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Geothermal Exploration in Damt Geothermal Field, Dhala province, Western of Yemen

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ABSTRACT

Damt geothermal field is one of the five significant geothermal fields in Yemen, which are (Al lisi - Isbil, Al Qafr, Damt, Taiz and Red Sea lowland geothermal field). Damt geothermal field is located in Dhala province, in the east-western part of Yemen and 200 km away from the capital city, Sana'a. Geology and geothermal detailed explorations carried out by the Yemeni Geothermal Development Project (GDP) team and presents in this paper. The main geothermal manifestations and surface hydrothermal alteration mapped include thermal springs (some of them associated with gas discharge), hot domestic wells and Travertine outcrop (Harada) along with slight hydrothermal alteration. Geochemical study executed by GDP in cooperation with CNR and BGR in order to estimate the subsurface temperature and define the chemical properties of the fluid. Fifteen thermal springs and other hot or cold domestic wells analyzed in Italy and Germany laboratories whereas temperature, PH and conductivity were measured during field trips. Surface temperature ranges from 31°C to 52 °C and pH measurement ranges from 6.4 to 9.4. The results of the chemical analyses indicated that this water belongs to the Ca-bicarbonate-Cl-Na water type, which mainly caused the high erosion in the ground to form Travertine deposition. Moreover, the radon measurement shows that as the temperature increased the radon ratio decreased in hot springs and domestic wells in Damt. Traditionally, the geothermal potential in Damt like everywhere else in Yemen is restricted to direct uses for balneology purposes for many years (including bathing and swimming) which is in general estimated in 2020 to be 5.0 MWt and 100 TJ/yr. The geothermal resources in Damt should be better developed indirectly for power generation and used as well for greenhouse and CO_2 or H_2S gasses exploitation.

1. INTRODUCTION

Yemen's high geothermal energy potential is based on the special location of the country in a tectonically active region at the southwestern edge of the Arabian Peninsula where the East African Rift meets the spreading zones of Red Sea and Gulf of Aden. The tectonic plate's boundaries, which accommodate the relative motion between the Arabian African, Eurasian, and Indian plates formed two of which active tectonic faulting systems N.NE and N. NW in the region trending parallel to the main Red Sea trend and Gulf of Aden. Most thermal zones in Yemen are parallel to the main Red Sea trend whereas the thermal features along the southern coastal plain parallel to the main Gulf of Aden trend, which connect to the opening of the Red Sea graben and the separation of the Arabian shield from Africa as shown in Fig 1. The major tectonic elements associated with the surface manifestations of

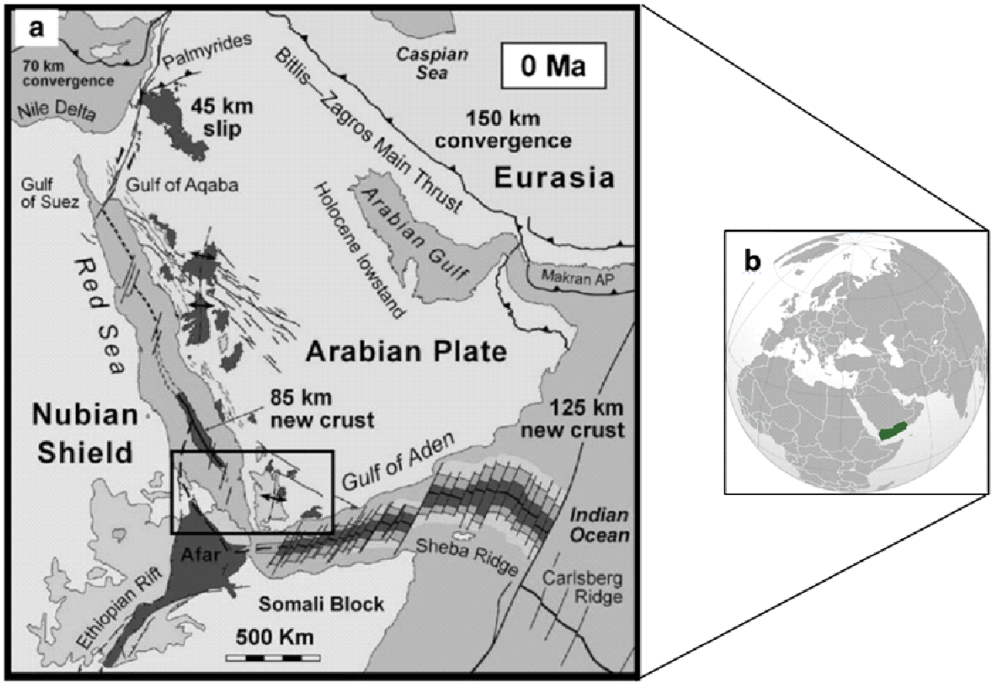

Figure 1: General map of the Afro-Arabian rift system, comprising the Red Sea, the Gulf of Aden and Afar triangle.

geothermal activity during the Cenozoic and Mesozoic have shaped the geological structures observed in the area today (Mattash, et al. 2013). According to recent geothermal studies and rely on previous work during the 1980ies, Yemen has five geothermal fields for harvesting geothermal energy, which are Al lisi and Isbil (Dhamar province), Al Qafr (Ibb Province), Damt (Dhala province), the Red Sea Coastline and Taiz (Taiz province) geothermal fields. Furthermore, the studies (geothermal surface exploration, geothermal mapping, geochemical, hydrogeology and geophysical studies and environmental assessment), which have been carried out by the GDP team since 2000 indicated that there was a project to drill the first geothermal well and build geothermal power plants for electricity generation in Al lisi and Isbil geothermal fields at Dhamar city. It represents the most promising field that is close to the national transmission network. The power plant would have constituted a total capacity of 125 - 250 MW, backed by a power purchase agreement (PPA) model (Ersoy. S 2022). Although the initial drilling preparation works had started, the project was suspended because of the war and conflict in Yemen. Al lisi - Isbil, Al Qafr and Damt geothermal field are competitive and economically feasible due to lack of electricity in the country, daily population growth and their proximity to agricultural regions and to the national grid and could potentially generate 28.5 GW (Al shetwi. A 2021).

2. OBJECTIVES OF THE STUDY

The GDP team carried out several studies in Damt geothermal field in order to find probable correlation existing between geothermal, volcanic, hydrothermal as well as tectonic setting and structural patterns in this field. The study results represented by: - 1) Mapping the geological and geothermal manifestations with a scale of 1:50,000. 2) Conducting geochemical measurements of hot and cold water. 3) Measuring the radon gas in water. 4) Carrying out periodic measurements of the study area. 5) Inventorying and studying of craters and Travertine outcrops that cover Damt.

3. LOCATION AND ACCESSIBILITY

Damt located in Dhala province, south of Sana'a the capital of Yemen and 54 km north of the administrative center of Dhala city. Damt geothermal field covers about 371 km², bordered by Qataba district (south), and Al Radma district (north), Goban district (east) and Alnadra district (west). The study area is located within (44°39’05" to 44°41’00” E; 14°04’48" to 14°06’10” N) and is known for the occurrence of several natural thermal springs over an area of about 25 km². Damt location nearby urban areas provides a good accessibility and a moderate connection to existing electricity grid and market.

4. GENERAL GEOLOGY OF DAMT

Damt geology frame is visualized in Figure 2, the Quaternary volcanic in the form of deposits and Travertine outcrop rest over the cretaceous Tawilah sandstone (Mesozoic), which exposed in the eastern part of the study area. Tawilah sandstone is the potential recharge aquifer of the region that underlie the Tertiary volcanic. From the stratigraphy, the Tawilah sandstone lies comfortably above the Amran limestone (Jurassic), however the contact between them is not visible around Damt. Tertiary volcanic series in Yemen (YTS) dominate the surrounding valleys and mountains of Damt (200 m thick) but mighty as shown in Fig 3 in comparison to other regions of central Yemen (2000 m thick).

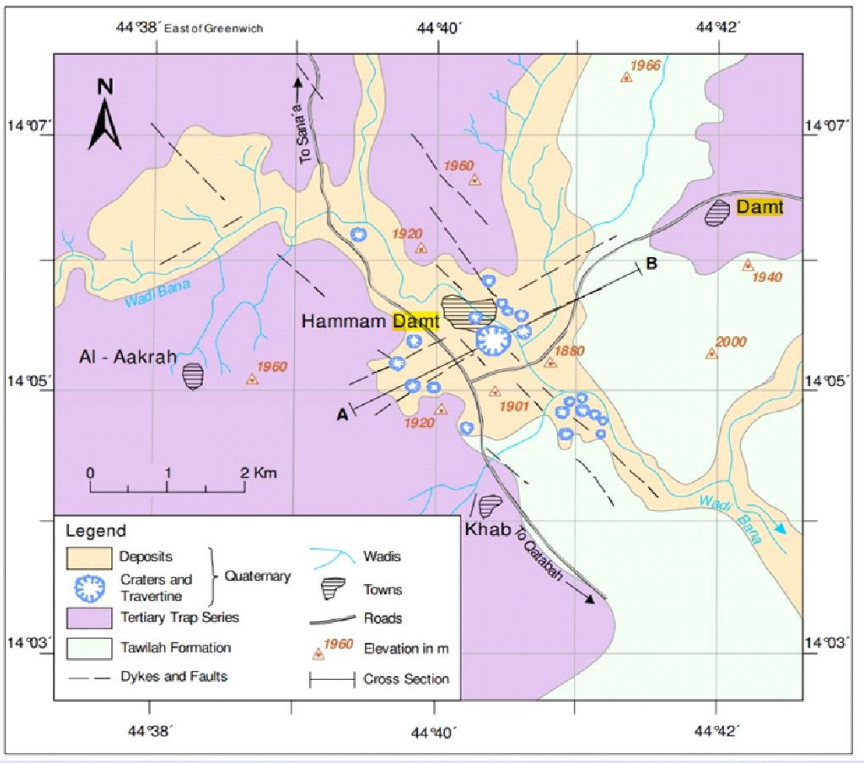

Figure 2: Sketch map of Damt area (modified after (El-Anbaawy. M 1993)**).**

Several craters of Travertine represent the final phase of the Quaternary (Holocene) volcanic activities exposed around Damt with NW-SE direction. The crater called Harada, which produced lavas of rhyolitic composition and widely covered with thick calcareous sinter deposits. Haradas consist of yellowish-brown carbonate and greyish limy terraces along NNW linear faulting trends at the boundary of YTS and Tawilah formation. The Travertine formation deposit is probably due to discharge of CO2-rich waters from fluids influenced by the Amran limestone that occurred on the base of Tawilah Sandstone. The hydrothermal system is mainly controlled by Quaternary tectonic and volcanic activities. Intensive tectonic and volcanic activities superimposed the region morphology. Structural features are represented by several extensional faults and fracture systems during the Quaternary striking NW-SE, almost parallel with the regional tectonic trend (Red Sea trend).

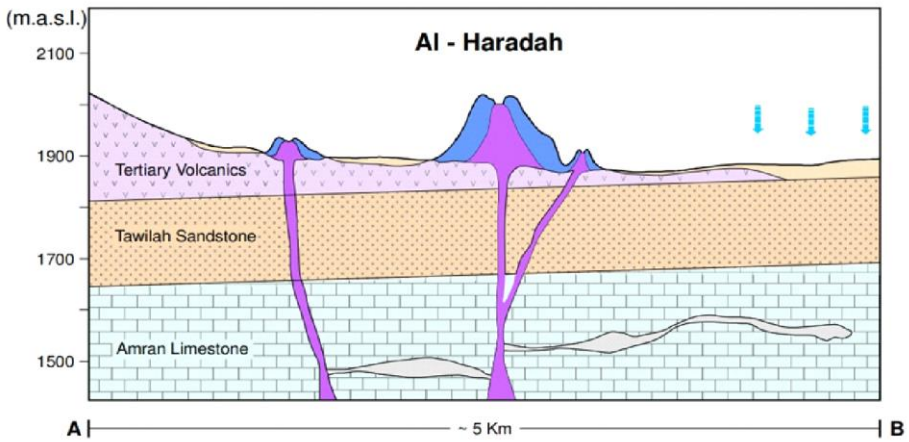

Figure 3: Geological cross section of Damt area, modified after (El-Anbaawy. M 1993)**. Location of profile in Figure 2.**

5. HISTORY OF THE GEOTHERMAL EXPLORATION IN DAMT

5.1 Geological mapping

Previous geological map was prepared by the German Institute for Geosciences and Natural Resources (BGR) in 1991 with the scale 1:250,000 and the topographic map produced by the military survey department in 1978 (scale 1:25,000). These maps and in addition to digital satellite images were used for the original drafting of the geological and geothermal maps. Reconnaissance geological and geothermal surveys were carried out by GDP from 2001 until 2012 covering Damt geothermal field. During this work, the GDP team produced Damt geological map in the scale 1: 50,000 (GSMRB 2012). The geological map (draft) as shown in Fig 4 illustrates in detail the rock classification and structural elements.

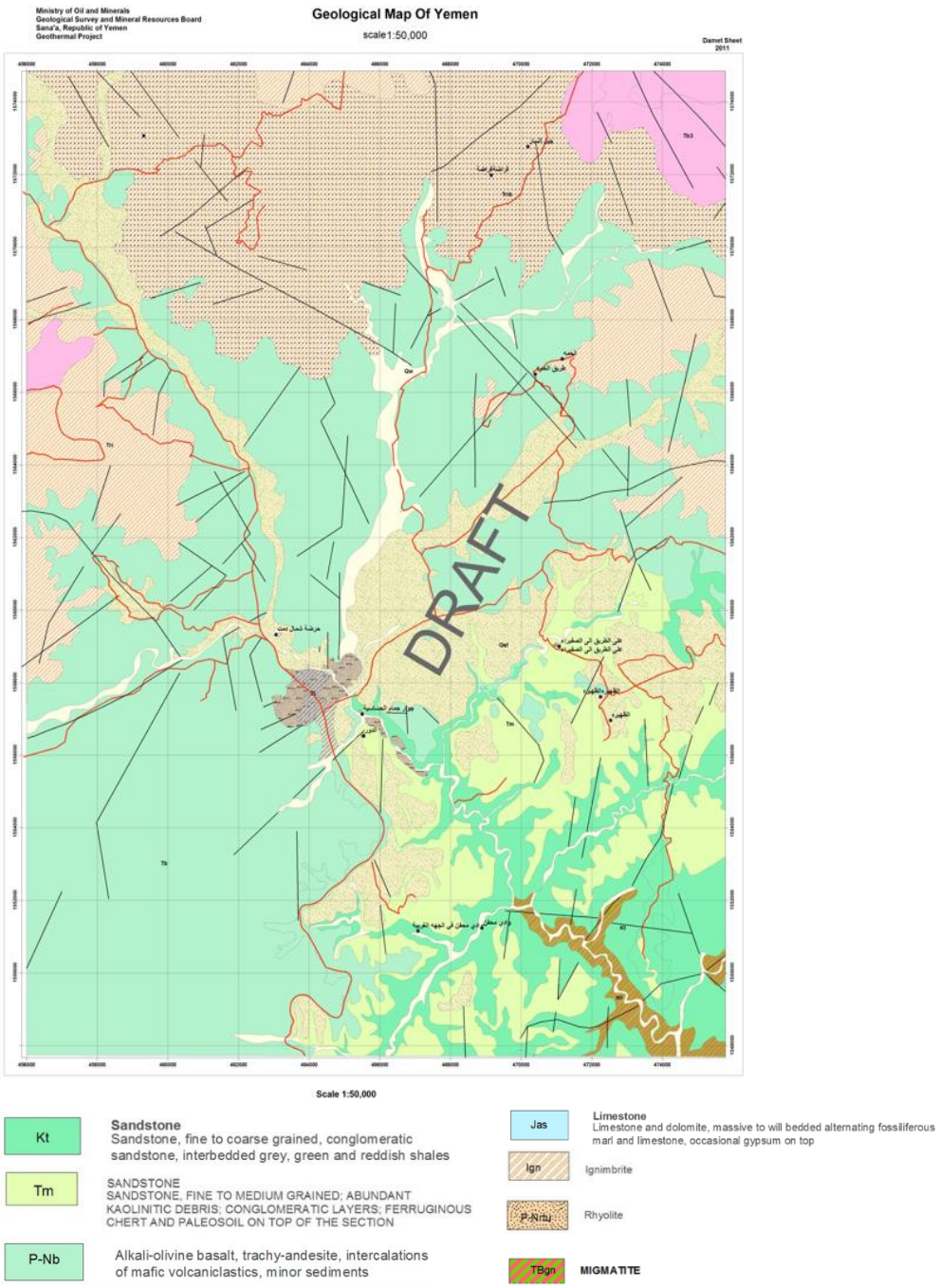

Figure 4: Geological map of Damt Geothermal Field, scale (1:50,000) by GDP team.

The study classified the rocks in Damt geothermal region into five stratigraphic units composed of Precambrian rocks (Pegmatite rocks); Sedimentary and sandy cretaceous formation (Al Tawilah sandstone) and the Eocene rocks (megzir sandstone), Tertiary rocks (Basalt, Andesite, Rhyolite, Trachyte, and Ignimbrite), Pyroclastite (Tuff) and Quaternary deposits and other volcanic materials were identified. In the meantime, many structural features were mapped, including faults and fracture swarms resulting from the process erosion and regional tectonics associated with the opening of the Gulf of Aden and the Red Sea. Some of these structures were tracked directly in the field using the GPS, while others were delineated from aerial photos. The geological map reveals the arrangement of major Travertine cones along NNW linear faulting trends at the boundary of Tertiary volcanic and Tawilah formation.

5.2 Geothermal mapping

5.2.1 Hot springs and hot domestic wells

Several manifestations in the form of hot springs in the region existed before the wells were drilled. According to GDP, nine hot springs that outflow from sandstone aquifers and their temperature ranges from 31°C up to 52 °C. On the other hand, GDP reported that there are 17 hot drilled wells, and their temperatures vary between 26 °C and 55°C. The hot springs are found to be of linear distribution trending in the same direction as the major fault system (NWSE) as shown in Fig 5.

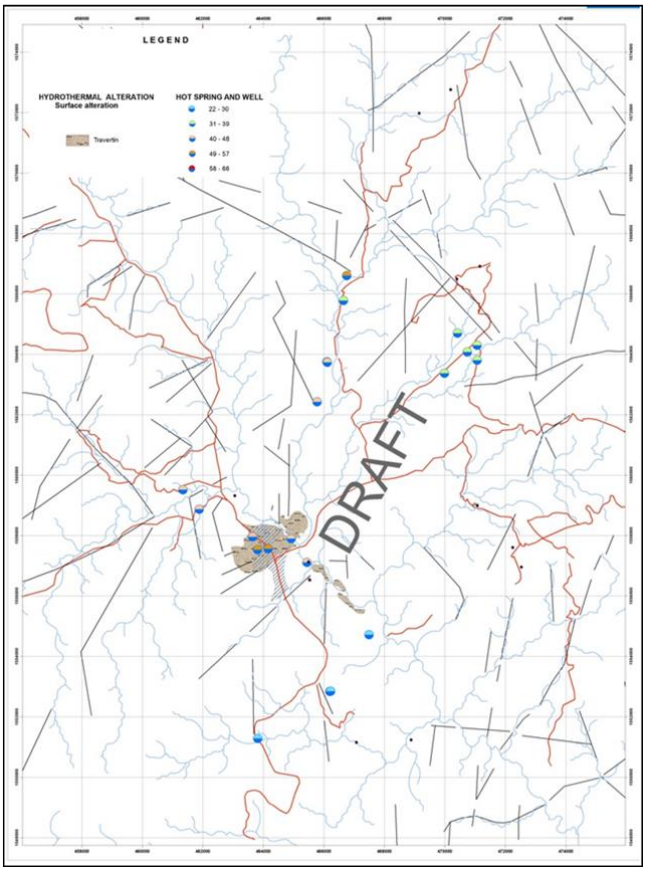

Figure 5: Geothermal map for Damt Geothermal Field, scale (1: 50,000) by GDP team.

5.2.2 Travertine outcrop deposit

Travertine is one of the geothermal phenomena that are formed due to the flow of CO_2-rich waters from fluids influenced by the limestone in Damt area. The formation of Travertine is characterized in Fig 6 by a yellowish-cream calcium carbonate to brownish color and composed of gray limestone terraces, all located along the direction of the main fault. Thermal springs and the greyish Calc-sinters (Travertines) deposited along the Bana river's bank as shown in Fig 2, which clarify the boundary between the Tertiary volcanic rocks and the sandstone rocks dating back to the Cretaceous period.

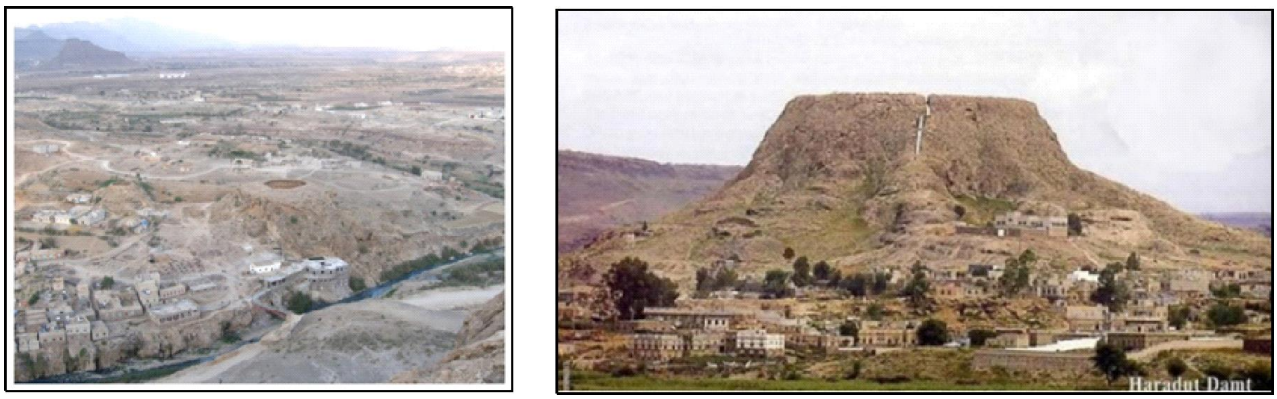

Figure 6: Picture shows the Travertine deposition (Great Haradah) in Damt area, Dhala province.

Damt area is covered by 51 Travertine Harada (small craters) and among them are 22 intact craters distributed in the east and west of the city. Some of them in the eastern part of the city on Bana valley bank, in which nine craters contain water and 13 are dry craters as Fig 7 illustrates the distribution of the Haradas or craters in Damt city.

Figure 7: Geothermal manifestations (Harada) and hydrothermal alteration in Damt geothermal field in Yemen (Source: Google earth 2021).

The diameter of the craters varies from 30 to 50 m and the most famous and largest Harada crater is called Al-Shawwal rises 160 m over the valley floor and has a base diameter of 500 m as shown in Fig 7. Most of the Travertine deposits are found in the southwestern side of Bana valley, where it was noticed that the deposits formed in the intersection of the sub-rift with the fault of Bana valley which was found to be of linear distribution trending as the major fault system (NWSE). Geological and geothermal maps illustrate the distribution of the Travertine and alterations, which are concentrated at the vicinity of the hot springs, indicating that the center of geothermal activity extends from northwest to the southeast of the study area as seen in Fig 4 and 5.

5.2.3 Hydrothermal Alteration

Rock alteration appears on the surface in the western and northeastern part of the study area as slight hydrothermal alteration in the form of veins and lenses or tubes of calcite and aragonite as seen in Fig 8. Low intensity of clay alteration witnesses active fumaroles where rock have been partially altered and replaced by secondary minerals in Damt. The occurrence of the alteration mainly exposed along fractures which is a good indicator of a geothermal system beneath the surface related to tectonic structure settings.

Figure 8: Pictures show the surface slight hydrothermal alteration composed of veins and lenses of calcite and aragonite.

5.3 Hydrology study

The hydrological study was done in 2006 to prepare the water resources assessment of the potential in geothermal energy in Damt field. The study indicated that annual precipitation in Damt region is around 300 mm and runoff occur mainly through Bana valley (Frank. W 2007). Groundwater recharge (meteoric and in part juvenile waters) occurs mainly through Tawilah Sandstone outcrops (north and south), possibly feeding not only shallow Tawilah aquifer in Damt area, but also deeper Tawilah aquifer further W, such as Al Qafr or Dhamar area. The direction of groundwater flow is from north, northwest, and northeast to the south. The Tertiary lava flows represented the low permeable cap rock covering the artesian groundwater, which is present in Tawilah sandstone and limestone of Amran group as aquifer. Tawilah aquifer obviously represents a yielding geothermal reservoir cropping out in Damt area (Fara M. 1999). Due to the lack of data of the original artesian pressure head, local citizens have reported a range of about 6 m above surface level. Over the last years, this estimation seems unlikely considering the various uncontrolled flowing drilled holes in the region. Therefore, large amounts of energy yielding thermal water flow unregulated to the nearby Bana valley and are thus wasted. This

abnormal draining water may lead to land subsidence of the area and pollution through toxic waste and sewage, which makes the groundwater supply unsafe.

5.4 Geochemistry study

The main purpose of the geochemistry study in Damt is to estimate the subsurface temperature and define the chemical properties of the fluid. The supporting data for this report was collected through the work implemented be Yemeni GDP team in cooperation with the Italian (CNR) and Germans (BGR) team. Fifteen thermal springs and other hot and cold domestic wells were selected to be analyzed in Germany and Italy laboratories whereas; temperature, PH and conductivity were measured during the field trips to the study area during 2007 and 2009. The surface temperature ranges from 31°C to 52 °C and pH measured ranges from 6.4 to 9.4 (Alnethary, et al. 2021). The results of the chemical analyses indicate that this water belongs to the Na-HCO_3 type of water while the cold-water samples approach Ca-HCO3 composition. The water is of meteoric origin and belongs mostly to the immature water group. The mineral contents of hot springs indicate that Cretaceous Tawilah sandstones are the major host aquifer of thermal waters. The CO_2- rich fluid-rock interaction controls the chemical signature of the hot spring waters, which mainly caused the high erosion resulting from epithermal alteration to form Travertine deposition. According to the hydrochemistry study by (Fara M. 1999), the temperature of the feeding system varies between 80°C and 120°C. This study indicated that thermal springs in Damt appear to be associated with recent volcanic activity related to a 10,000-year-old volcanic activity that led to the appearance of several craters in the area. In addition, seven hot springs and six domestic wells were selected in Damt region for Radon measurements which were carried out by (Motahar. A 2011) during the GDP field trip in 2011 to Damt. The results show an inverse relationship between the water temperature and the radon ratio, as the temperature increased the radon ratio decreased. GDP recommended to carry out isotopic analytical data for the gasses associated with thermal waters to determine the source of the CO_2, which was estimated by Minissale, 2007 to represent metamorphic in origin with the signature of mantle derived CO_2.

5.5 Geophysical study

According to previous geophysical study carried out by the department of geophysics in GSMRB for visualizing the geological framework of Damt area, the geological stratigraphy defined: Recent sediments layer (clay) intertwined with weathered and altered volcanic rocks range from the surface to the depth of 50m near to the great Harada. A layer of sandstone rocks (Megzir sandstone formation) occurred to the depth of 70 near the great Harada but reaching to the depth of 120m in its south and east, away from the great Harada. A sandstone rock layer (Tawilah sandstone formation) begins to appear from a depth of 70 in the area near the great Haradah, which extends until the end of the depth of the study, 250m.

6. HEAT SOURCE

Yemen is known to have high to moderate temperature geothermal resources (Minissale, et al. 2007). Most of these resources are related to important fracture systems in the area, which are oriented to the Red Sea and Gulf of Aden. The geothermal systems of western of Yemen are all structurally similar geothermal occurrences. The faults system penetrates deep to communicate a deep heat of naturally convicting meteoric waters in the metamorphic crust. The Damt geothermal system is thought to be controlled by the active fault and probably driven by higher heat flow. Therefore, Damt geothermal system resembles the fracture zone systems with high temperatures sweeping the Travertine to the surface. The geothermal high enthalpy resource is expected to range between 150 - 200 °C in Damt area while the source of CO2 is estimated to be derived from the mantle (Minissale, et al. 2007)**.**

7. GEOTHERMAL UTILIZATION IN YEMEN

The first and oldest evidence of the geothermal utilization in Yemen was during the ancient period's time. The thermal water is used due to their curative effects and recreational purposes as shown in Fig 9 in the form of balneology and bathing. The best hot springs known in Yemen are called Hammam Ali (Ali's bath), name given for many hot springs which mainly used to take baths for relaxation and recovery. Geothermal springs, which are located in areas of tourist attraction, have become an important source of local and regional tourism. For instance, Damt hot springs are famous for their water, which is good for people suffering from rheumatism, and skin allergies. The overall potential capacity is estimated to be 600 MW (Al shetwi. A 2021). However, the utilization of the resources is still limited to direct applications by private tourism activities for entertainment and balneology, which was estimated use in 2000 to be 1.0 MWt and 15 TJ/yr (Davidson 2000). Today, the use of geothermal resources in tourism activities (hotels, swimming, and therapeutic applications) has increased through constriction of hotels and recreational facilities in several areas within the country with the estimation of 5.0 MWt and 100 TJ/yr (Lund and Toth 2021). Generally, these resources are restricted to direct uses, even though Damt geothermal field was shortlisted in 2008 for establishing 1 MWe with financial assistance from UNDP. It is considerable as a further possible economic resource, shallow exploratory wells at Damt could be drilled to produce and sell CO2 to Yemen industry (Minissale, et al. 2007).

Furthermore in view of the fact that the characteristics of Damt geothermal field (Yemen) are very similar to that of the Jizan geothermal field (Saudi Arabia), a few hundred kilometers NW of Damt, it is presumed that Damt and associated geothermal field independently is capable of generating greater than 134 × 106 kW (1057 billion KWh) of electricity (Chandrasekharam D 2016) and (Minissale A 2019)**.** Accordingly, geothermal energy can be utilized for irrigation purposes by generating freshwater through desalination of seawater from the Red Sea.

The Geothermal Development Project team suggested that the geothermal resources in Damt should be better developed and utilized indirectly for power generation. On the other hand, they can be used for greenhouse and CO_2 or H_2S gasses exploitation. Swimming facilities can be used within the framework of the international standard bathhouses based on their flow rate and water geochemistry or geothermometric characteristics.

Figure 9: Pictures of hot springs and hot domestic wells in Damt region

8. SUMMARY

Five main geothermal fields identified in Yemen: Al lisi and Isbil, Al Qafr, Damt, Taiz and Red Sea Coast. Damt geothermal field is one of the promising of these fields for energy utilization in Yemen. Damt is located in Dhala province, about 200 km south of Sana'a, the capital city of Yemen. The area located within the tectonic fault zone extends NW-SE, which accompanied the opening events of the Red Sea and the Gulf of Aden. The geological and geothermal maps have been prepared by the GDP team at a scale of (1:50,000). The maps illustrate the geological and geothermal situation of the study area. Geological formation consists of basement rocks (pegmatite), sandstone, volcanic rocks (Rhyolite, Ignimbrite and Tuff) and basalt rocks (Quaternary). The surface geothermal phenomena in the study area are represented by the Travertine deposits in the form of Haradah (small craters), the most important of which is the great Haradah, which is in the center of the city of Damt. There are other geothermal manifestations represented by eight hot springs and some outcrops of slight rock alteration.

Geochemical studies by the Yemeni - Italian and Yemeni - Germans team for fifteen thermal springs and other hot or cold domestic wells which were selected to analyze in Italy and Germany laboratories whereas temperature, PH and conductivity were measured in the field during the field trips. The surface temperature ranges from 31°C to 52 °C and pH measurement ranges from 6.4 to 9.4. The results show that the water analysis of these hot springs contain dissolved calcium carbonate ($CaCO_3$) and the concentrations formed Travertine deposits in the study area. The radon measurement shows that as the temperature increased the radon ratio decreased in hot springs and domestic wells in Damt. In addition, the geothermal data indicated that the water temperature in the reservoir ranges from 80°C - 120°C. Traditionally, the geothermal potential in Damt like everywhere else in Yemen is restricted to direct uses for balneology purposes for many years (including bathing, and swimming) which is estimated to be 5.0 MWt and 100 TJ/yr but can be better developed and used in indirect utilization.

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