the number of detectors created by the autonomous system for each of the four stations, the number of detectors that had multiple detections, and the number of detectors developed on local events based on visual inspection of the event waveforms.

Station	Number of detectors created	Number of multiplet detectors	Number of local event detectors
RHT01	370	45	13
RHT04	2290	40	9
RHT14	486	9	3
RHT15	572	22	5

Station RHT01 was the top performer in producing detectors constructed from local events, and, thereby, in producing large numbers of local event detections. However, most of the detections appeared to be surface explosions. One group of events was very likely to be a pair of earthquakes (Figure 5). These events were selected for the second correlation detection step. We refer to them as a group by the identification number (673576) assigned by the autonomous system to the detector that found them.

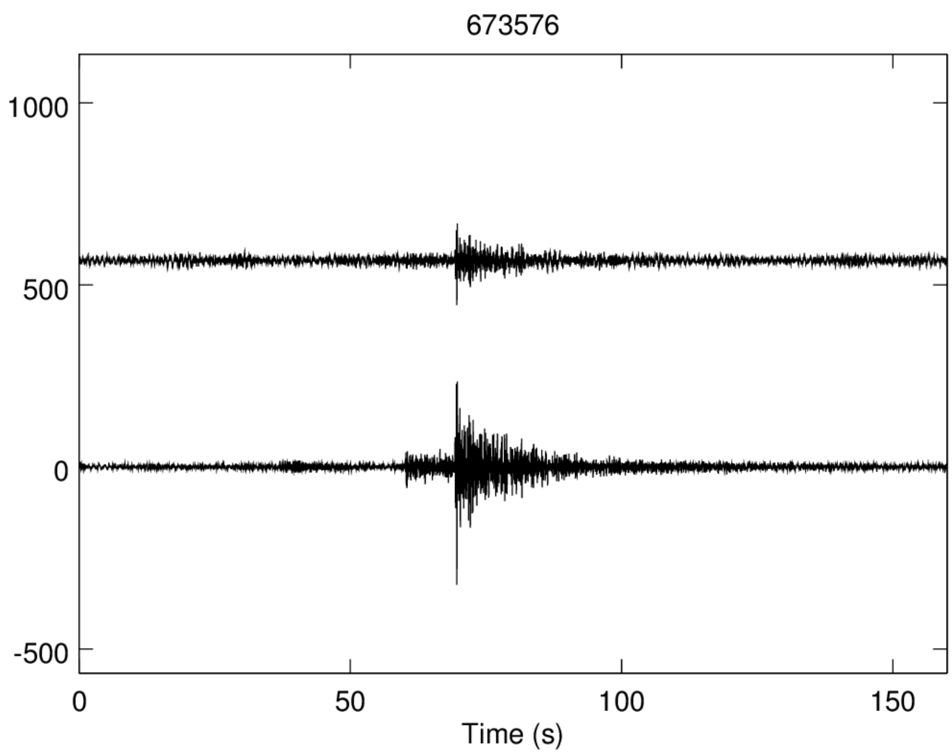


Figure 5. Local earthquakes selected for a second pass of correlation detection.

Figure 6 shows the waveforms for all vertical-component sensors in the network for the first of the two detector 673576 events.

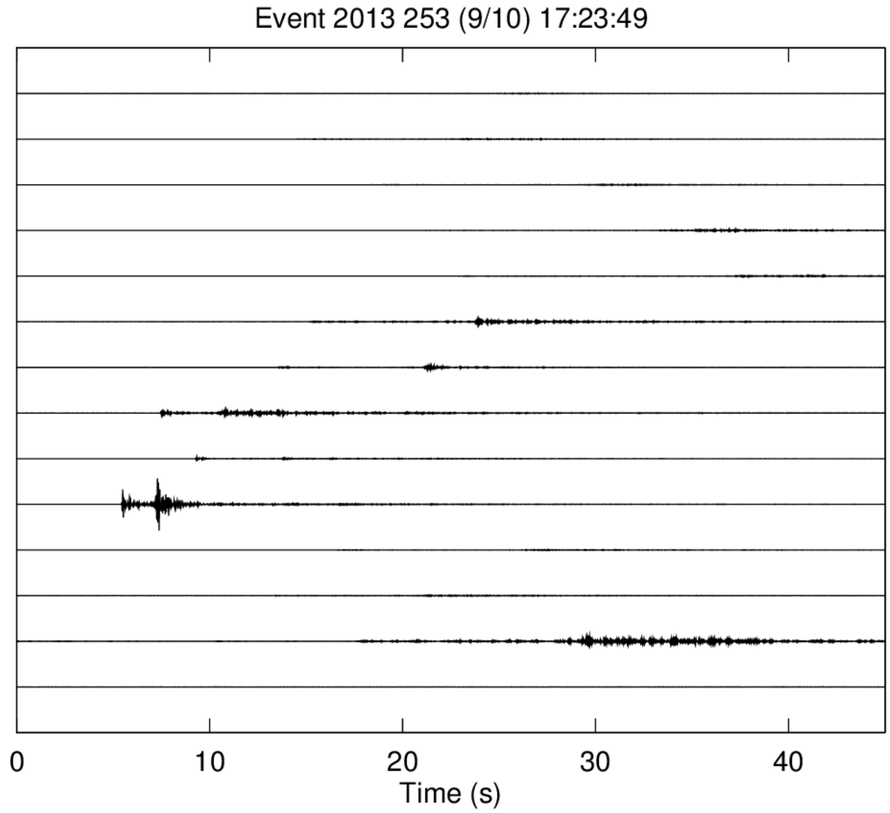


Figure 6. Vertical-component waveforms from all stations of the network for the first event in the 673576 pair. The large waveform (10th trace) is the recording at station RHT11. This station is closest to the source and was selected for high-frequency correlation processing.

We configured a subspace detector [Harris, 2006], a type of generalized correlation detector, to operate on the three channels of station RHT11, using the detector 673576 event pair to construct a rank-one detector. The detection statistic produced by the subspace detector in the high-frequency band (4-20 Hz) is shown in Figure 7. This detection statistic produced twelve valid event detections, which are displayed in Figure 8. Most of the events are quite small, with corresponding low SNR signals. These smaller events are properly considered to be microseismic, since they were detected only at station RHT11.

The events of Figure 8 are events of the correct size that we seek to understand volcanic processes in the Harrat Rahat. These particular events occurred to the north of the Harrat, and, therefore, may not be associated with volcanic processes. However, the process of discovery developed here will be applied to additional event groups in an effort to find microseismicity in the target region shown in Figure 3. The procedure was successful in finding events of the right type, if not in the high-interest location.

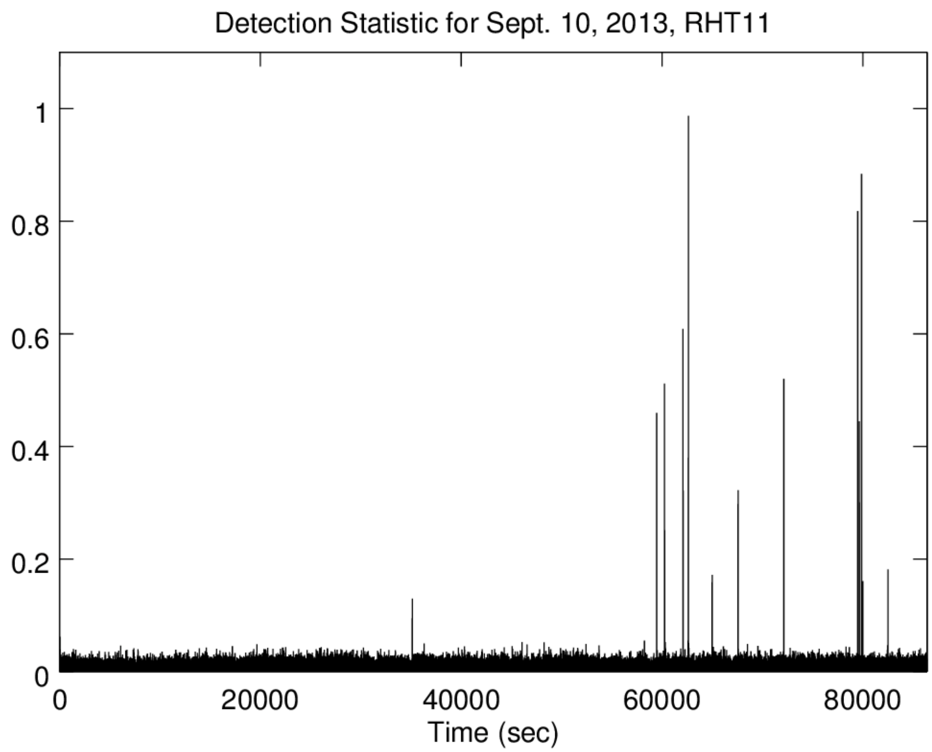


Figure 7. Detection statistic produced by the subspace detector constructed from the large events of Figure 5. Twelve valid event detections resulted in this time period, with an additional detection on 10/24/2013 (corresponding to the second large event of Figure 5). Many of these events are much smaller than the two large design events and would properly be considered microseismicity.

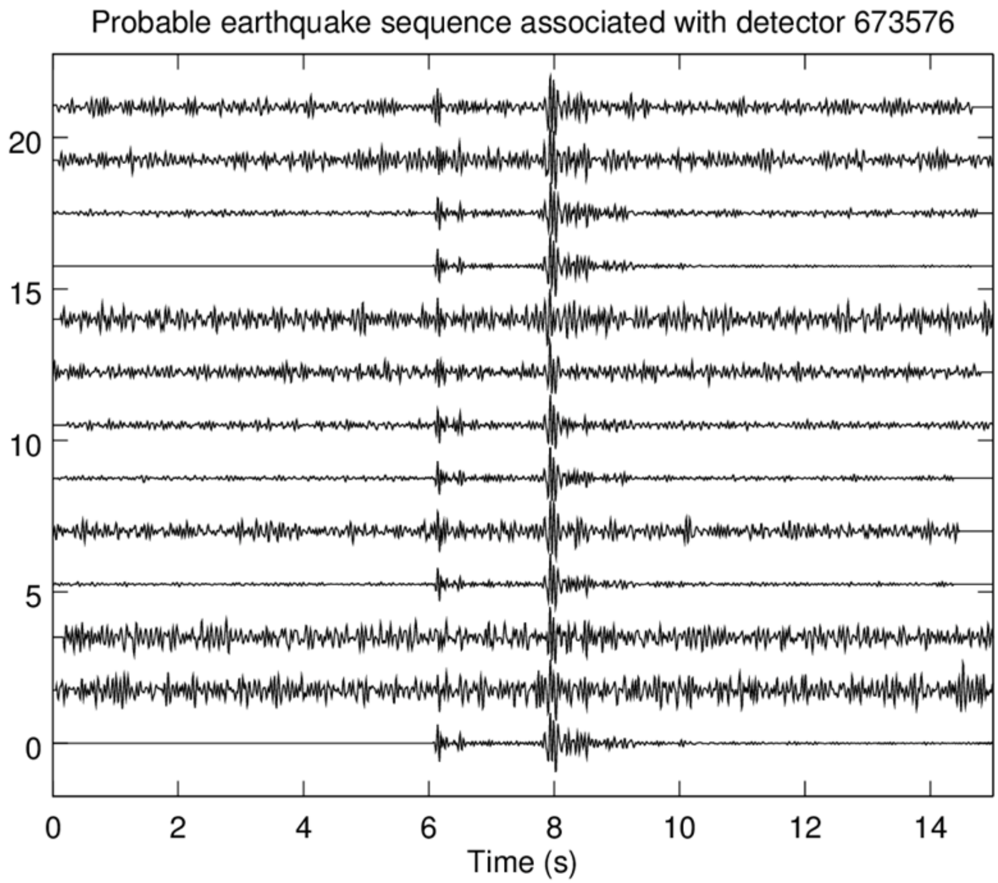


Figure 8. The collection of vertical-component event waveforms found in the RHT11 continuous stream by the high-frequency subspace detector. The events clearly are highly repetitive, consistent with a small source region.

Discussion & Conclusions

Most of the harrat volcanic fields erupted from northerly trending linear vent systems that lie oblique to nearly all basement trends. There is no evidence of prevailing east-west extension in the western Arabian Shield. It therefore seems unlikely that these north-trending vent systems are structurally controlled, and more likely that they result from magmatic stress and forceful dike injection controlled by a sublithospheric process. The north-trending Nabitah orogenic belt forms the eastern boundary of the harrat province and may well reflect a major lithospheric boundary where thicker continental lithosphere provides a barrier to sublithospheric mantle flow, allowing basaltic lavas to rise into thinner, denser lithosphere of the western arc terranes.

The main zone of mantle upwelling beneath the harrats appears to be reflected in the Makkah-Madinah-Nafud volcanic line, a linear system of vents that extends in a northerly direction over a distance of ~600 km (Camp and Roobol, 1992). This volcanic line marks the main eruption sites for Harrats Rahat, Khaybar and Ithnayn. Petrologic data suggest that this feature delineates the axis of mantle upwelling with lavas along its length generated by higher degrees of partial melting when compared to the harrat lavas lying farther to the west and east (Camp and Roobol, 1992). This main axis of upwelling is consistent with seismic tomography that has resolved alarge north-south prong of hot mantle with an axis coincident with the Makkah-Madinah-Nafud volcanic line (Chang and van der Lee, 2011; Chang et al., 2011).

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We therefore believe that all of the units of Qm6 are at least as young as 6000 years B.P., and possibly younger than 4500 years B.P. Since this time, there have been 13 post-Neolithic and historic eruptions on northern Harrat Rahat. If we assume that all are younger than 4,500 years, the average eruption rate since that time has been one per 346 years.

Eroded vents older than Qm4 are spread across a wide region of northern Harrat Rahat. However, all of the young non-eroded vents (Qm4-Qm7), denoted in blue in Plate 6, lie within a distinct northwest-trending linear axis in the central part of the harrat, the only exception being the 641 A.D eruption SW of Al-Madinah. The geologic data suggest that this central area should be the focus of geothermal exploration.
In addition, we processed a year of data from thirteen stations within and near the Harrat Rahat using sensitive correlation detection software developed by LLNL and Deschutes Signal Processing LLC. After removing redundant groups, this process found 29 groups of repeating events, 22 of which appear to be in the neighborhood of the Harrat. It appears that most of the events are surface explosions. However, of the 22 groups local to the Harrat, it appears that 7 are small groups of possible natural events based upon earthquake-like waveform and population characteristics. Our more detailed correlation operation on one of these groups of events resulted in discovery of a brief swarm of 13 events near the northern edge of the Harrat.

Ambient noise tomography indicates that the entire Harrat is underlain by a region of low velocity and likely above average geothermal gradient and that this region may extend north of the highly volcanic region. Based on the elevated temperature and the associated lower velocities, Harrat Rahat is a potential geothermal resource and is a comparable setting to the Tres Virgines geothermal plant in Baja California, Mexico. This plant currently produces 10 MW but is estimated to overlie a resource capable of 40 MW. As Harrat Rahat is a much larger area, the associated resources may be much larger.

A preliminary investigation based on available seismic data showed that advanced detection algorithms could increase the number of detected events and that ambient noise tomography is effective at estimating crustal velocities on a regional scale using only one month of data.

Geology indicates that the volcanism and seismicity roughly correlates with the northerly trending faults, which may be associated with higher permeability, as is the case in Mexico. Work in other areas suggests that intersecting fault are often productive and especially at a high angle. Ideally, areas with dense northerly trending faults intersecting with northeast trending faults would be the preferred areas to investigate further. The flow of groundwater in the region is unknown but it is possible that it flows outward from the slightly higher volcanic. Therefore, areas at the edge may be preferable as well as easier logistically for drilling equipment and power lines.

This investigation could be based on detailed remote sensing combined with spectral analysis to detect zones of surface alteration, which are frequently associated with geothermal fluids.

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