

Geothermal Exploration and Geothermometric Characteristics of Western Area in Yemen

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ABSTRACT

This paper presents geothermal exploration in the western part of Yemen. Geologically this volcanic province totals approximately 45,000 km². Tectonically the study area is considered as one of the most active areas in the Arabian Plate boundaries and affected by the opening of the Red Sea and the Gulf of Aden as well as by the African rift valley.

Extensive field work had been carried out to evaluate the geothermal characteristics of this area. Water and gas samples were collected from hundreds of thermal springs and shallow domestic wells and geochemically analyzed and reported. Temperatures and PH values ranged from 35 to 96.3 °C and from 4.5 to 8.5 respectively. Deep geothermal gradient indicated that the geothermal gradients in the western part of the province (Red Sea coast) were relatively high, up to 182 °C at the depth of 3290 m. Volcanic units were affected by hydrothermal processes and were intensively altered.

By applying geothermometric methods, four geothermal fields have been primarily identified, they are: Al-Lisi -Isbil (Dhamar province); Damt (Dhala province); Al-Qafr (Ibb province) and the Red Sea coast geothermal fields.

Results from the Al-Lisi and Isbil geothermal sites were considered the most promising. Geothermal detail studies have been achieved and location of the first geothermal exploration well has been located.

INTRODUCTION

Yemen is located on the Arabian active Tectonic Plates, on top of the Afar hot mantle plume, faulting results from tectonic activity. Western part of Yemen composed of Tertiary and Quaternary rocks along with the directions NW-SE, E W and NE-SW faults trending parallel to the Red Sea and Gulf of Aden. Fumaroles and Thermal springs widely distributed in western Yemen (Fig 1). In excess of one hundred thermal springs have been reported with temperatures ranging from 38°C to 96.3°C. (Mattash et al., 2002). Geothermal fields in the western Yemen identified as Dhamar, Dhala, Ibb and Red Sea coastal geothermal fields. Temperatures and PH were measured directly in the field, geochemical analysis were done in Laboratory for the samples collected from the springs. The most promising geothermal area is located in the western part of the Yemen (Yemen Volcanic Plateau), centered on the city of Dhamar. (Minissale et al., 2007).

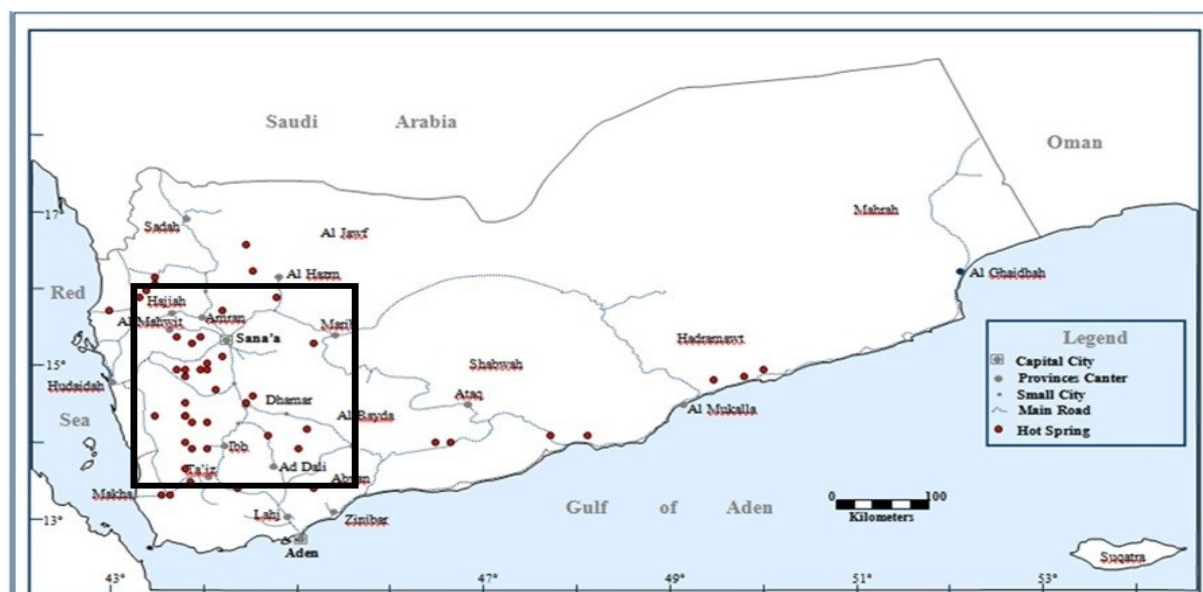


Figure 1: Location of hot springs and fumaroles in Yemen.

Dhamar area has several evidences of promising geothermal site for electricity generation, since it was affected by volcanic activity in the 1980's (Chiesa et al., 1983a). To the south of Al-Lisi- Isbil geothermal field, an important geothermal site (Ibb) was identified with the highest temperature up to 96.3°C, moreover, the exposed Travertine extend with about 12 km. To the east where Damt geothermal field, several hot springs and hot domestic wells reported and analyzed. Geothermal gradient wells in the western coastal area that drilled by oil companies showed that the average geothermal gradient was 70°C/km.

GEOLOGY AND TECTONIC SETTING OF THE WESTERN AREA OF YEMEN

Yemen is located at the major geologic part of Arabian and African plate boundaries characterized by crustal spreading, active rift volcanism, and seismic activity. The structural pattern display in the rift related volcanic area (study area) is associated with major tectonic component of the Red Sea and less commonly with the Gulf of Aden. The majority of faults and dikes which belong to Cenozoic volcanic frequently have WNW trend. Some other faults strike through N-NW which are more or less parallel to the main Red Sea trend Shawki, 1997. In addition, the relatively widespread epithermal altered and mineralized haloes within the Tertiary volcanic fields of western Yemen predicted for a fracturing structural pattern. The majority of thermal zones in the western province have NNW-SSE linear, parallel to the main Red Sea trend, whereas the thermal features along the southern coastal plain have NE-SW linear, parallel to the main Gulf of Aden trend, which is connected with the opening of the Red Sea graben and the separation of the Arabian shield from Africa produced faults running, in many cases, approximately N-S (Fig.2). These faults are the reason for the present major morphological division of the country, especially as far as the step-like Western Escarpment is concerned as suggested by Brown, 1980 (for the Saudi Arabian coastal region). The Highlands include an N-S running zone of tectonic grabens forming intermundane depressions. The tectonic is complicated by numerous diagonal faults running mainly NE-SW and NNW-ESE. Geological and tectonic features associated with the surface manifestation of geothermal activity in Yemen (western Yemen) major tectonic elements during the Cenozoic and Mesozoic have shaped the geological structures observed in the area today. These features are produced by interaction of the Indian, Arabian African, and Eurasian Plates. Tectonic movements along these plates give rise to localization of hot springs, steam and fumaroles. Occurrence of several tertiary volcanic fields (late Miocene-recent) at different locations throughout the country has encouraged searching for geothermal resources. The western Yemen volcanic province is characterized by several hydrothermal features, such as thermal springs, condensates, fumaroles and in many cases hot well waters. These thermal features are related to relatively shallow felsic magma chambers (Mattash, 1994; Mattash et al., 2003).

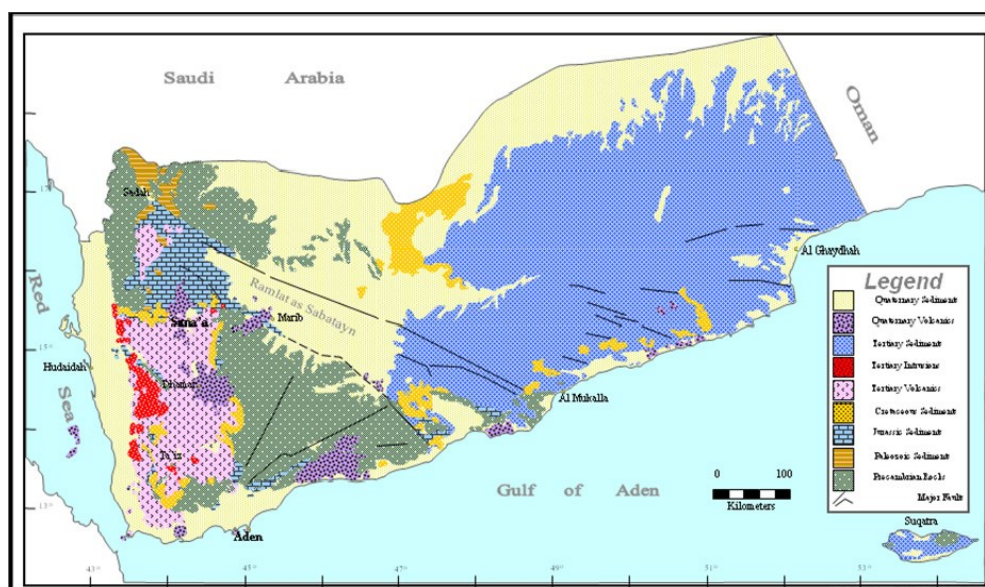


Figure 2: Geological and tectonic map of Yemen (study area)

GEOCHEMISTRY OF THE STUDY AREA

Geochemical survey on thermal spring areas all over the world has been largely used in the past to assess the potentiality of a promising area for the development of geothermal energy. The chemical signatures of thermal waters and gases play an important role in evaluating the reservoir processes and evaluation of geothermal systems. Such evaluation is very important during predrilling stages of geothermal energy development projects and assists power project developers. The emergence of the thermal springs, fumaroles and steam vents are the main evidences of the potential presence of deep exploitable geothermal fluids (energy) in Yemen. Minissile, 2002. Temperature and pH values of the thermal springs range between 38 °C and 96 °C, and 6.3 and 8.7, respectively. However, TDS values range between 800 ppm and 3500 ppm and in some cases may exceed 10000 ppm. The gases collected from fumaroles and vents have low pH values (<4.5) and TDS (<250 ppm).

Chemical analysis of major components and trace or rare earth elements and isotopes and associated gases as more details study done in Yemen. This geochemical investigation helps to identify the origin of CO₂ and to evaluate the geothermal potential of Yemen.

The result of the geochemical analysis indicate that the Yemeni thermal waters have high variability in composition since they are Na (K)-Cl, Na-HCO₃, and Ca (Mg)-SO₄ types, whereas the surficial waters have the typical worldwide Ca (Mg)-HCO₃ composition (Al-Kohlani, 2009). In the western areas of Yemen, the water samples display high and relatively constant Na/Cl which is higher than the southern regions in Yemen. The reason can be related to the fact that the thermal waters in the western and

northern areas are mainly associated with CO₂-rich gas, whereas the others areas are associated with N₂-rich gas. The existence of CO₂-rich gas increases the water-rock interaction processes that led to a higher alteration degree and exchange reaction with Na-rich silicates. These waters thus turn to be Na-HCO₃ in composition.

Chemical Geothermometry Equilibrium temperatures have been used to evaluate the thermal reservoirs in Yemen, by using different chemical geothermometers, such as SiO₂, K₂/Mg and Na/K. Figure 3 indicates that thermal waters from the volcanic province approach the full equilibrium conditions, suggesting the occurrence of prolonged water-rock interaction at a temperature of 150°C. SiO₂ temperatures range between 70 and 140 °C which the other geothermometers display quite different values (Moneer, 2010). This is because the SiO₂ temperatures were also affected by mixing processes with seawater or connate waters.

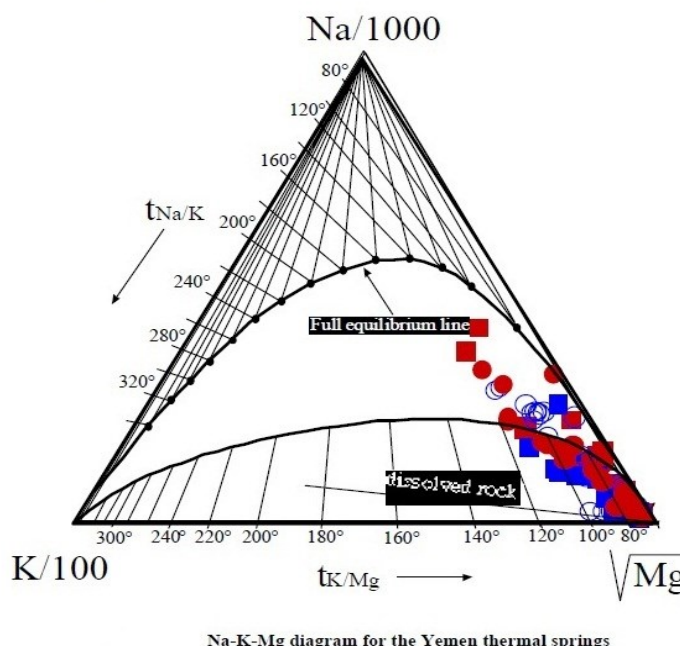


Figure 3: Na-K-Mg diagram for Yemen Thermal Springs

HEAT FLOW AND GEOTHERMAL GRADIENT OF YEMEN

Volcanic and geothermal areas are the most spectacular places where cooling ($1.2 \mu\text{cal/sec/cm}^2$) is taking place. The average heat flow of the tectonically stable continental regions is about 60 W/m². High enthalpy areas in active regions organic belts may have values up to 400 m W/m². Although thermal conductivity of rocks varies from 3 cal/cm.sec.10–3 in schist up to 16 cal/cm.sec.10–3 in quartzite's, as an approximation it is apparent that Φ_c for a given region is directly proportional to the geothermal gradient (Minissale, 2002).

The high heat flow within the time span 40-10Ma, characterizes active rift zone, indicating elevated crustal temperatures which gave rise to the generation of some acidic magmas by crustal melting, i.e. involvement of the crustal material in their petrogenesis and/or mixing of crustal and mantle partial melts (Mattash, 1994; Mattash et al., 2003). However, the present heat flow in the Red Sea region ranges from 94 to 154mW/m², the present geothermal gradient varies from 49 to 77°C/km. Increases towards the southern Red Sea axial trough, to which Al- Hudaidah city is closer (see Table 1). The geothermal system is probably maintained by deep circulation of meteoric water in the coastal plain environment, which is characterized by high heat flow, with convective upwelling along normal fault zones. In support of this claim, heat flow and geothermal gradients data from several oil and gas wells drilled up to 3000 meters of depth in the Red coastal area are reported since the sixties up to now.

Table1: Heat flow and geothermal gradients from wells drilled in the Red Sea area (Onshore and Offshore)

Well Name	Depth (m)	Maximum T (°C) recorded	Equilibrium gradient	Project depth to 200 (°C)	Estimated heat flow HFU	Reference
Salif1	1378	-	59	2950	3.00	Mecom
Salif2	2223	-	59	2950	3.00	Mecom
Hudaidah1	1729	96	53	3280	2.75	Mecom
Hudaidah2	2733	129	51	3410	2.75	Mecom
Zaydiah1	3018	152	50	3480	2.50	Mecom
Kathib1/1A	2459	167	70	2490	4.00	Mecom
Al-Auch1	2812	170	54	3220	2.75	Mecom
Abbas1	3414	174	50	3480	2.75	Mecom

THERMAL FEATURES AND WESTERN YEMEN THERMAL SPRINGS

Geothermal fields in the western part of Yemen are distributed according to their high temperature to; the highest temperature was found in both Al-Qafr area (Mosh Al-kafer) and fumaroles and steam were found in Al Lisi and Isbil geothermal site (Dhamar province). These two areas suggested to be exploited for Power generation (electricity). In Damt geothermal site (Dhala province) to the east of the study area are exposed thermal springs which have the same characters of the thermal springs in the western Yemen. These springs can be exploited for balneology, mineral water industry, and swimming pool. Green houses therapeutic-healing, drying fishes, aquacultures. Along the Red coastal, to the west of Yemen, heat flow and geothermal gradient from drilled oil and gas wells indicate a high geothermal system in the area.

ALISI AND ISBIL GEOTHERMAL FIELDS

General information of Dhamar field

This area is extending to the south Sana'a (Yemen capital city) which covered with Tertiary and Quaternary volcanic, basaltic cones, acidic domes. The geothermal manifestations of the area emergence from volcanic field, ten thermal springs have been found in this area and in the neighboring areas, fumaroles and several thermal wells are in geothermal systems attributed to deep circulation (1000-2000 m) of meteoric water, refer to existence of geothermal reservoir. The Dhamar area has been affected by intensive near vertical faults resulting in the formation of horst and graben structural patterns. It is also characterized by a sequence of pyroclastic flow deposits (Dhamar ignimbrites), which widespread on the floor of the graben. Near vertical NW-SE trending faults parallel to the Red Sea rift, and associated with the opening of the Red Sea, less commonly NE-SW and E-W trending faults, which connected with the spreading of the Gulf of Aden. Structurally, the thermal springs of Dhamar area is mainly connected to NW-SE trending faults and less common to NE-SW, E-W trending faults (Mattash, 2003)

Geochemistry of Dhamar field

The classification of Dhamar thermal waters indicate a Na-K-Cl composition, Al-Lisi and Isbil volcanoes are of Na-HCO₃ type with discharges often associated with CO₂-rich gas phase Fig 4. The existence of CO₂-rich gas phase increases the water-rock interaction processes that lead to a higher degree of alteration and ion-exchange reactions with Na-rich silicates. Thus, these waters become Na-HCO₃ in composition (Mattash et al., 2001).

Those thermal springs have been used for very simple ways like swimming bath, washing and laundry; if these thermal springs can be developed, they can be used for power generation (electricity).

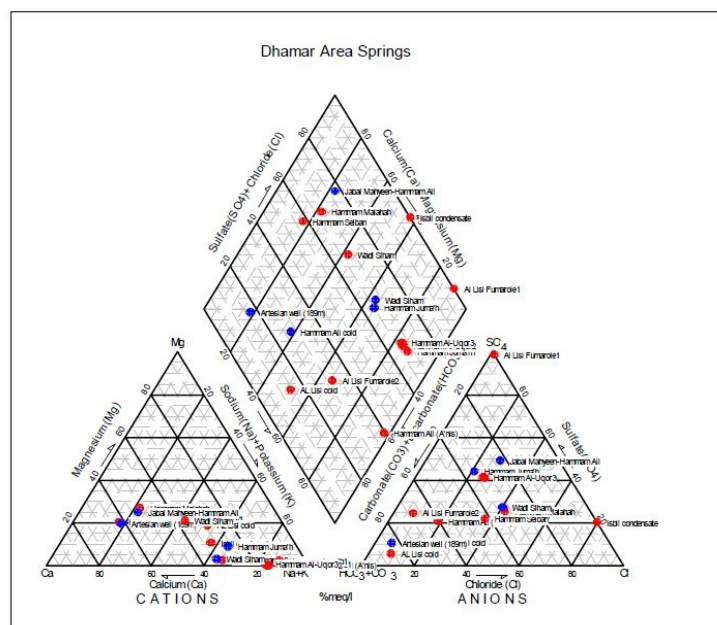


Figure 4: Interpretation of the Geochemical Investigation of hot springs in Dhamar Area.

Geophysical of Dhamar geothermal field

As a result of the previous geophysical survey in 1981 by the Italian company (ELC), two drilling sites suggested as shown in Figure 5 and Table 2 which represented the geophysical anomaly map of the geothermal interest in the area. GSMRB carried out more geophysical survey in 2007 and suggested a site drilling in the area that have low resistivity anomaly in that map in order to compare between the results of all studies. It is clear that there is connection between the two studies with the reinterpretation result of this study in the zones of low electrical resistivity anomaly (high conductivity), except one zone in the north of the area (Wahib, 2010).

Table 2: summary of the deep zones of low and very low electric resistivity

Deep zones of very low resistivity	Profile No.	3	4	4	7	7	7	10	11	11	4, 8	7, 11	9, 11	* The lowest values (<5 ohm.m) ** Moderate depth of low resistivity					
	VES No.	9**	40	65	20	78*	97*	36	23	37	51A*	G4*	32A*						
Deep zones of low resistivity	Profile No.	4	4	4	4	6	6	6	7	7	8	8	9	9	10	10	10	6, 8	8, 9
	VES No.	3	18	28	G3	2	4	55A	77	108	15	16	21	22	17	42A	43A	G5	96

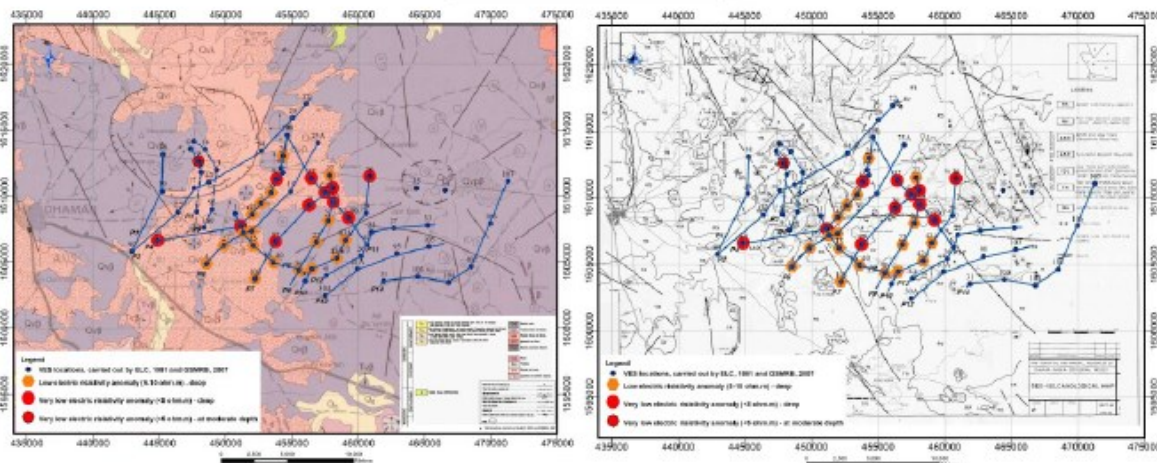
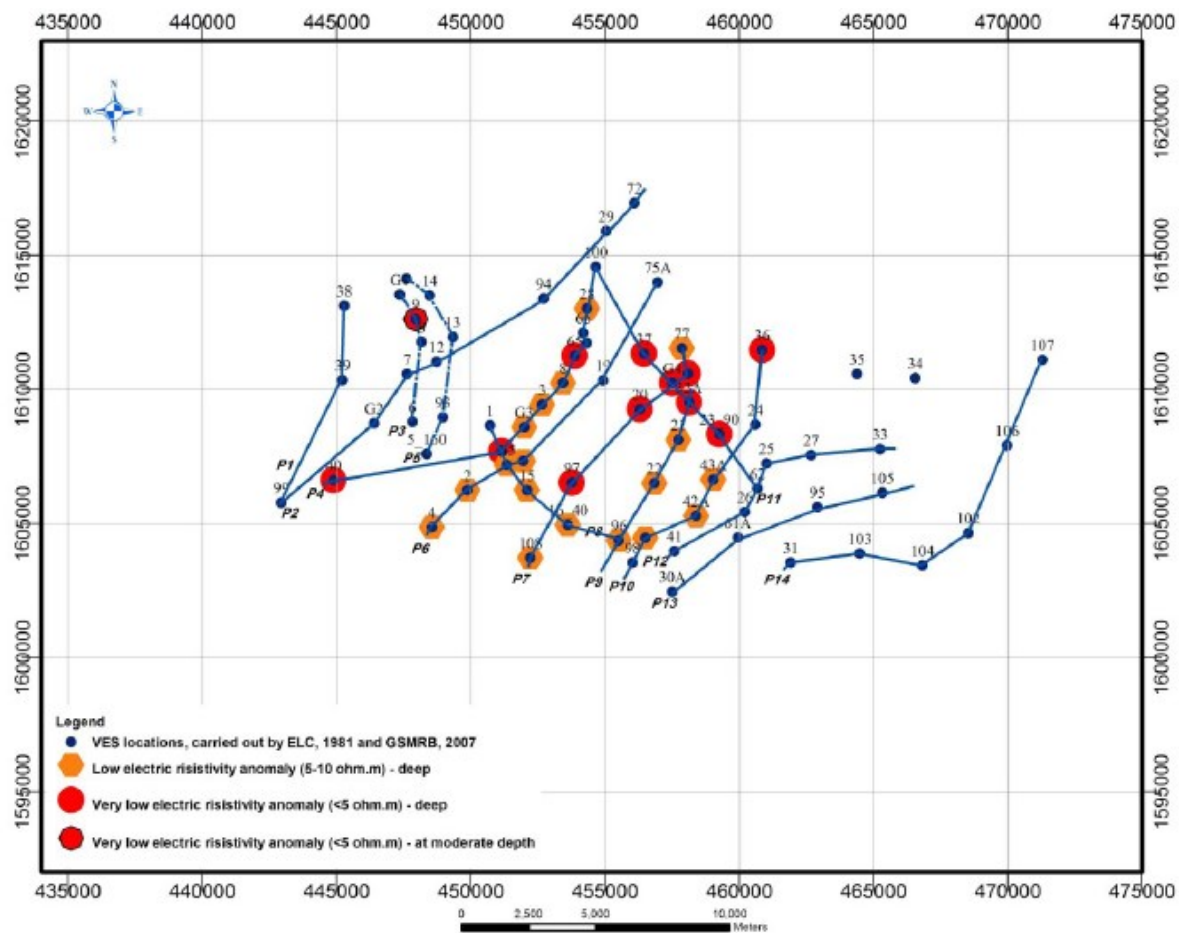


Figure 5: Anomalous Zone in the Geophysical Map that show the relation among, low electrical resistivity anomalously of ELC, 1981 results, GSMRB drilling site suggestion, and the low resistivity anomalies of the resent study (Wahib, 2010).

Heat Flow study in Al-Lisi and Isbil geothermal field

The prospect area is about 66.845 m². Heat flow measurement carried out in the area of the hot ground in the field of Al-Lisi (see Fig 6). Boreholes serve as gradient holes for temperature gradient computation, results used to estimate geothermal reservoir temperatures. The following one dimensional heat conduction equation (Eq. 1) was used to compute the heat flow of shallow holes, temperature gradients assuming that the soil's thermal conductivity is constant at 2 W/m °Cm, the average temperature gradient is computed and tabulated.

$$Q = Ak(dT / dy) \quad (1)$$

Where Q, A, k, dT , dy, are conductive heat flow (watts) , surface area of hot ground m², K (=2) : is thermal conductivity of rock (W/m °C), and T: is temperature (°C) and y is depth (m).

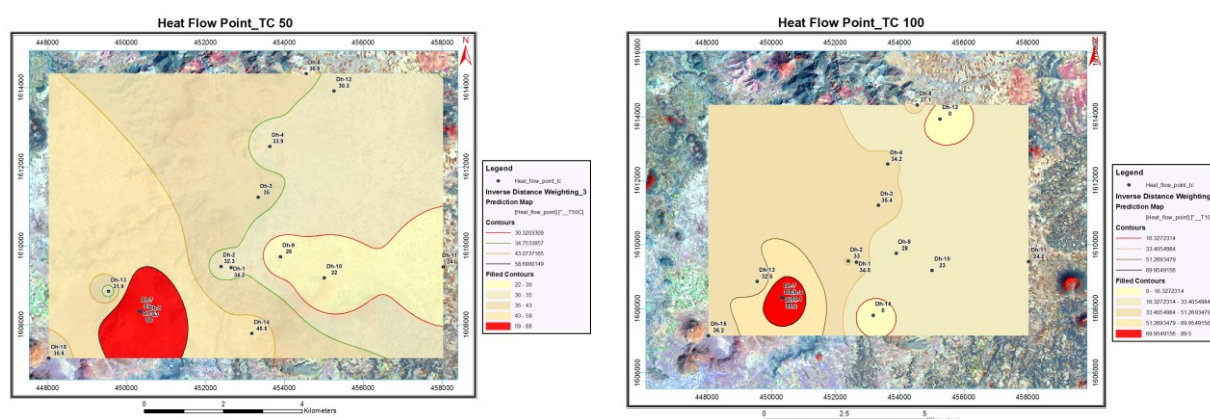


Figure 6: Heat Flow in Al-lisi- prospecting geothermal site from shallow holes (50-100cm)

SUMMARY AND DISCUSSION

Hot springs, fumaroles and gas vents emergence from sedimentary, metamorphic rocks but the majority emergence has been founded associated with Tertiary and Quaternary volcanic fields in western Yemen. Hot thermal spring locations associated with Tertiary felsic intrusions, related to the NW-SE, E-W and NE-SW trending faults which parallel to the main Red Sea and the Gulf of Aden trends. Several earthquakes and landslides have occurred in these volcanic areas and structurally connected to N-NW faults.

Geothermal system of Yemen occurred between the Arabian plate and African plate boundaries. The present study of the hot springs in the western Yemen explained the relationships between the different types of hot spring waters and the geological rock composition, where the type of the hot springs water derived from the chemical composition of the geological rocks when ascending to the surface through them (water-rock interaction). The relationship between the types of hot spring waters related to the magma chamber in depth and the chemical composition of the volcanic rocks.

The western Yemen hot thermal springs classified into two waters types of which they are Na-HCO₃ and Na-K-Cl, whereas the surficial waters have the typical worldwide Ca (Mg)-HCO₃ composition. Equilibrium temperature evaluation of the thermal reservoirs has been performed by using different liquid phase geothermometers, such as, SiO₂, K₂/Mg and Na/K. Estimated reservoir temperatures range between 70 and 140 °C. Western Yemen shows a good potential with subsurface temperatures around 150°C in the Al-Lisi - Isbil geothermal site (Dhamar) and Al-Qafr (Ibb) in which considered to be the most prospected area for the power generation. Red coastal area which contains hot springs is indicated another geothermal site and it can be used for balneology and tourist proposes. Another area in Dhala, central Yemen, is very important for geothermal energy because of the location of this area and the surface temperatures ranging between 40 - 45 °C. Na-HCO₃ type of water can be used for tourist. Temperature and pH values of the thermal spring are in the range between 37 °C and 96 °C, and 6.3 and 8.7, respectively.

The present geothermal gradient in the Red Sea region ranges from 49 to 77 °C/km (data collecting from deep drilled wells over 3000 m) and the present heat flow varies from 94 to 154 mW/m². Such high and moderate heat flow values have more or less been affected by the thermal equilibrium between the upper mantle and the crust.

CONCLUSIONS

This geothermal study in western and the Red coastal parts of Yemen has concluded the following:

1. There is a relationship between the locations and the structural geology where thermal springs of Yemen were occurred on the main trending faults (NNW-SSE, S-E and NE-SW), which are parallel to the Red Sea and Gulf of Aden.
2. Geothermal systems have been occurred on the plate boundaries associated with volcanism, where Yemen geothermal system is located between the Arabian and African plate boundaries which associated with volcanism. Thermal springs and fumaroles, steam gas vents, earthquakes, volcanism, and landslides are good surface indicators of the geothermal system in the study areas.

3. Mainly, thermal springs in Dhamar and Ibb areas are located on the similar tectonic region and associated with deep faulting. This region had a prolonged history of volcanic activity since Tertiary (Yemen Volcanic Series) and Quaternary (Quaternary volcanic). These volcanic rocks cover considerable areas associated with the rifting of the Red Sea and Gulf of Aden that are still spreading and causing accumulations of stresses on the region.
4. Types of the thermal spring waters refer to the geological rocks where the thermal water contacted or ascent to the surface through them, and the processes between the hot waters and the rocks (water- rock interaction) during the ascending of hot waters from the reservoir to the surface passing the rocks.
5. The sources of CO₂ in Damt area could either be magmatic or the limestone reservoir rocks, which could release CO₂ as a result of thermometamorphic or hydrolysis.

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