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The Geothermal Potentiality of the Saudi Arabian Volcanic Eruptions 'Harrats': An Overview

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ABSTRACT

The Saudi Arabian volcanic fields or what is called 'Harrats' are young Cenozoic lava that cover approximately 80,000 km^2, mostly along the west coast of the KSA. They consist mainly of basaltic lava that extends along the coastal part of the Red Sea (1,400 km long and 200 km wide) in Western Saudi Arabia. These basaltic lava include 10 major fields, the most important of them are those of the Ithnayn, Khaybar and Rahat fields. In past very, few studies have dealt with these Harrats. The field observations and some previous studies have indicated a good potentiality of these eruptions, where geothermal fumaroles were observed in some spots of these fields. However, a more research and field surveys are needed to decipher the ambiguity of these resources. This article represents an overview of the composition, geological setting and the previous exploration activities of these Harrats, as well as a discussion of its geothermal potentiality and possible energy production.

1. INTRODUCTION

The geothermal resources of Saudi Arabia are mainly concentrated at the western coastal parts represented mainly by wet and hot dry geothermal systems. It can be categorized into four systems: 1) the low-enthalpy resources that are represented mainly by normal geothermal gradient deep-seated aquifers encountered in the thick sedimentary basins in the eastern part of Saudi Arabia. These resources are low grade confined systems and accessed only by deep wells drilled by oil companies, 2) medium-enthalpy hydrothermal systems that are mainly encountered along the western and southwestern coastal parts. It is represented by unconfined shallow hot springs with direct access to hot subsurface anomalies through an open network of active faults and fractures (i.e. Al-Lith and Jizan hot springs). The most important of these hot springs is that called Ain-Al Harrah hot spring located at Al-Lith area, with a surface outlet temperature of more than 95^{o}C, 3) the high-enthalpy volcanic eruptions represented by basaltic lava fields 'Harrats', 4) hot dry rocks represented by high production granite enriched with radioactive minerals (uranium, thorium and potassium). Good examples of these hot dry rocks are those of the Midyan and Haal granites located in the north and north-western part of Saudi Arabia (Lashin and Al-Arifi, 2010; Lashin et al .2015).

The Harrats are young Cenozoic basaltic eruptions that cover approximately 80,000 km^2, mostly along the western coast of the Saudi Arabia. It comprises a 1,400-km-long, 200-km-wide belt of coastal plains, stretched Precambrian crust, escarpment faulting and a passive inland plate boundary under the volcanic Harrats. These basaltic lava fields include 11 major Harrats, i.e., Ithnayan, Khyabar, Rahat, Lunayyir, Al Sirat, Kuraama, Al Buqum, Shama, Al Birk and Raha,. The preferred locations for high-enthalpy power production are the Harrats of Ithnayn, Khaybar and Rahat (Fig. 1). The Harrats of Khaybar and Rahat are believed to have the highest heat flow and enthalpy (Roobol, 1995). These Cenozoic basaltic fields (Harrats) and cinder cones are widely distributed in the western part of Saudia Arabia. Some of these fields are still active and have a possible eruption potential. Historically several records of eruptions has been documented within the Harrats of Saudi Arabia and Yemen (Camp et al., 1987). Being located close to Red Sea, tectonically is thought to be controlled by regional and local tectonics of the Red Sea rifting (Cochran and Martinez, 1988). Therefore, these Harrats fields would be promising areas for geothermal energy potential.

The geothermal activities of Saudi Arabia concerning exploring the hydrothermal systems and the basaltic lava fields have begun long time ago. One of the earliest and good surveys was done by the French BRGM company, where extensive geophysical investigations (seismic and electric) were done at Harrat Khaybar, prior to drilling for geothermal resources (BRGM, 1984). From the period between 1990-2010 an extensive work of the geology, petrography, geochemistry and geomorphology of the Harrats was done by international and local researchers (Camp and Roobol 1992; Roobol et al., 2002; Forti et al., 2004; Forti, 2005; Pint et al., 2004, and Pint 2006). A more recent work has been executed by researchers from Saudi Academia in the last ten years (2010-2019) to investigate the potentiality of the hydrothermal systems and the Harrat fields. The different geothermal systems along the western coastal parts of the Saudi Arabia and the high production granites, as well as the evolution of geothermal systems along the Red Sea in relation to the east African systems were investigated (Lashin and Al Arifi 2010; Hussein et al. 2013; Lashin et al. 2014; Chandrasekharam et al. 2015a,b, 2016a,b and 2018). Regarding the Harrat fields, he most interested work was that done by Koulakov et al. (2014 and 2015), Sychev et al. (2017) and Aboud et al. (2018). It included a combination of geophysical tools using 3D inversion technique of magneto-telluric data, seismic velocity tomography and seismic attenuation tomography. This work represents an overview of the composition, geological setting and the previous exploration activities of these Harrats as obtained from previous results as well as a discussion of its geothermal potentiality and possible energy production.

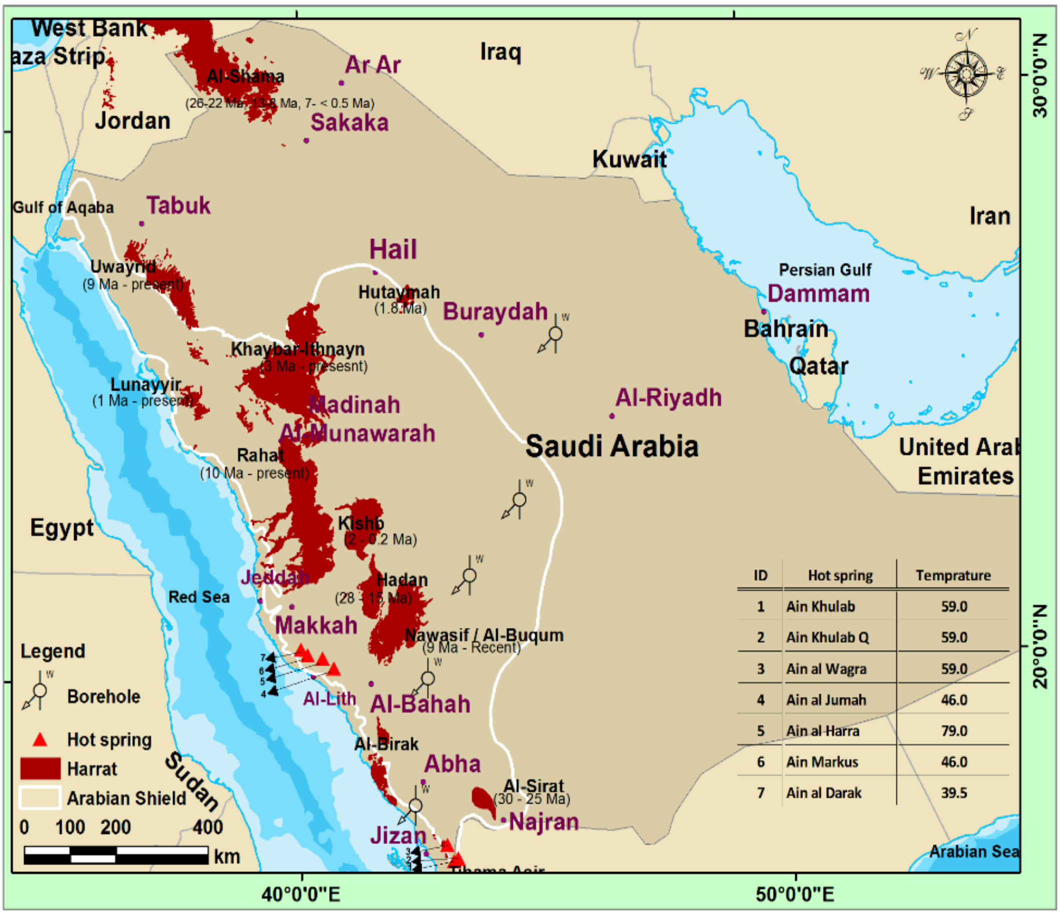

Figure 1: Major geothermal features in Saudi Arabia. Volcanic fields (filled red polygons), hot springs (filled red triangles), heat flow measurements (Gettings 1982).

2. GEOLOGIC SETTING

The western coastal parts of the Arabia Shield of the Saudi Arabia encounter a complex system of geothermal resources due to the tectonic or volcanic activity associated with the opening of the Red Sea/Gulf of the Suez Rift in this area (Camp and Roobol 1992; Lashin, 2007, 2012; Chandrasekharam et al. 2014b, 2015a,b, 2018). Recent geological events resulted in the opening of the Red Sea and the present-day shape of the Arabian shield. The Arabian shield is about 650,000 km2 and constituting part of a larger geologic province known as the Arabian-Nubian shield. Today, the Nubian shield is exposed in eastern Egypt, Eritrea, western Ethiopia, northern Somalia, and Sudan, whereas the Arabian shield is located in western Saudi Arabia and has smaller exposures in southern Levant, southern Jordan, and Yemen. The shield is composed of Proterozoic island arc terranes that were accreted 600-900 Ma, and the basement rocks in this region have little to no sedimentary cover (Fig. 1).

The Arabian shield is slightly metamorphosed and constitutes one of the best-preserved and well-exposed Neoproterozoic assemblages that resulted from the accretion of volcanic arcs. To the east, north, and south, the shield is covered by a thin succession of Phanerozoic sedimentary rocks and is bounded to the west by the Red Sea. At the western parts of the Arabian shield, relatively close to the eastern coast of the Red Sea, a series of young Cenozoic basaltic eruptions 'Harrats' are located scattering along wide area covering approximately 80,000 km2. These volcanic eruptions are composed mainly from alkali-olivine basalt forming many morphological forms of lava tubes, lava flow and near surface channels. The Lava tubes are naturally roofed feeder channels of lava flows within the length of the flow. As a lava flow lengthens during the course of an eruption, the margins of the flow (with the exception of the advancing flow front) cease to flow and a central channel forms in the older part of the flow to feed the advancing flow front. With time, this may become roofed over to form an arterial passage or lava tube. At a late stage in the eruption, usually after the lava supply from the vent has ceased, parts of the lava tube may drain to produce an open like passage or lava tube. Local collapses of the roof along its length provide access. Inside, lava stalactites, stalagmites, lava levées and channels may be preserved. Most lava tubes are known in basaltic lava, which is the most fluid of molten volcanic rocks (Roobol et al. 2002). The following is a brief description of the location and major characteristics of the most important of these Harrats.

2.1 Harrat Raha- Harrat Al Uwayrid

It consists of 50 km-long chain of volcanic centers with a maximum elevation of 1,900 m above sea level. It forms a plateau of 7,200 km2. The lavas are bimodal suite of basalts and silicic rocks with the most recent activity recorded at the northeastern parts.

2.2 Harrat Lunayyir

Harrat Lunayyir is located to the northwest of Al-Madinah between Latitudes 25° 06/ and 25° 10.2/ N and Longitudes 37° 27/ and 37° 45/ E, and occupying an area of about 3,575 Km2. It is composed of relatively old flows in the southwestern part and very young pyroclastic cones and flows to the northeast. Earthquakes swarms with different intensities have been recognized in the last ten years.

2.3 Harrat Ithnyan

Harrat Ithnyan is north of Harrat Khaybar and is composed of a 40 km-wide belt of volcanic centers aligned in north-trending chains.

2.4 Harrat Khaybar

Harrat Khaybar is located north of Medina in western Saudi Arabia, between 39° and 41° longitude E and 25°and 26° latitude N. It has an area of approximately 12,000 km^2. The lavas and volcanoes in Harrat Khaybar are mildly alkaline with low Na and K content and include alkali olivine basalt, hawaiite, mugearite, benmoreite, trachyte and comendite. The age of the Khaybar lavas ranges from ~5 million years old to post-Neolithic and black historic lava flows (Pint, 2006).

2.5 Harrat Rahat

Harrat Rahat extends southward from Al Madinah (24^o 30$^/$ N.) to Wadi Fatimah near Makkah (21^o 40$^/$ N.). It covers an area of 18, 1000 km^2 with average width of 60 km. Recent volcanic activity has been recognized in the central and northern parts of the Harrat. It preserves a volcanic record that began in the Miocene with sporadic activity continuing up to historical times (Coleman, et al. 1983).

2.6 Harrat Kishb

Harrat Kishb is a young basaltic lava field with an area of 5,892 km^2 centered about 270 km northeast of Jeddah. The age of this volcanic eruption is younger than 2 million years, based on the Based K/Ar isotopes. The lava is stratified forming three major stratigraphic units, i.e. the Diakah, Nafrat, and Hil basalts, from oldest to youngest. The Hil basalt is considered a more younger lava-tube caves eruptions less than 1 million years in age (Roobol et al. 2002). High relief Lava-tube caves of up to 10 m has been reported on Harrat Khaybar (Roobol and Camp, 1991).

2.7 Harrat Al Buqum-Harrat Nawasif

It occupies an area of 10,000 km^2 and is considered the fourth largest lave field in Saudi Arabia. It is an elongated lave field that have been erupted in three episodes forming a sloping plateau with a maximum elevation of 1400 m (Coleman, et al. 1983).

2.8 Harrat Al Birk

Harrat al Birk is located on the Red Sea coastal plain, mainly between Wadi Hali and Wadi Nahb. The flows form an irregular elongate volcanic field of approximately 1,800 km^2. The lavas cover paleo-topographic features (i.e., river valleys, pediment surfaces, etc.) and aggregated into nearly level plateau surface just above the sea level (Coleman, et al. 1983).

2.9 Harrat Al Sirat

Harrat as Sirat extends from Al Jawf to the Yemen border covering an area 750 km^2. It is deeply eroded and forms a series of mesas and buttes along the edge of erosional escarpment of the Asir region. The as Sirat flows have a maximum total thickness of 580m and approximately 20 separate flows have been recognized.

3. EXPLORATION OF THE HARRAT FIELDS & PAST/PRESENT DAY ACTIVITY

The geophysical exploration of the Harrat fields went back to the mid of the 1980-1990th period. The first actual work was that of Demange (1982) who carried out geophysical surveys in Khayber volcanic field for geothermal exploration. He measured 730 gravity station as well as 170 AMT stations, beside the available aeromagnetic surveys. From the analysis of the field surveyed datasets he concluded that two promised zones can be selected, as potential geothermal targets, for direct investigation by slim-hole drilling. Berthier (1982) studied the center of Khayber and Rahat volcanic fields from the volcanology and geochemistry point of view. He concluded that, in Khayber volcanic field, shallow reservoirs may exist in Cambrian sandstone, besides a more deeper reservoir.

Demange with others started the real investigations by drilling two boreholes in Khayber volcanic field. They carried out also hydrochemistry and geophysical surveys (gravity, magnetic and AMT). They concluded that a conductive body at 500 m depth and 50 m thick was mapped. This body may be due to the presence of saline and/or hot water than to the presence of a mineralized or clayey zone (Demange 1984). Additionally, cold fumaroles were observed near Jabal Al Abyad suggesting a geothermal anomaly at a depth. Based on the above-mentioned results, they suggested drilling two boreholes up to 700 m in depth. Al-Dayel (Al-Dayel 1988) evaluated the geothermal potential in the volcanic fields and hot springs and suggested that Khaybar and Rahat volcanic fields are considered as zones of high heat flow, south of Kishb volcanic field has locally significant heat flow, and Hutayma and Lunayyir volcanic fields have heat flow spots above the average. Additionally, from hydro-geochemistry studies, Al-Lith and Jizan areas have circulated aquifer with high temp (e.g. 100 ^oC at Ayn Al Wagarah and 90 ^oC at Ayn Al Harrah).

Roobol at al. (1992 and 1995) studied the mineralogical composition and lava tubes of Harrats, and suggested that three high-enthalpy locations are suitable for geothermal power production, where steam fumaroles were observed. Bjornson and Guðmundur (2009) visited the volcanic fields in Saudi Arabia through Saudi Geological Survey (SGS) in order to evaluate the geothermal potentiality in the kingdom. They suggested that the western part of Saudi Arabia appears to host volcanic systems of sizeable geothermal potential with high temperature geothermal situation, ideal for electricity production, and in areas with lower temperature fluids better suited to other uses than electricity generation. Despite the considerable volume of geological data, some geological investigations to be missing when considering geothermal applications.

More recently, a comprehensive seismic velocity tomography and seismic attenuation tomography was done at Harrats Lunayyir HL (Koulakov et. al. 2014 and 2015 and Sychev et al. 2017). HL basaltic field is one of the most recent volcanic activities in western Saudi Arabia. In April–June 2009 more than 30,000 local earthquakes have been occurred due to seismic unrest in HL, however this crisis was related to subsurface magmatic activity, there is no surface volcanic activity has been featured. Local earthquake tomography has been carried out by Koulakov et. al. (2014, 2015) and Sychev et al. (2017) using the P and S waves arrival times of 2009 HL Crisis. The produced seismic image of VP,VS and VP/VS indicate high VP/VS anomalies at depth 7 km representing the area of 50 recent volcanic cinder cones older than 10ka, this anomaly interpreted as steady state magma reservoir.

Aboud et al. (2018) carried a more detailed magneto-telluric geophysical survey on Harrat Rahat. 3D inversion technique of the measured resistivity data applied in order to image the subsurface resistivity setting. The resistivity distribution was mapped at different depths of 1 km, 6 km, 15 km associated with the main structures. The high resistivity layer (>1000 Ω.m) at the surface is likely to reflect unaltered basaltic lava flows. The layer of moderate to low resistivity (50–200 Ω.m) beneath this surface zone that extends to the east where it ends on contact with outcropping Precambrian basement may be interpreted as old and altered lava. A thick high resistive peak (red-color zone) began to appear at depth of 15 km and continue to a depth of 20 km at the northern-western part of Harrat Rahat . Since this peak is located approximately underneath the historical eruption, it can be considered good signature of a good geothermal reservoir of partial melting zones (Aboud et al. 2018).

4. COMCEPTUAL RESERVOIR MODEL OF THE HARRATS

Based on the results of the seismic velocity tomography and seismic attenuation tomography made by Koulakov et. al. (2014); (2015) and Sychev et al. (2017) at HL, a conceptual model was constructed for the geothermal reservoir (Fig. 2). A prominent high-attenuation zone (associated with high seismic activity) is observed at shallow depths 5-7 km. It may represent a zone of accumulation and ascending of gases created by decompression of ascending liquid volatiles. The gases are escaping to the earth's surface through the weakest joints and tectonic fractures and several faults. The geothermal reservoir appears to be at depth range of 9-15 km, with a deeper source of magma located at depth more than 15 km.

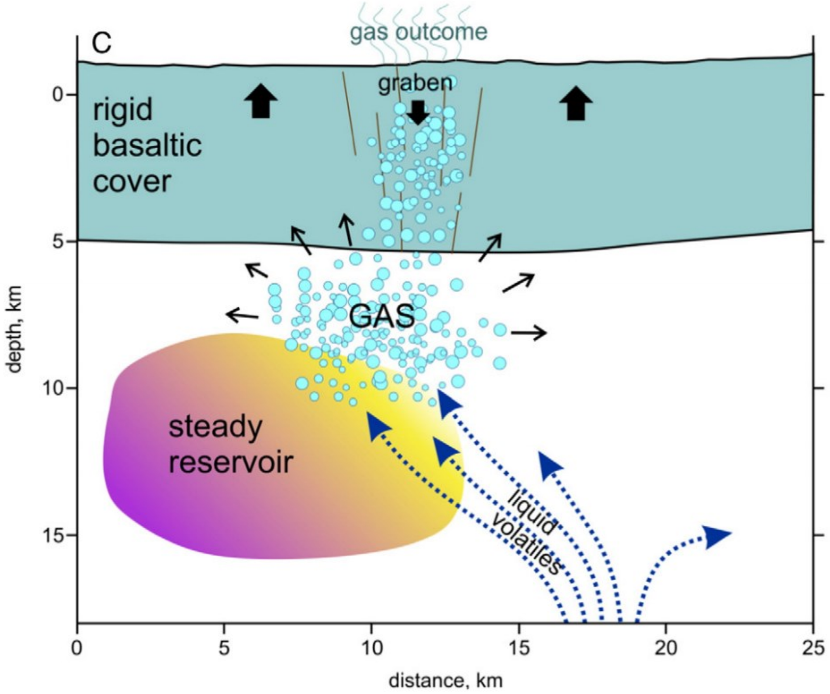

Figure 2: Conceptual model for the geothermal reservoir and fluids at the HL. The pathway of fluids is shown by blue lines. Arrows of blue dots point to gas formation due to decompression; a possible area of volume increase is indicated by thin black arrows; uplift and subsidence areas are indicated by bold arrows; brown lines refer to fracture zone (after, Koulakov et. al. 2014; 2015 and Sychev et al. 2017).

5. GEOTHERMAL ACTIVITY & ECONOMIC CONSIDERATION

At the regions of plate boundaries and rifting, where volcanic eruptions are located, the vertical permeability and magma intrusions allow the convective flow of heat and mass and thus the depths are relatively accessible and the temperatures are favorable for power generation (150-300°C). The entire coast of the Red Sea in Saudi Arabia besides the area extending inland towards the Harrats and beyond has anomalies of good geothermal potential. It is anticipated that the fractured, Precambrian rocks are best suited for power applications due to their high temperature (Grimur Bjornson, RG personal communication).

Long time ago the geothermal activity is recognized in some locations at the Harrats fields. One of the good examples is that reported by a local Saudi Geologist, that someone had suffered severe leg burns inside a cave located in the Harrat Khaybar indicating a renewed thermal activity in the area. Another arranged visit to the cave proved that the source of heat was a smoldering fire beneath the surface of a large bed of dry guano. Another guano fire has been documented in Ghar Al Hibashi cave in Saudi Arabia (Pint et al. 2005, Pint, 2006). Moreover, Roobol at al. (1992 and 1995) while studying the mineralogical composition and lava tubes of Harrats, suggested three high-enthalpy locations (Harrat Ithnayn, Khaybar and Rahat) where steam fumaroles were observed, that would be suitable for geothermal power production (Fig. 3).

Figure 3: The basaltic lava field of Harrat Khyabar with team fumaroles escaping at the surface (Roobol et al. 1992 and 1995).

According to previous geothermal studies in other geothermal areas the available geothermal resources of Saudi Arabia are sufficient for utilization on an economic industrial scale. The large volcanic systems of the Saudi Arabia Harrats (80,000 km^2) should be a favourable for geothermal power generation. Being close to the coastal parts of the Red Sea enables fast recharging and provides continuous water supply for the subsurface geothermal reservoirs. Electricity can be generated using binary technology in case of high geothermal systems where the temperatures of the geothermal fluids exceed 150 °C, which is more common in several parts of the world (Lashin and Al Arifi, 2010, 2014; Lashin et al. 2014, 2015; Chandrasekharam et al. 2014a, 2015b, 2016a). However, a more field exploration, research and scientific work is further needed in future to identify adequately the characteristics and the potentiality of the Harrat fields.

6. SUMMARY

The Harrats are young Cenozoic basaltic eruptions that cover approximately 80,000 km^2, at the western coast of the Saudi Arabia. It comprises a 1,400-km-long, 200-km-wide belt of coastal plains, stretched Precambrian crust, escarpment faulting and a passive inland plate boundary. These basaltic lava include 10 major fields, the most important of them are those of the Ithnayn, Khaybar and Rahat volcanic fields. The composition of the Harrat is mainly alkaline including alkali olivine basalt, hawaiite, trachyte and comendite. Structurally, it forms Lava tubes which are naturally roofed feeder channels of lava flows within the length of the flow as well as lava stalactites, stalagmites, lava levées and channels. Local collapses of the roof along its length provide access. The conceptual model of the geothermal reservoir at the Harrat Lunayyir shows accumulation and ascending of gases at shallow depths 5-7 km. These gases could escape to the earth's surface through the weakest joints and tectonic fractures and several faults. The geothermal reservoir appears to be at depth range of 9-15 km, with a deeper source of magma located at depth more than 15 km. The field observations have indicated a good potentiality of these eruptions, where geothermal fumaroles were observed in some spots of these fields. The large volcanic systems of the Saudi Arabia Harrats should be favourable for geothermal power generation. Binary power plants can be utilized for expected high temperature geothermal systems at Harrat Khaybar and Rahat with fluids temperature of more than150°C. However, a more comprehensive exploration and field surveys are needed to better characterize the geothermal potentially of these resources.

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