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Geothermal Exploration at Al-Qafr Geothermal Field, Ibb Governorate, Yemen

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ABSTRACT

Al-Qafr geothermal field is one of Yemen's significant fields, so it is important to carry out geological and surface hydrothermal alteration mapping for this geothermal field. The main manifestations mapped include thermal spring, some of them associated with gas discharge, boiling pool and hot wells as well as travertine deposits along with slight hydrothermal alteration. Geology of the area is mainly composed of Tertiary basalts, Cretaceous sandstone (Tawilah Group), with small outcrops of sandy limestone and Quaternary deposits of travertine, pediment deposit and alluvium with several acidic, basic and silicified dykes. Structural features are represented by several extensional faults and fracture system striking NW-SE, almost parallel with the main Red Sea trend.

The main goal of this study is to conduct mapping of the geothermal manifestations in order to find out probable correlation existing between geothermal, volcanic, hydrothermal as well as tectonic setting and structural patterns in this field. The surface alteration and manifestations are found to be of linear distribution trending in the same direction as the major fault system (NW-SE). Hot spring surface temperatures (75-97 °C) are measured at Al-Qafr area, along with precipitation of SiO2 on the surface as indicated by geothermometric analysis of these thermal waters. The geothermal map illustrates the distribution of the alterations, which are concentrated in the central part of the study area at the vicinity of the hot springs, indicating that the center of geothermal activity extends from northwest to the southeast of the study area. Different hydrothermal alteration products, including quartz, calcite, zeolite, albite and clay mineralization are indicated by XRD analysis.

1. INTRODUCTION

Al-Qafr geothermal field is one of the most important three geothermal fields composing thermal triangle in the western Yemen volcanic province. Such a province is considered as an unstable, as it is characterizes by volcanic and seismic activities as well as by intensive hydrothermal processes and geothermal manifestations. They are connected to the synrift (late Oligocene-early Miocene) and particularly to the postrift (late Miocene-Recent) phases of the Red Sea and the Gulf of Aden.

Geological survey and geothermal exploration are amongst the most significant targets and research methods to evaluate a geothermal resource that can lead to ultimate economic potential and utilization. Commonly, the siting of exploratory drill holes in geothermal fields has been based on geological mapping of geothermal manifestations and their relationship to geological structures; therefore it is necessary to implement this study which is based on the first detailed map of Al-Qafr geothermal field at a scale 1:50,000.

This study aims to carry out surface geological and geothermal mapping in the Al-Qafr area by classifying the rock units, mapping the main structural features in the area and outlining the locations of surface thermal water manifestations as well as hydrothermal alterations, in order to figure out the relationship between the geothermal activities and the tectonic setting of the targeted area.

The surface geothermal manifestations in the Al-Qafr geothermal field consist of hot springs occur in several sites some of them associated with gas discharge, boiling pool and hot wells as well as Travertine deposits, most of them located in a 12 km long valley zone, which strikes NW-SE. Thermal water temperatures measured are between 75 ºC and 96.3 ºC, one of the hottest hot spring area identified so far in Yemen. It is located at an altitude between 1200 and 1300 m above sea level. Geothermometry indicates that the thermal waters and the well hot waters are characterized by Na-HCO_3 type, whereas pH values range between 6.34 and 8.23 respectively.

1.1. Location

The Republic of Yemen has strategic position among the Middle East's countries. It is located on the south Arabian Peninsula, between latitudes 12 and 20˚ N, and between longitudes 13˚ and 54˚ E; and totals 527.970 km^2. Yemen consists of 22 governorates. Ibb governorate is in the middle of west Yemen province. Al-Qafr area is located 32 km to the northwest of Ibb city. Study area lies within 44°00' to 44°15' E; and 14° 12' to 14° 25' N (38 393000 to 420000 E; 15 70000 to 15 94000 N UTM) covering an area of approximately 144 km2 (Figure 1).

1.2 Previous work

Although there are 12 natural baths in Al-Qafr area, but no any detailed geothermal study had been achieved. Most of the previous investigations pointed out to Al-Qafr geothermal field within the framework of the general geothermal studies in whole Yemen. it The first geological and geothermometric report on the Al-Qafr geothermal field, particularly Mosh Al-Kafer hot spring area is given by Mattash et al., 2005.

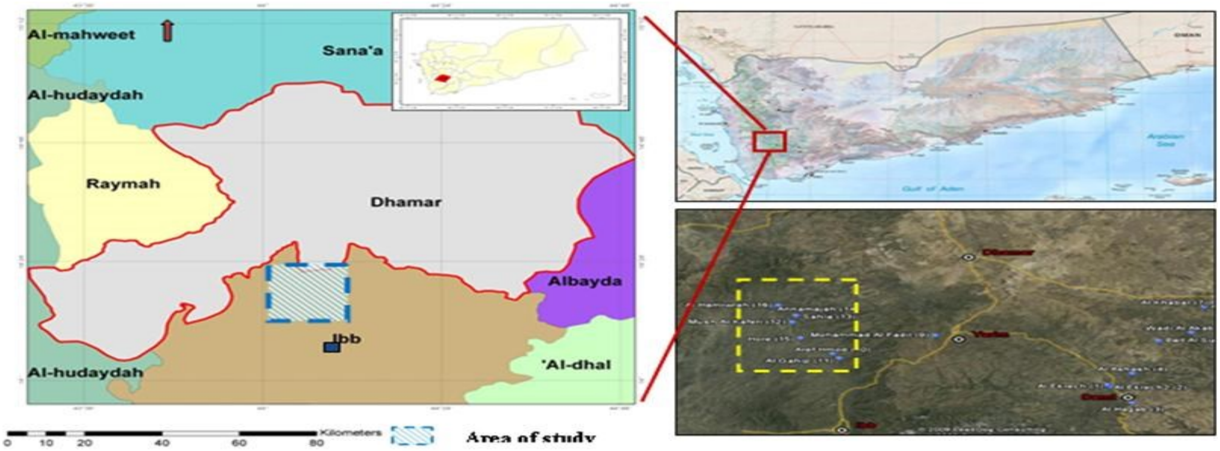

FIGURE 1: Location map of the Al-Qafr area, North West of Ibb city in Yemen; the area of the present study is within the dashed box.

Mattash et al. (2005) carried out an exploration programme for three geothermal fields in the western volcanic province of Yemen and found out that this field is associated with a relatively deep faulted zone, and located 30 km to the southwest of Dhamar Quaternary volcanic field, in which Al-Qafr area could be considered as an extension of that field. Therefore, such discovery should enhance exploration of a large geothermal area in western Yemen. Thermal waters occur through a 12 km long zone at the Al-Qafr area. The highest thermal water temperatures measured (75 ºC to 96.3 ºC) are in Mosh Al-Kafer hot spring area, which are used only for irrigation. Corn and other vegetable plants are produced. Geothermal phenomena at Al-Qafr include hot springs with boiling temperatures (boiling point at altitude 1600 m above sea level).

Minissale et al. (2007) studied the applied geochemistry for thermal springs and associated gas of continental Yemen and it's geothermal potential, but mostly focused on Dhamar geothermal field. They describe several boiling pools associated with abundant gas release at Mosh Al-Kafer area, along a river-bed.

Wagner et al. (2007) reported the suitability of Al-Qafr for geothermal development and found out that the reliable geoscientific studies and data are almost completely missing. The geological and hydrogeological setting is unclear, only assumptions were derived from other areas. Nevertheless, geothermal potential obviously seems to be high assuming that the very hot fluids from the hydrothermal springs in Al-Qafr are transported from greater depth to the surface. However, exploration activities would need to start from the very beginning (including geological mapping etc.).

Al-Kubati (2005) studied the geothermal systems in western Yemen in several governorates and found out that Ibb hot spring areas are in mountainous plateau within the Tertiary volcanic rocks of the western Yemen province and closer to the Quaternary cones and domes and calderas of the Dhamar volcanic field.

Odyssey Resources Ltd. (1997) had focused its study on the alteration and mineralization using remote sensing technology to identify important epithermal mineralized zones. Results of this investigation revealed low to moderately anomaly for gold (Au) and medium to elevated values of some other epithermal elements, such as Ag, As, Sb, Hg, Pb, Zn, etc., throughout the Tertiary volcanic province. These findings are taken into consideration during our geological and geothermal mapping

1.3 Topography and climate

In view of its topographical structure, the Republic of Yemen is divided into four regions (Figure 2):

Region I - Tihama plain: This area includes the coastal plains overlooking the Red Sea, the Gulf of Aden and the Arabian Sea. They are connected to each other forming a coastal strip that extends for 2400 km. The width of the plains ranges from 30 to 60 km.

Region II - Highlands and high plateau: This represents a large area of the country. It stretches longitudinally from the north to the south and transversally from the west to the east, resembling the letter "L". These heights descend in different directions. There are a number of basins, of considerable agricultural importance. The elevation in this region is in the range 1000-3666 m. Al-Qafr area is located in this region. Generally, topography is mountainous characterized by medium to low elevations (up to 1300 m above sea level) at Mount Wallan in Mmsaa Dagmar area, increases the elevation in parts of eastern and north-eastern direction of Yarim, as well as we head into Ottmah and Wasab areas. Their valleys are narrow to open in the eastern parts a wide and tendency simple as we head west, where the water flow in most of the seasons of the year (Figure 3).

Region III - Hadramawt – Mahra uplands: This area lies to the east and south of the heights going in parallel to the heights towards the Empty Quarter. The maximum elevation of this area is 1500 m in the western part and 1000 m in the eastern part.

Region IV - The Empty Quarter (Alrub AlKhali) and Ramlat As Sab'atayn: This is a Yemeni desert area located to the north of the Hadramawt highlands, and to the south of the western heights. This area consists of desert plains covered with gravel, sand and sandy dunes.

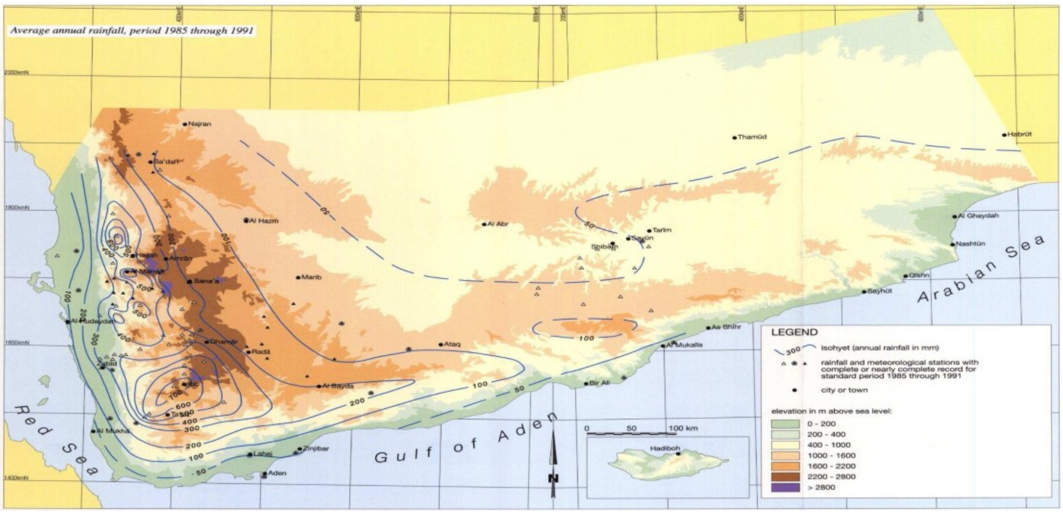

FIGURE 2: Topographic map of Yemen with average annual rainfall for the period 1985-1991, (WRAY-35, 1995) with hexagon marking the location area

In general, the climate varies from part to another, but the Yemen highlands are characterized by two rainy seasons: (1) spring, from April to May or June and (2) summer, the more important of the two, from July through September. Much of the rainfalls occur in torrential showers. Southwestern part of Yemen, notably the region around Ibb, receives the greatest precipitation in the country. Rainfall is controlled by the monsoon, and it is estimated that the average annual rainfall higher than 250 mm are only observed in the western and southwestern parts of the Yemen mountainous area, with the maximum rate near Ibb (1510 mm). Anywhere else the average annual rainfall is low. The average temperature ranges from 10 to 19 °C in summer and from 8 to -1 °C in winter. In Al-Qafr geothermal field low area where thermal manifestations the average temperature ranges from 19 to 25 °C in summer, and annual rainfall varies between 400 and 500 mm which is more or less permeable surface (Figure 2).

FIGURE 3: landscape of Al-Qafr geothermal field

1.4 Seismic activity in Al Qafr area

Several historic earthquakes have been reported between the sixth and the nineteenth centuries (Annual Seismological Bulletin, since1994). Most earthquakes are concentrated in the Gulf of Aden, the Red Sea, Afar and the western continental province of Yemen. Intensity of the earthquake of 1982 was determined at 7.6 on Richter scale (Mattash et al., 2005). It means that Yemen is far from being a stable continental zone. Most earthquakes in Yemen occur within two main trends of regional faults, faults parallel to the opening of the Gulf of Aden (appears as throng in Tihama plain perpendicular to the general trend of the Red Sea) and the faults parallel to the opening of the Red Sea such as earthquakes in Ibb governorate.

Seismological Observatory Center has reported 19 earthquakes in 2003 in which the highest reached 2.7 on the Richter scale. It is noted that the region is a witnessing of drop in seismic activity in comparison with what was happening in the year 1998. It is worth noting the occurrence of earthquakes annually in the area of Ibb and nearby areas of Al-Qafr such as Al-Odain area (Figure 4).

1.5 Methodology

Mapping of geothermal surface manifestations is very important in the exploration of geothermal resources. In order to achieve the main goal of this research and verify the relationship between the tectonic setting of the study area and the hydrothermal alterations and geothermal resource exploration, geological survey was carried out during April and May 2011. The local points and tracks of cold and warm springs, wells, and tectonic structures were all recorded by GPS (Garmin 60 CSx), in addition to mapping the main rock units and the areas that show hydrothermal alteration of different types are also considered. Aerial photographs and landsat7 images have been used to trace the aerial extent of the major structures and their distribution within the study area. These photos were combined with topographical map (scale 1:50,000) in order to draw these structures. Sampling was also carried out to better understanding the type of alteration. The clay and altered samples were analyzed using XRD technique. All the received data were downloaded into the computer and exported into ArcGIS and edited for final processing. Information obtained can be used to formulate a tentative geothermal reservoir model for the geothermal resource. Such a model may then be used as guide in subsequent exploratory work such as geophysical survey and exploratory drilling works.

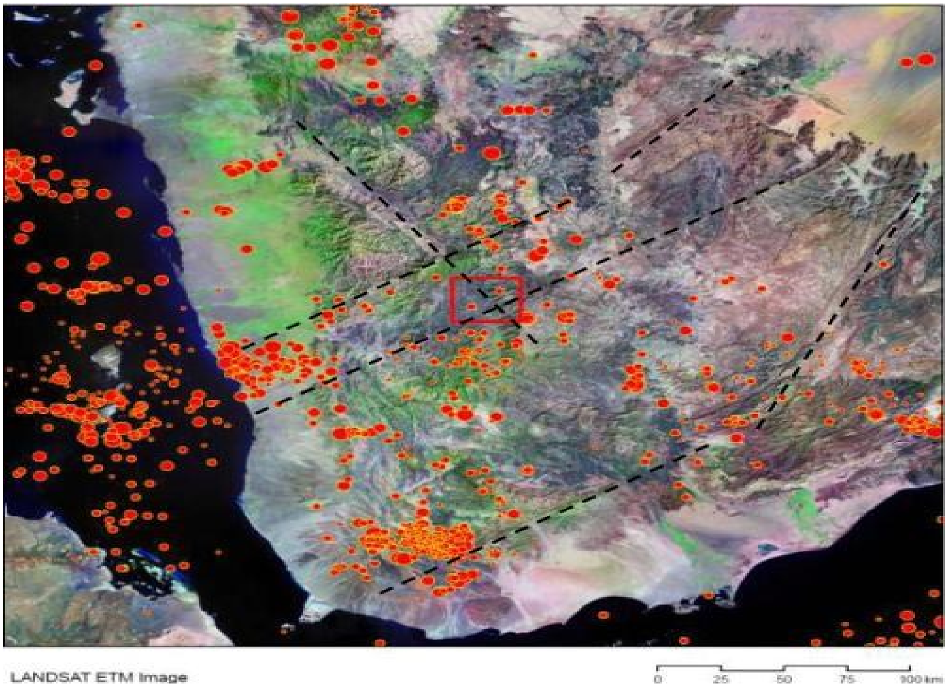

FIGURE 4: Shows quake epicenters in Yemen during the last ten years with Al-Qafr area marked by a red square and major faults (mod. after RG, 2009)

1.6 Geochemistry

During the period from 2001 to 2009 and within the framework of geothermal exploration program in western Yemen 21 water and gas samples have been collected from Al-Qafr geothermal field by an Italian -Yemeni team and a German-Yemeni team. The samples were analyzed at the laboratories of the Department of Earth Sciences at the University of Florence, Italy, and the CNR – Institute of Geosciences and Earth Resources in Florence. Some of samples were analyzed at BGR– Institute of Geosciences and Natural Resources, Germany in order to determine the following elements and compounds; Ca, Mg, Na, K, HCO_3, SO_4, Cl, NO_3, B, SiO_2, F, Br, Li, and total dissolved solids (TDS) whereas NH_4, pH, conductivity and temperature were measured in the field. All the solutes were determined with standard procedures using AAS (Analyst 100 Perkin Elmer), Ion Chromatography (Dionex 100) and Colorimetry (Philips Unicam). Water samples were collected from hot and cold springs as well as from hot well waters as follows:

1. 125 ml in a plastic bottle for the determination of anions and B; and

2. 50 ml in a plastic bottle for the determination of cations, acidified with 0.25 ml of concentrated and purified HNO_3.

Despite a lack of significant results in some of the elements such as Li, B, CO_2, $\delta^{18}O$, δD and TDS for technical reasons, but the interpretation of these results has done within the framework of full interpretation of hot spring in republic where the most important results:

- The water samples from the western regions of Yemen are associated with CO_2-rich gas. The latter increases the water-rock interaction processes that led to a higher alteration degree and favors ion-exchange reaction with Na-rich silicates. These waters thus turn to be Na-HCO_3 in composition (Mattash et al., 2001).

- The significance of the oxygen and deuterium isotope ratios ($\delta^{18}O$ versus δD) is that the values representative of the various samples have indicated the meteoric origin of these waters (Mattash, 2008).

- 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 (Mattash, 2008).

- Equilibrium temperature evaluation of the thermal reservoirs has been performed by using different liquid phase geothermometers, such as SiO_2, K_2/Mg and Na/K. SiO_2 temperatures range between 70 °C and 140 °C, the highest values being measured in Mosh Al-Kafer hot spring (Al-Qafr area) (Vaselli et al., 2001).

- The thermal waters from the volcanic areas, which have the highest pH and lowest total dissolved solids content, also have the highest REE content, in both the filtered and unfiltered aliquots (Mattash, 2008). But these results need detailed studies and confirmed by drilling. Results of chemical analysis for the samples from the 21 hot spring and wells are listed in (Table 1).

TABLE 1: Chemical composition of geothermal waters from Al-Qafr area in Yemen (Concentration in mg/kg)

no.	Locality	longitude	latitude	elev	type	T°C	pH	Cond.	pCO_2	TDS	Ca	Mg	Na	K	HCO_3	SO_4	Cl	SiO_2	B	F	Br	Li	NH_4	NO_3	$d^{18}O$	dD
1	Al Makhaya 1	44.0900	14.3119	1250	bp	96.3	7.35	nd	-1.084	1256	18	5.6	320	32	634	169	78	112	1.97	14.06	0.38	1.24	0.1	0.94	nd	nd
2	Al Makhaya 2	44.0902	14.3168	1250	tsg	75.0	6.56	nd	-0.372	1344	45	2.1	294	26	738	163	76	84	1.72	5.94	0.38	1.12	0.5	4.10	-2.32	-10.7
3	Al Makhaya 3	44.0903	14.3165	1250	bp	96.0	7.13	nd	-0.82	1282	15	5.8	315	29	689	150	78	79	3.22	6.88	0.38	1.19	0.2	0.38	-2.43	-12.2
4	Mosh Al-Kafer 1	44.0898	14.3169	1250	ts	58.0	6.35	nd	-0.25	1423	51	8.5	306	27	799	156	75	68	2.84	6.31	0.25	1	0.2	0.44	-2.44	-11.6
5	Mosh Al-Kafer 2	44.0897	14.3170	1250	r	27.3	8.23	nd	nc	533	47	33	55	2.5	302	43	51	38	3.22	0.63	0.20	<0.01	0.1	47.5	nd	nd
6	Mosh Al-Kafer 3	44.0869	14.3105	1277	ts	93.0	7.46	nd	nc	1437	20	5.9	320	23.9	637	166	73	91.2	1.13	5.73	0.30	1.06	0.1	0.2	nd	nd
7	Mosh Al-Kafer 4	44.0869	14.3105	1277	ts	61.0	6.7	nd	nc	1524	68	11.1	274	20.0	737	139	64	101	0.95	4.79	0.30	0.87	0.1	0.2	nd	nd
8	Mosh Al-Kafer 5	44.088	14.3136	1340	ts	63	6.37	3.45	-0.45	nc	70	18	330	27	830	203	87	97	nd	6.56	0.32	nd	0.05	0.29	nd	nd
9	albarty	413751	1563453	1627	w	31	7.33	0.792	nc	nc	75	21	50	1.4	348	44	25	43	nd	1	0.08	<0.01	0	35	nd	nd
10	yaksop	405445	1573763	1305	w	39	7.82	0.964	nc	nc	35	30	142	2	445	81	75	29	nd	1.3	0.08	<0.01	0	3	nd	nd
11	Bani garban	408620	1574313	1449	w	33	7.12	0.814	nc	nc	82	28	59	1	378	59	32	27	nd	0.43	0.06	<0.01	2.38	27	nd	nd
12	Bakla	407583	1574134	1428	w	31	7.32	0.865	nc	nc	78	26	56	1	384	72	27	25	nd	1	0.04	<0.01	1.20	14	nd	nd
13	Aref Hmod	44.16	14.2097	1470	w	36	7.8	0.663	-2.53	nc	30	6.3	69	1.4	185	47	37	29	nd	0.59	0.27	nd	0.05	2.40	nd	nd
14	Al Gahip	44.172	14.1953	1495	w	41	7.75	0.658	-2.69	nc	23	3.5	70	1.3	114	51	50	42	nd	0.66	0.30	nd	0.04	0.87	nd	nd
15	Sahla	44.104	14.3331	1340	w	37	7.25	3.2	-1.66	nc	119	157	190	3	384	232	441	34	nd	0.53	3.62	nd	0.05	92	nd	nd
16	Annamajah 1	44.05	14.3658	1260	tsg	66	6.48	3.5	-0.53	nc	66	14	363	28	881	160	74	88	nd	5.49	0.26	nd	0.09	0.17	nd	nd
17	Annamajah 2	44.1501	14.3135	1300	tsg	71.5	6.51	nd	-0.28	1604	67	12	358	30	872	181	84	109	1.22	6.50	0.63	1.24	0.4	0.50	-2.60	-11.7
18	Annamajah 3	44.0494	14.3655	1263	ts	67.1	6.9	nd	nc	1774	71	13	342	24	902	164	73	87.2	1.05	5.08	0.33	1.02	0.2	n.d.	nd	nd
19	Hore	44.103	14.2614	1260	ts	48	6.7	2.52	-0.79	nc	77	34	274	22	805	134	67	110	nd	3.62	0.26	nd	0.05	1.61	nd	nd
20	Al Hamrora 1	44.064	14.39	1235	w	34	6.85	2.32	-0.89	nc	53	16	398	16	909	149	83	86	nd	4.34	0.28	nd	0.06	0.03	nd	nd
21	Al Hamrora 2	44.1706	14.3220	nd	ts	44.0	6.34	nd	-0.38	1292	74	7	260	13	726	125	87	80	0.72	5.44	0.69	0.47	0.2	0.88	-2.38	-11.9

Type: ts = thermal spring, tsg = thermal spring with gas, bp = boiling pool, w = well, r = river, d18O and dD in 0/00 SMOW, nd = not determined, nc = no calculated

2. GEOLOGICAL MAPPING

2.1. Background

The complex geologic setting of Yemen is the result of regional tectonic forces and geological events due to its location at major geologic plate boundaries (figure 5 and 6) characterized by large outcrops of Archean–Proterozoic metamorphic basement blocks belonging to the Arabian Shield, covered by rocks of Ordovician, Permian, Jurassic, Cretaceous, Tertiary and Quaternary age (Beydoun, 1966; Robertson Group Plc., 1992; Mattash, 1994; Beydoun et al., 1998; As-Saruri, 1999). These units can briefly be summarized as follows:

- Basement and metamorphic rocks are found with grades from greenschist to lower amphibolite facies, where the final deformation event occurred between 950 and 450 Ma.
- Ordovician (Wajid Sandstone) a mature quartzose fluviatile deposit was deposited on a gently sloping surface of eroded basement.
- Permian glaciomarine sediments (mainly shales).
- Jurassic fluvial sandstone, followed by carbonate platforms sequence (Amran Group) and accumulation of organic-rich shales in the Jawf Graben, as part of the Gondwana break-up (170–160 Ma).
- Cretaceous limestone marine sedimentation, followed by fluvial sandstone (Tawilah Group) Paleocene marine deposition of carbonates (Umm Er-Radhuma Formation) followed by faulting and uplift from late Eocene and extension in Miocene culminated with the separation of Arabia from Africa along the Red Sea and the Gulf of Aden.
- Rift formations of the Gulf of Aden, Red Sea and Afar triple junction. This rifting activity produced the Yemen trap series (YTS) with extensive basaltic bimodal volcanism, which known as Tertiary volcanic (31.6-15 Ma).
- Post-rifting volcanic activity resumed in central and southern Yemen, which Known as Yemen volcanic series (YVS) or Quaternary volcanic 10 and 5 Ma ago (Mattash, 1994; Minissale et al., 2007).

2.2. Geological setting and lithological units of Al-Qafr geothermal field

Generally, the geological setting of the Al-Qafr area is dominated by Tertiary basaltic rocks (YTS). Furthermore, younger tertiary peralkaline rhyolite flows, tuffs, ignimbrites and dikes occur in that area (Strachan and Diner, 1997; Wagner et al. 2007; Mattash et al., 2009). Extensive laminar travertine plateaus occur along an area of few kilometers close to Mosh Al-Kafer. Mesozoic sediments such as the permeable Tawilah Group Sandston is present as small outcrops in the east, southeast and northwest parts also there is one outcrop of Amran Group limestone. The existence of the latter is indicated by the siderite, aragonite and travertine terraces and the recent precipitations in the surrounding area. Quaternary deposits found in isolated basins and narrow wadis channels (Figure 13).

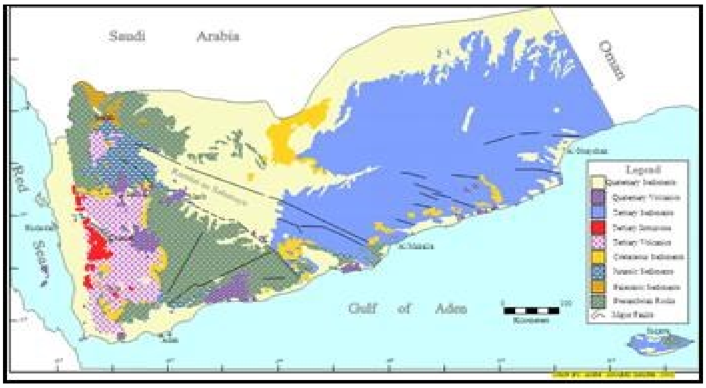

FIGURE 5: shows generalized geological map of Yemen

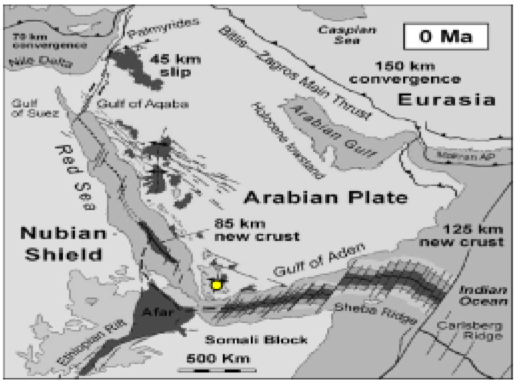

FIGURE 6: Generalized map shows the extensional areas in the Gulf of Aden and the Red Sea, with study area in yellow circle.

The chronological sequence of lithological units is as follows:

• Pleistocene to Holocene – Quaternary	travertine, Alluvial and wadi gravel
• Paleocene Tertiary volcanics	Yemen Trap series (YTS)
• Mesozoic - Cretaceous	Tawilah Group sandstone
• Mesozoic - Jurassic	Amran Group limestone

Amran Group Limestone (Mid to Upper Jurassic): In fact there are several formations within Amran Group, but in Al-Qafr area there is one small outcrop present as the upper formation (sandy limestone) at south of Annamajah hot spring area, lenses of gossan and some bodies of siderite and aragonite close to the hot springs sites especially near Mosh Al-Qafer hot spring are also reported.

Tawilah Group Sandstone (Cretaceous): This group consists of cross-bedded continental sandstone. It lies directly above the Amran Group. The sandstone beds have thicknesses up to 100 m in southern part of the study area and small outcrops in the northern and eastern parts. In some parts quartzite is reported as result of contact with Tertiary basalt also slickenside due to faults. The sandstone varies from typical sandstone to pebbles (Al-Kubati, 2005).

Tertiary volcanics, Yemen Trap series (YTS): Genetically, the YTS has been associated with the Tertiary continental and oceanic rifting (the Gulf of Aden and the Red Sea), and also with the geodynamics of the Afro- Arabian lithosphere plates in the late Oligocene-early Miocene (Mattash, 2006). Tertiary volcanics rest directly on the Tawilah Group and the metamorphic basement, and consists of thick bimodal volcanics including alkaline to mildly alkaline basalt lavas and peralkaline rhyolites and their associated ignimbrites, tuffs and rhyolitic obsidian (Mattash, 1994, 2009). Thickness of the YTS may reach up to 2000 m; but in study area this thickness is decreased toward west.

It is clear that the lower parts of the volcanic sequence of study area begins with olivine basalt rocks to picritic basalt, then trachybasalt which indicates high partial crystallization rate of magma with a little processes of mixing magma. The upper parts of the volcanic sequence, which represent by ignimbrite, andesitic ignimbrite, Porphyritic rhyolite, glassy welded rhyolitic, which are possibly formed by mixing processes magma. The presence both of phenocrysts of plagioclase and xenoliths in all rock types indicate that mixing processes magma.

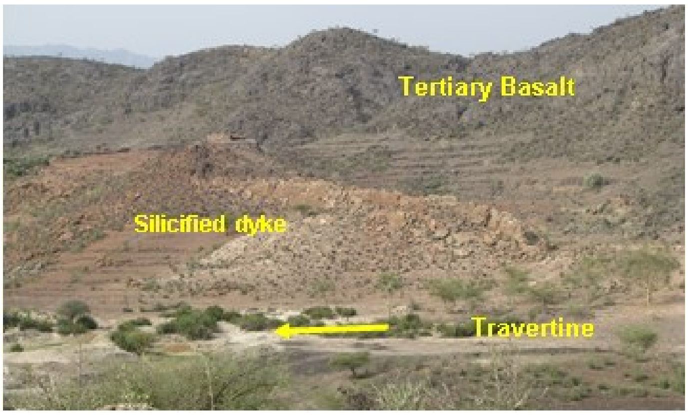

FIGURE 7: Geological setting near Mosh Al-Qafer hot spring

FIGURE 8: Volcanic neck in Al-Qafr geothermal field

Quaternary deposits:

Quaternary deposit are represented by wadis and outwash plain deposits such as gravel, sand, silt and loess also basin alluvium (mafic origin) especially in south part. Travertine deposits and sabkha deposits are present along of main fault such as Annamajah hot spring.

2.3. Structure setting

The study area is affected by intensive faulting trending NNW, NW and by secondary faults striking N-S, E-W intersect or orthogonal sometimes with each other, all these faults are mapped (Figure 7). Most other fractures, faults, veins and dikes strike north within 340° and 020°. All this structural patterns are related to volcanic regions (western Yemen) and associated with major tectonic components of the Red Sea and the Gulf of Aden rifting. The most important fault in area (315-330) which controls almost all geothermal manifestations is parallel with the main Red Sea trend.

FIGURE 9: slickenside in Sandston rock near of main fault at northern part of the study

FIGURE 10: Step faults near Al-Hamrora hot spring with down throw to the north east

Hot springs in Mosh Al-Qafer and Annamajah are associated with the major NNW fault system. Possibly, deep faults are cutting a deep hot aquifer below the low permeable Tertiary volcanics and open pathway to the surface for near-boiling fluids (Wagner et al. 2007). NE trending faults in the volcanic area follow the transform system in the Red Sea trough. East-west structures and less commonly north-south faults have very important role in controlling epithermal mineralization (Mattash, 2006). Brecciation and slickenside considered as additional evidence for alteration and faulting (Figures 9 and 10).

2.4. Dikes

Several dikes have been mapped in the study area. Basaltic dikes are common and the largest are located in the northern part especially southeast of Al-Hamrora hot spring. They trend NW-SE, some dikes are found in the Midwest part where they cut altered basalt or in some areas hyaloclastite rock (Figures 11 and 12). Dikes are considered to be feeders, as they have considerable length and width (0.6-3 m) (Figures 26). Generally, dikes in the study area trend E-W, NE-SW, NW-SE and are fine grained porphyritic alkali olivine-pyroxene-plagioclase basalts. Others are aphanitic basalt except felsic or silicified discontinuous dike that is located closer to Mosh Al-Kafer hot spring area having a N-S trend, it can be suggested that this dike is related to hot spring discharge. Pale colored dikes are affected by alteration and weathering.

FIGURE 11: tow dykes of basalt (NW-SE) in the north east of the study area

FIGURE 12: Basaltic dyke striking N80°E in the Midwest part of the study area

3. GEOTHERMAL MAPPING

The Al-Qafr area has been affected by geothermal activities in several sites. This can be seen clearly from the geothermally altered rocks in the area. So, in order to determine the distribution of the altered zones and the degree of alteration geothermal mapping was carried out. Samples were taken in the altered areas to figure out the mineral assemblages. The collected data were downloaded into the computer after each field mission and edited by the GIS Programme. The final result was a geothermal map on a scale of 1:50,000 produced by a GIS department in GSMRB. (Figure 24) shows the geothermal map.

3.1. Geothermal manifestations

Within the research area the main geothermal manifestations are located in middle to Midwest map along main fault valley and they are represented by 6 active sites of hot spring each of site contains several hot discharge water, 16 hot wells, and several alteration sites. Most of them associated or located on or near intersection two or more faults especially NW with NE direction. Mosh Al-Kafer site is the most important (Figures 14 and 15). This active site is characterized by dikes of silicified and bodies of calcium carbonate, iron carbonate and deposits of travertine along the Valley and the site.

The largest hot spring area is Annamjah site which is characterized by bubble CO_2 gas discharge with water and travertine deposits seem to be common around the hot springs as a sabkha (Figures 16 and 17), the temperature ranges in this site between 66 and 71.5 °C. Warm and cold springs also occur in the area, the temperature of these springs is 44-48 °C. They are usually run-off surface water that seeped through surface deposits above the thermal manifestations. Numerous hot wells are observed in the area, with temperature ranges between 31 and 41°C and occur at elevations from 1235 to 1627 m above sea level. The coldest groundwater springs were about 27.3°C.

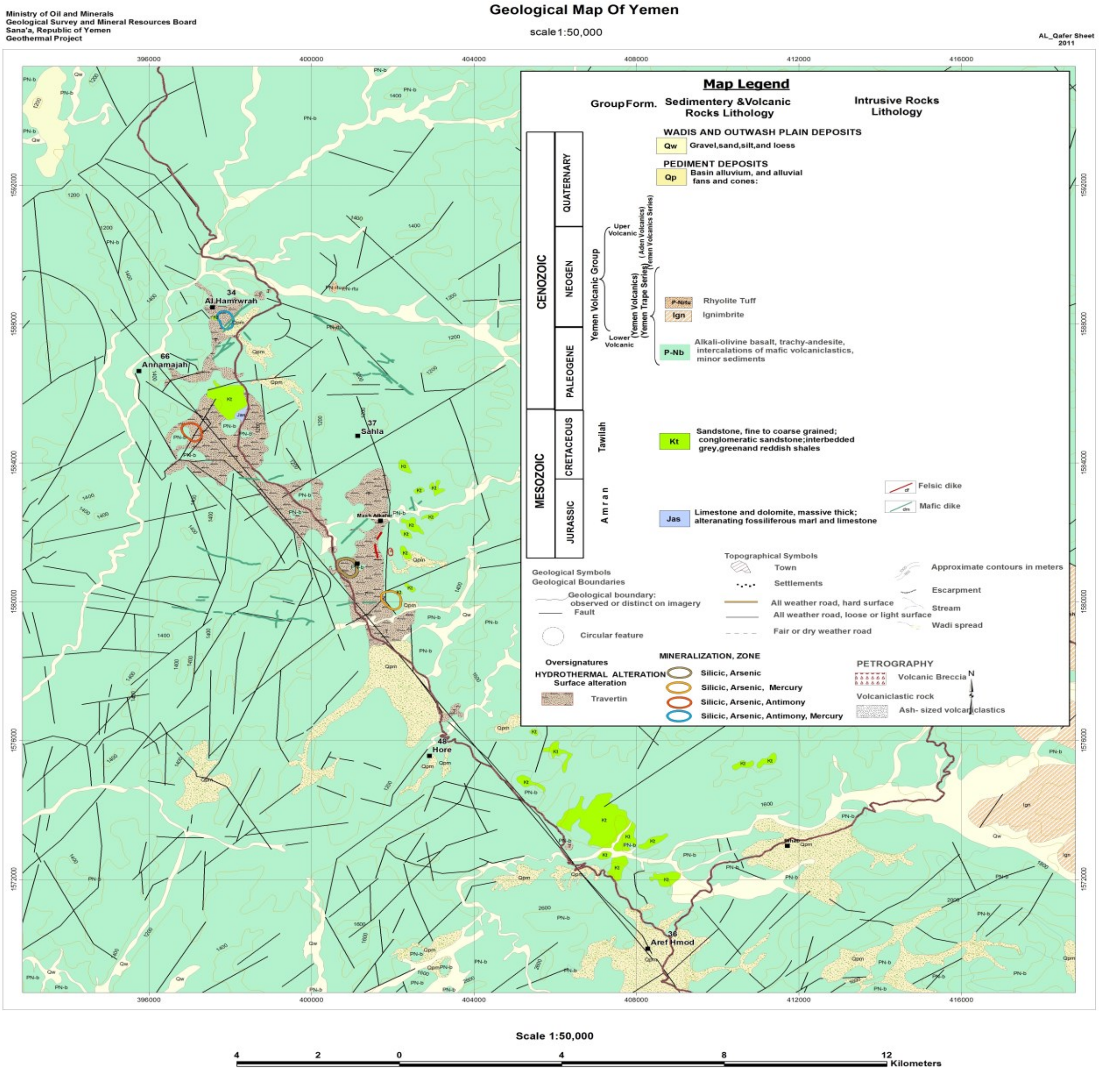

FIGURE 13: Geological map of Al-Qafr area

3.2. Surface alteration

Hydrothermal surface alteration, hot or cold, indicates the presence of a hydrothermal system beneath. Therefore, mapping surface alteration is useful in delineating a hydrothermal system. The magnitude of alteration is dependent on the rock type, temperature, permeability of the rocks and water composition (Tomasson et al., 1974).Generally, the surface geothermal alterations in the study area are found to be intense to weakly (slight alteration) on the Midwest along main fault valley. The occurrence of alteration and distributed along this fault clearly indicate that a geothermal system in area relates to tectonic structure setting. There are some local hydrothermal alteration zones in other parts of the study area.

FIGURE 14: Calcite precipitation at Mosh Al-Kafer

FIGURE 15: Boiling pool at Mosh Al-Kafer

However, results of XRD analysis for samples showed three major types of hydrothermal alteration: 1. zeolite-calcite alteration, 2. clay alteration, and 3. silica-plagioclase feldspars alteration. But at the surface two kinds of alteration were recognized during mapping, slight alteration and clay alteration. In weakly altered areas silica-quartz and calcite were the common minerals. In some samples, zeolite was found to be a secondary mineral. A lot of calcite was found to be deposited on the surface as travertine or in fractures of siderite, aragonite and basalt rocks (Figure 18).

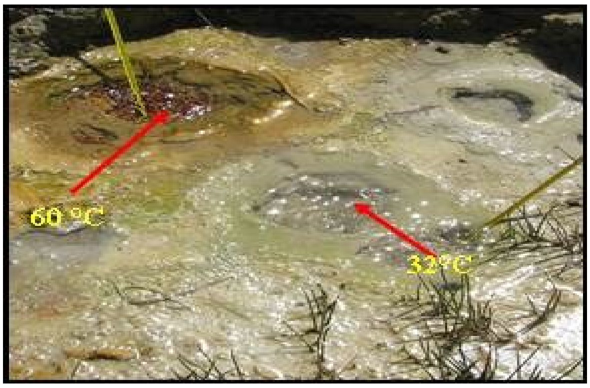

FIGURE 16: Annamajah hot spring

FIGURE 17: Gas discharge at Annamajah hot spring

Slight alteration is determined by the presence of secondary minerals in the rocks such as calcite-Zeolite alteration, this alteration is found in the form of white mineralization that fills the pores within the basaltic and carbonates rocks like Siderite and Aragonite (Figure 19). The analysis shows three types of zeolites such as mordenite (80 – 240 °C) (Saemundsson, et al., 2002), faujasite, stellerite (Figure 20), this latest is considered the most important due to temperature range is formed (200 – 400 °C) (Alberti et al., 1978) in addition to the presence of calcite, quartz, plagioclase feldspars especially samples that taken from deposited minerals on wadis (like QF-2, QF-3, QF-8) , or from veins. Travertine was seen at most of sites and then mixed with soil.

FIGURE 18: Poker chip calcite crystals in siderite

FIGURE 19: lens of quartz, opal in west area

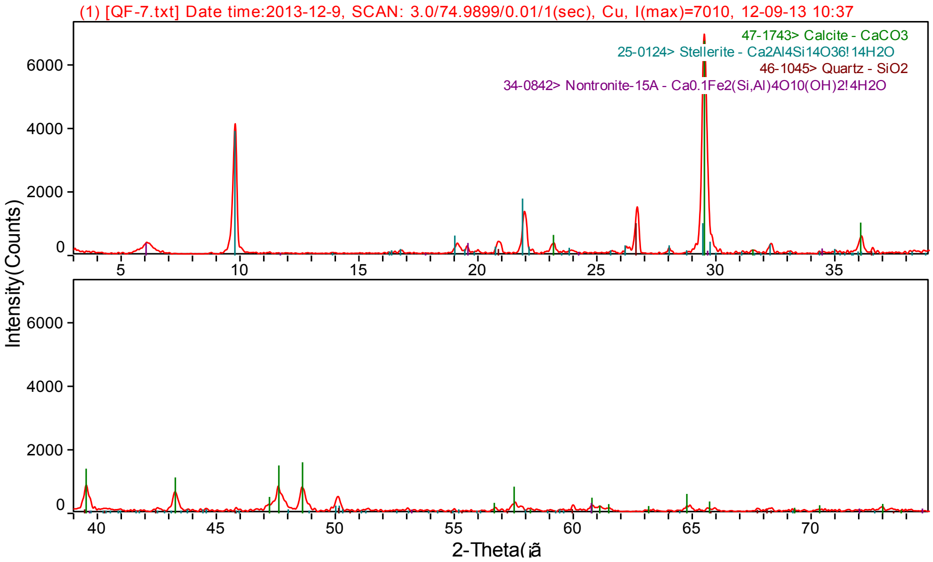

FIGURE 20: XRD analysis of sample No. QF-7 from Al-Ramaha west study area

Clay alteration, one type of clay alteration could be recognized in the study area is weak-partial to extinct within basaltic rocks. Clay samples from the alteration zone near Mosh Al-Kafer and Hore hot springs were analyzed by XRD to determine the type of clay; it was shown to be kaolinite, illite, nontronite (Figures 21and 22). Gradation of colours within the original material caused by alteration was observed. Colours ranged from pale brown, reddish, and yellow to white depending on the degree of alteration.

The presence of minerals such as quartz, opal (silicification), clay minerals (kaolinization), fluorite, dolomite, calcite, zeolite, trace of chalcopyrite, malachite, azurite (results of XRD analysis) and arsenic, antimony (O. R. Ltd, 1997) also some spot of gossan (oxidation) may indicate that the area of study affected by hydrothermal type of epithermal to mesothermal in temperature range between 50 – 250 ºC in depth near to the surface.

The presence of kaolin in the analysis of clay samples (like QF-1 and QF-4) by XRD within alkaline rocks like basalt, (kaolin seldom forms in alkaline environments), and this confirms that the area of study has undergone acid leaching of the rocks (Figure 23). Within the clay alteration in Mosh Al-Kafer ulexite satin spar gypsum mineral was found (Figure 22). Some of plagioclase likes anorthite; albite was also detected in samples QF-9 andQF-5.

FIGURE 21: Travertine deposits with illite, calcite, quartz alteration

FIGURE 22: Clay alteration of kaolinite, dickite, hematite, and ulexite

3.3. Primary conceptual model for Al-Qafr geothermal field

The geothermal model of the study area (Figure 25) implies the presence of a heat source focus in Midwest that is responsible for all geothermal alterations and shows that the possible heat source is found at deeper levels, to the south and east
The conceptual model assumes a boiling reservoir at some depth below the surface with the active geothermal surface manifestations. From the geothermal conceptual model, the geothermal system seemsto be more active in the Midwest than in the east or south. This implies that the system is cooling down because of recharge water from east and south. Heat is transferred from hot rock into groundwater descending through faults and fractures.

There is a high probability that heat source from large dikes which heated groundwater due to the bases of those dikes connected by magma chamber. Therefore, the chief effect of the Al-Qafr area dikes and faults is to guide the geothermal fluids upwards (Figure 26).

In order to envisage the underground conditions of the researched area and based on the geological and geothermal maps (Figures 13 and 24), the primary conceptual geothermal model of the study area almost from east to west was sketched (Figure 25). This model is used to show schematically the geothermal conduits to the surface manifestations.

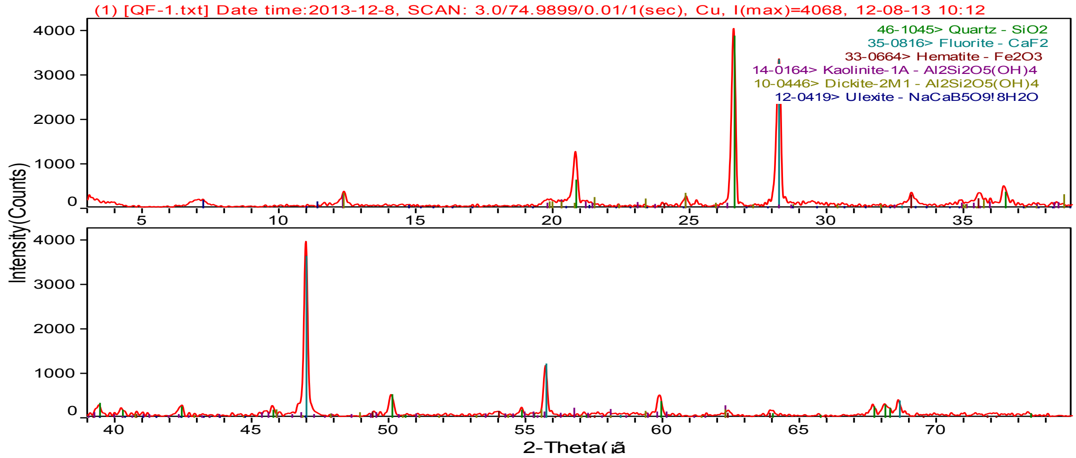

FIGURE 23: XRD analysis of sample No. QF-1 from south Mosh Al-Kafer hot spring

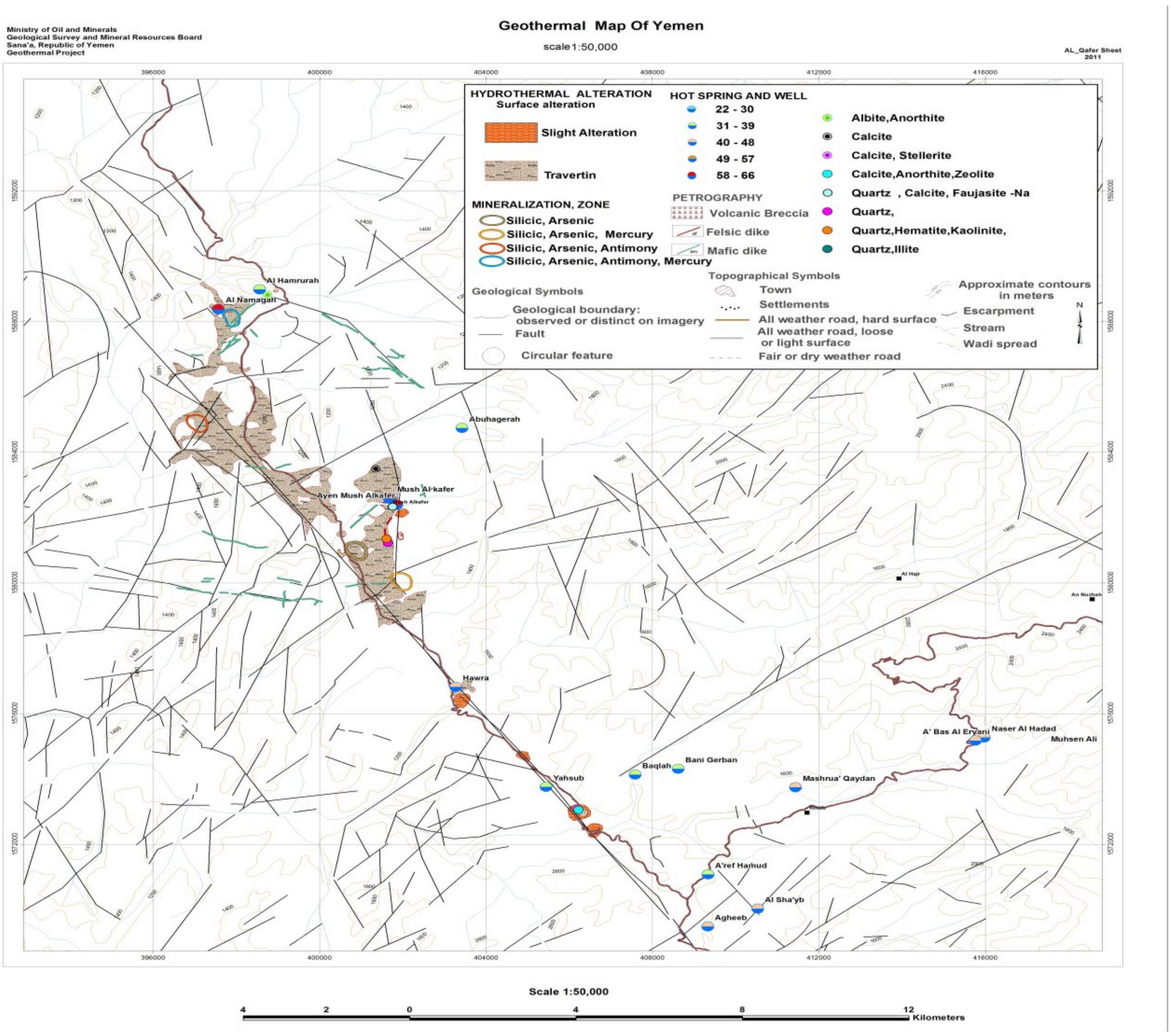

FIGURE 24: Geothermal map of Al-Qafr area

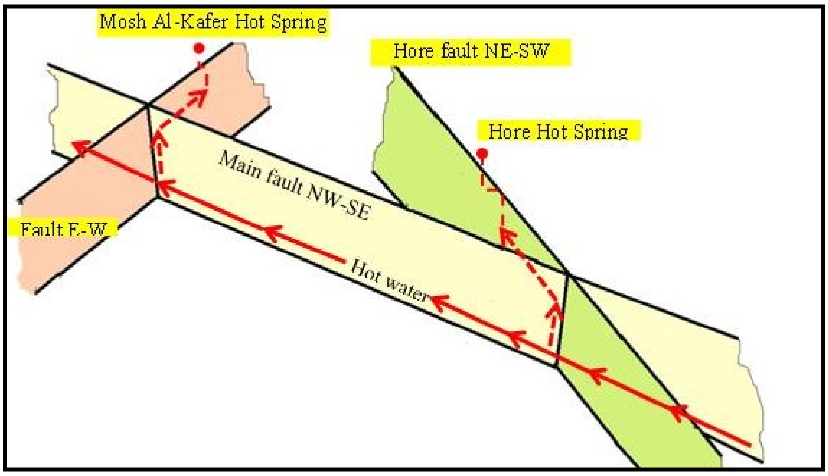

FIGURE 25: Conceptual Model of Al-Qafr geothermal field

FIGURE 26: Largest dike in the study area

CONCLUSIONS

- Exploration of geothermal sources in Yemen has been conducted since 1982 and scientific studies have been carried out since 2001 to assess the energy potential and possible use of geothermal energy for direct and indirect utilization in Yemen; until recently, these sources were only used in tourism, bathing and for irrigation purposes.
- Tectonic structures in AL-Qafr geothermal field seem to have a significant influence on the distribution of the geothermal manifestations, since faults and fractures work as channels where hydrothermal fluid finds its way towards the surface. The most active geothermal areas are above and along faults with downthrow towards Midwest.
- The NW-SE linear distribution of alteration and hot springs trending in the same direction as the main fracture system suggests the geothermal system is structurally controlled which is parallel to the main Red Sea trend.
- It could be noticed from the geothermal map that the geothermal alterations have the same trend as that of the main zone fault zones in the study area. Some of these alterations are associated with faults such as the slight alteration near the Mosh Al-Qafer and Hore hot springs.
- It was noticed in the field that the geothermal alteration is quite old, as can be clearly seen in the most of study area, where alteration affected the older and withering part of volcanic basalt unit.
- The geothermal system is seemingly cooling down due to extinct clay alteration and the deposition of secondary minerals which reduce porosity and permeability.
- There is no doubt that the numerous fissure systems are responsible for the recharge of the system from precipitation especially from the Highlands eastern parts also there are some intersect faults especially N-W with N-E or E-W are responsible for outflow zones.
- Calcite precipitation, attached to most hot springs and presence of silica like quartz, guide to the passage of hot water through the Amran limestone and Tawilah sandstone rocks at subsurface.
- Colour changes in vegetated manifestations, of yellow to green moss and grass, reflect temperature distribution pretty especially in Annamajah and Al Hamrora hot springs, the yellower the hotter.

RECOMMENDATIONS

- It is highly recommended to carry out detailed geological and geothermal studies such as surface geophysics, exploration drilling of Al-Qafr geothermal field for better understanding of the history of the area, especially the Midwest part.

- There is a need to create and increase awareness among decision makers and politicians on the importance of geothermal energy as a clean renewable energy source and the mobilization of funds for detailed geothermal resource assessment.

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