Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Geophysical Exploration of the Western Saudi Arabian Geothermal Province: First Results from the Al-Lith Area

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Keywords: Geothermal exploration, geophysics, Saudi Arabia, Al-Lith.

ABSTRACT

Hot springs with temperatures around 96°C and 56°C are located in the Ain Al-Harrah and Wadi Markub sites (Al-Lith province, Western Saudi Arabia). They are part of a number of surface geothermal evidences spread in the southwestern part of Saudi Arabia. Based on recent geological and geochemical surveys, a geophysical data acquisition was completed in the area in 2013, encompassing MT and seismic reflection. The main objective of this geophysical work is imaging of the local structural setting, with particular reference to fracture/fault systems that may enhance porosity/permeability of the granite rocks in place and let the hot water escape from the reservoir through the hot springs. Geochemical analysis indicates that meteoric water is heated at rather shallow depth in the area of study. Geochemical indications and logistic constraints drove the design of a high resolution geophysical survey that utilized a 96-channel seismograph and a 100 kg weight drop seismic source to complete 10 seismic profiles in the area centered about one of the hot springs. MT measurements were performed (16 stations) on a 12 hour time-span. The results show a clear resistivity anomaly located around 2500 m from topographic surface. Several fractures are further observed in the imaged volume up to an approximate depth of 500 m. Surface geology and geophysical data provide information that is compatible with a circulation of fluids in a complex system of fracture related to at least two principal directions (i.e. N and NW-SE trending). Local conditions (temperature, flow rate, structural setting) encourage an extension of the geophysical work done to date for the reconstruction of the regional geothermal conditions in the perspective of direct uses and electricity generation.

1. INTRODUCTION

The geothermal resources of the Kingdom of Saudi Arabia are mainly located along the western and southwestern coastal parts. Such resources are associated with the main tectonic activities and features of the Red Sea and Gulf of Suez rift. The Al-Lith area is located along the western coast of the Red Sea, about 180 km south of Jeddah city, and is a promising target in the perspective of geothermal heat extraction.

The hot springs of the Al-Lith area are located mainly in four different sites (Ain A1 Harrah-Ghamika, Wadi Al Sader-Bani Hilal and Wadi Markub areas). A temperature range from 41°C to 96°C is observed at these hot springs with the highest recorded value at Ain A1 Harrah hot spring (Hussein, et al. 2013, Lashin, at al. 2013 and Lashin & Al Arifi, 2012, 2014).

Reflection seismics is considered one of the most effective and widely used methods in geothermal exploration. It is based on measurements of amplitudes and travel times of seismic waves generated by artificial energy sources.

Magnetotellurics (MT) is another geophysical method that is being extensively used in geothermal studies. The ability of MT soundings to provide information about the subsurface electrical stratigraphy at depths ranging from the near surface to several kilometers is an advantage over most of the other methods in geothermal exploration. It measures the fluctuations in Earth's natural magnetic field; the induced electric fields are also measured. It can detect low-resistivity layers in geothermal systems, but it can also provide valuable information about the resistivity structure at greater depths, which can be associated with heat sources and deep hot spots. The collection of MT data is logistically simple compared to the controlled source methods and allow fast and relatively inexpensive field campaigns. The results can be interpreted in 1-D, 2-D or full 3-D, providing valuable information about the geothermal system (Arnason, et al., 2010; Cumming and Mackie, 2010).

The purpose of geophysical investigation (seismic reflection data in conjunction with MT survey) is to provide information about the subsurface structural pattern and the possible fault/fracture systems that control the geothermal system.

2. GEOLOGIC SETTING & GEOCHEMICAL CHARACTERISTICS

The geology of the Al-Lith area is represented mainly by two sequences of the rocks. The first is basically a group of basement rocks, while the second is composed by recent Quaternary deposits and Wadi fills (Fig. 1).

2.1 Basement rocks

The basement rocks are huge massive bodies of granitic schist complex (Hurqufah suite), granodiorite and tonalite (Jumah suite) and diorite, tonalite and gabbro (Al Lith suite) that extend along a northeast direction.

Figure 1. Geological map of Arabian shield showing the study area.

2.2 Ghamika suite, Baish and Sadiyah rock units

Ghamika suite is represented by gabbro and monzogabbro dykes with several intersections of basic dykes. Some felsic dykes are also found. Most of these dykes are following the main prevailing structural trends in the area.

The rock units of the Baish group and Sadiyah Formation are found bounding the basement rocks in the middle between these rocks and the quaternary rocks. Some younger granitic rocks are located in the southern parts of the area.

2.3 Quaternary deposits & Wadi fill

These sediments are located mainly close to the shoreline along a northwest-southeast direction. Wadi fills are filling the main valley of Al-Lith area, unconformably overlying the underlying crystalline rocks.

Table 1 reports in situ field measurements at the main four hot springs in the Wadi Al-Lith area.

Table 1. Field measurements at the main four hot springs in the Wadi Al-Lith area.

Hot Spring	Surface Temp. (^oC)	Elevation (m)	PH	TDS (ppm)	EC (μScm^{-1})
Ain Al Harrah	Up to 95	167	7.8	2180	3633
Wadi Markub	56	136	6.85	2960	4933
Al Darakah	41	151	7.6	2900	4825
Bani Hilal	45	170	7.5	2426	4043

The chemistry of the hot springs is studied through the analysis of a number of water samples that are collected from the hot springs and some neighboring wells. It indicates that the majority of the hot springs is composed by a mixing of meteoric and volcanic water. The geo-thermometers calculated for such hot springs indicate heat flow, discharge enthalpy and subsurface temperature between 136 mW/m^2 - 182 mW/m^2, 193 Kj/Kg - 218 Kj/Kg and 105°C - 136°C respectively (Table 2).

Table 2. Calculated heat flow, discharge enthalpy and subsurface temperature from the hotsprings.

Hot Spring	.Subsurface Temp (^oC)	Discharge Enthalpy (Kj/Kg)	Heat Flow (mW/M^2)
Ain Al Harrah	136	218.96	182.79
Wadi Markoub	120.06	193.3	159.23
Al Darakah	105.1	169.21	136.93
Bani Hilal	120.34	193.74	159.63

3. GEOPHYSICAL EXPLORATION

3.1 Field procedures

Due to the promising geothermal characteristics of the Ain Al Harrah hot spring, an MT and reflection seismics geophysical investigation was completed at the beginning of 2013. A 96-channel StrataVisor seismograph was used for the seismic reflection survey (Fig. 3A). Due to the geometry of the Wadi Al-Lith area, the extension of the seismic lines across the Wadi (i.e. perpendicular to the Wadi direction) was limited to less than 400 m. The seismic lines along the Wadi direction reached a maximum 1000 m length (Fig. 2). The seismic lines were subdivided in four segments for each profile and the first shot was at geophone number 16. A 100 kg weight drop seismic source was used to complete the proposed 10 seismic profiles. We adopted a 10 m receiver spacing, a 10 m shot spacing and a 3 s record length.

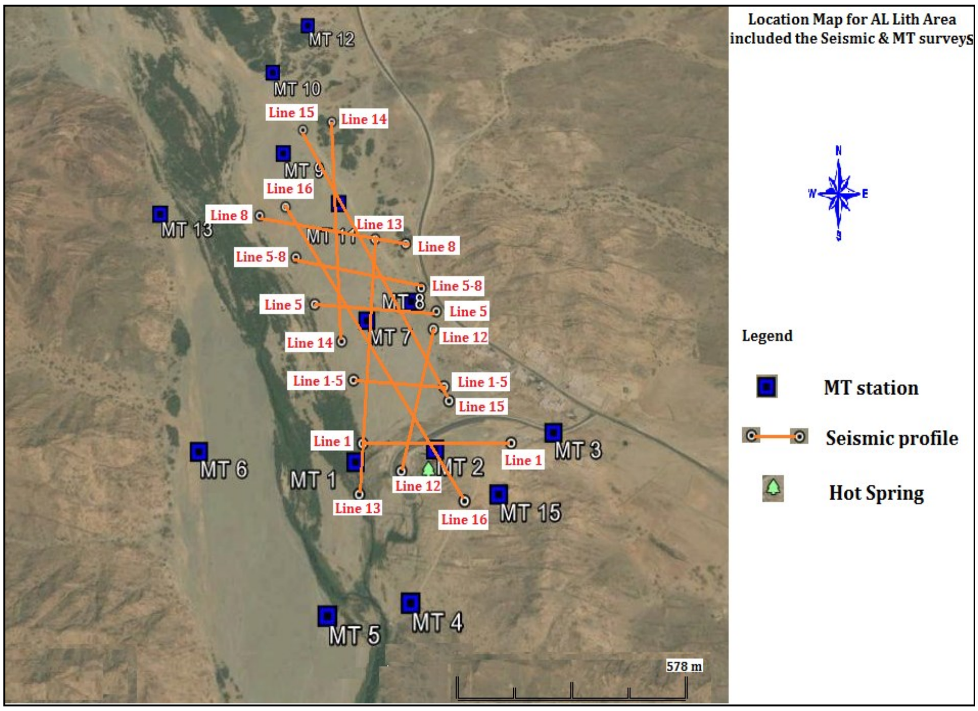

Figure 2. Seismic sections and MT stations location map, Wadi Al Lith area.

16 MT measurements on a 12 hour time-span were further completed in the area centered about the hot spring with an MT24/LF equipment (property of Schlumberger: Fig. 3B).

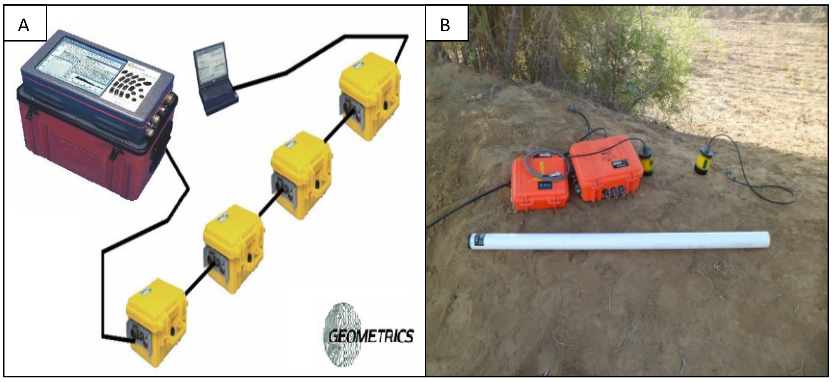

Figure 3. Equipment's that are used in the geophysical surveys a) Strata Visor and b) MT24LF.

3.2 Data processing and interpretation

We applied the following seismic data analysis and processing sequence: quality control and trace editing/muting, amplitude analysis and preliminary AGC correction, velocity analysis (every 10 CMP), AGC removal and spherical divergence correction, NMO correction, Stack, time-variant bandpass filtering, and f-k migration.

The MT data were processed and interpreted by using WinGLink. Eight profiles were selected coincident with seismic profiles to generate pseudo-sections covering the whole study area. These profiles also were used to estimate the resistivity maps at different depths using Occam layer model and Bostick layer model. The resistivity at various depth levels is estimated (e.g. 250 m, 500 m, 750 m, 1000 m, 1500m, and 2000 m).

3.3 Results and discussion

Surface geology and geophysical data provide information that is compatible with a circulation of fluids in a complex system of fracture related to at least two principal directions (i.e. ENE-WSW and NW-SE trending). This is well shown in the interpreted seismic sections shown in Fig. 4, which is selected to demonstrate the prevailing structural elements that may control the whole geothermal system in the area. The Red Sea NW-SE normal and ENE-WSW strike slip fault systems are responsible for the complex fracture pattern that is highlighted by the seismic profiles (Fig. 4). Figure 5 shows that Wadi deposits are resting unconformably over the underlying basement rocks.

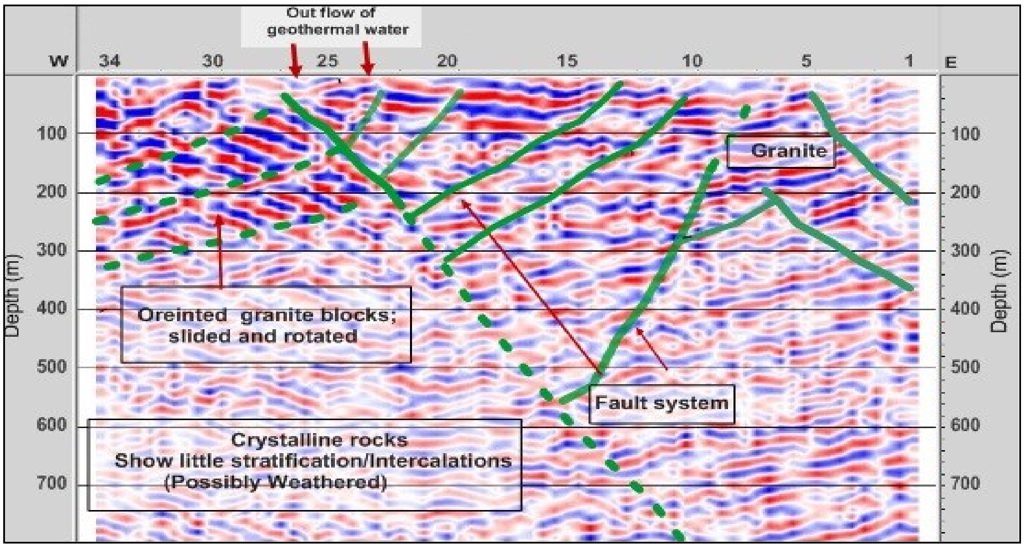

Figure 4. Interpreted seismic section-1 passing Ain Al Harrah hot spring, Wadi Al Lith area.

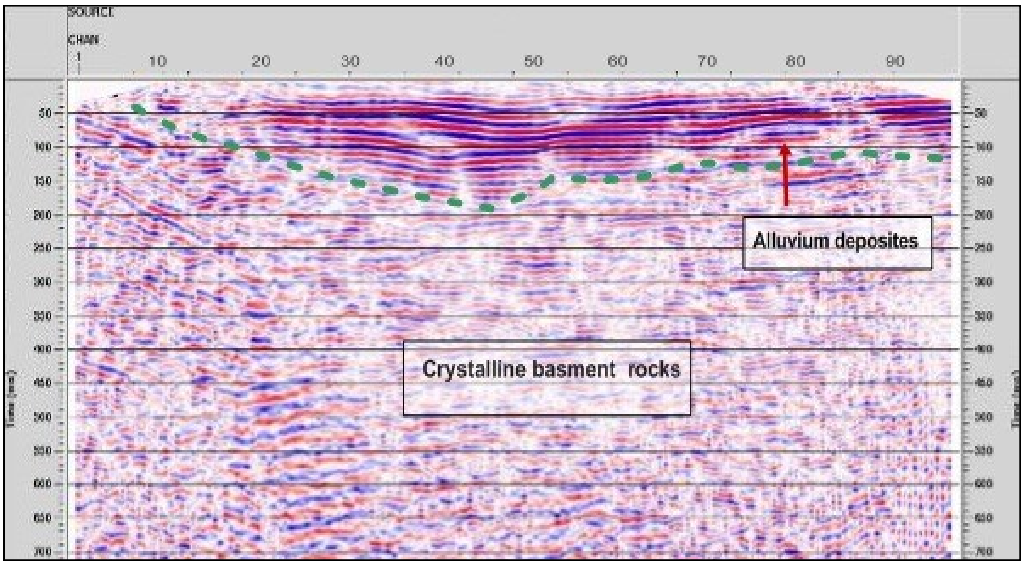

Figure 5. TWT seismic section (line No. 15) Wadi deposits of good reflection geometry are resting unconformably over the underlying basement rocks.

The results show a clear high resistivity anomaly located around 2000 m from topographic surface, which is most likely linked to the geothermal anomaly at the site. The anomaly is oriented along a northwest-southeast direction, which is the main structural trend of the Red Sea rift (Fig. 6).

Several fractures are further observed in the imaged volume up to an approximate depth of 500 m. At that shallower depth the geothermal anomaly changes gradually rotating towards a north-south trend. This means that the main fracture zones that control the geothermal system in the area exhibit variations in azimuth and dip at different depths. Such variations may be related to the combination of the principal stresses and fault systems linked to the Red Sea rift.

CONCLUSIONS AND ROAD AHEAD

The Ain A1 Harrah - Ghamika hot spring is the main geothermal spring in the Wadi Al-lith area, with surface temperatures up to 96° C.

The analysis of seismic data indicates that the NW-SE (Red Sea rift) and the transform strike slip faults (ENE-WSW) are the main structural elements that control the up flow of geothermal water.

The MT survey showed that the deeper geothermal source at 2500 m is aligned following the NW-SE trend, while it tends to be oriented towards the N-S at shallower depths.

Based on the results of the geophysical survey, exploratory geothermal wells shall be drilled to calibrate the geophysical results, to give accurate estimates of the geothermal gradient and to detect precisely the orientation of the fracture and feed zones.

The Ain A1 Harrah - Ghamika area needs to be further investigated to evaluate its potential in the perspective of energy production.

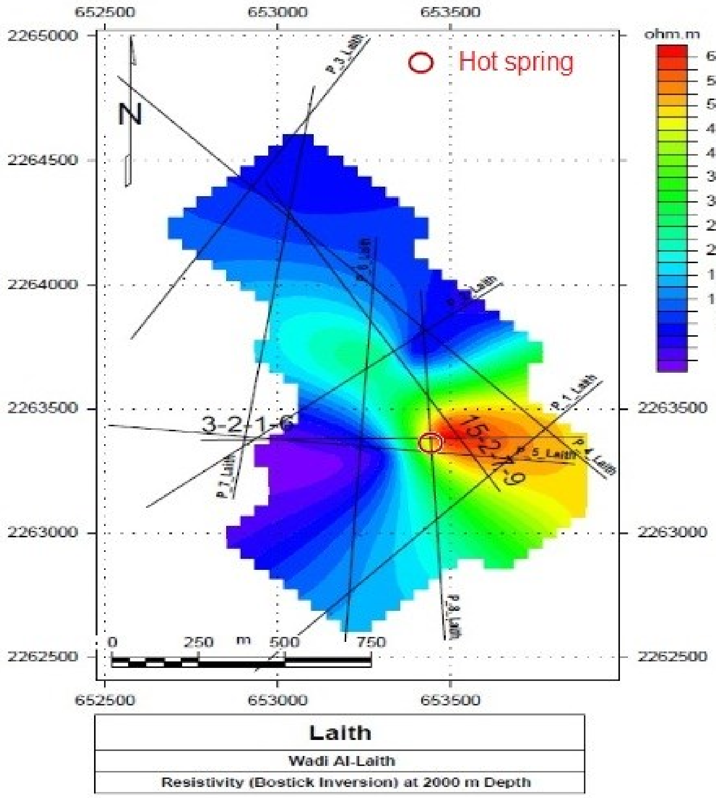

Figure 6. MT slice map at a depth level of 2000 m of showing high-resistive geothermal anomaly.

ACKNOWLEDGEMENTS

This work is funded and supported by NSTIP strategic technologies programs, King Saud University, project number 10-ENE1043-02, Kingdom of Saudi Arabia. We thank Dr. Essam Aboud, King Abdulaziz University for helping us in the field acquisition and interpretation of MT data.

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