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The Role of the Yemeni Geothermal Development Project (GDP): Twenty Years of Research, Training and Geothermal Development in Yemen

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ABSTRACT

The purpose of our paper is to present the achievements of the Yemeni Geothermal Development Project (GDP) since the establishment of the project in Yemen from 2000 until today. The GDP is the first and only project that focuses on geothermal resources studies and creates a comprehensive road map for geothermal exploration and development in Yemen. Inclusive work carried out by the geothermal project team includes geothermal surface explorations, geothermal mapping, geochemical, hydrogeological, and geophysical studies and environmental assessment. Based on these studies, geothermal areas in Yemen are classified into five main geothermal fields: Al lisi - Isbil, Al Qafr, Damt, Red Sea Coast and Taiz. Al lisi - Isbil is promising for electricity generation for near-term exploitation where the first well allocated in 2010 to the depth of 1500 m and temperatures above 200 °C was expected to be found, whereas the other fields have good potential for moderate and low enthalpy resources. The objective of the GDP is to estimate the geothermal potential for electricity generation from the prospective geothermal field (Al lisi - Isbil) and on the other hand to develop the other new geothermal fields in the country.

In parallel with geothermal exploration, the workforce steadily increased in GDP during the last two decades. The majority of them strengthened their geothermal knowledge and experience by involving themselves in related training courses and conferences that helped pave the way for the future of the project. Thereby, they published numerous local and international scientific papers, books and presentations that provided reliable and objective information about geothermal resources in general, and the explorations and developments worldwide by GDP team.

The institution financial support for the GDP came as an operating budget annually from the Ministry of Oil and Minerals (MOM) through the Geological Survey and Mineral Resources Board (GSMRB) since 2000, to execute the exploration and development works in the geothermal areas in Yemen. Moreover, the prospected geothermal drilling project in Al lisi - Isbil geothermal well and previous studies were completed by the governmental authorities (GSMRB, MWE and MEE), with scientific and technical assistance from international partner (CNR, BGR and GEF/UNEP).

The geothermal potential capacity estimation to be harvest from geothermal resources in Yemen is 2900 MW. However, the utilization of these resources is still limited to direct applications by private tourism activities for entertainment and balneology, with an estimated use of 1 MWt and 15 TJ/year in 2000. Today, the use of geothermal resources in tourism activities has increased due to the building of more hotels and recreational facilities in several areas, and so the estimation is 5.0 MWt and 100 TJ/yr.

1. INTRODUCTION

The foundation of the GDP was initiated following the discussions by a group of scientists in the GSMRB and MOM on the possibilities to create a research center, which could address the great need for renewable energy access and low emission geothermal energy. During the discussions, the main scientific reasons, and justifications for establishing the project were identified as the following: 1) Lack of sufficient scientific information about the distribution of hot springs in various regions in Yemen. 2) The occurrence of Quaternary and Tertiary volcanic fields in the western part of Yemen, which represent the scientific basis for the existence of high temperature underground, which can be exploited in generating power, similarly to some countries that have the same geological conditions. 3) The presence of some gas fumaroles and hot sulfur fumes in Al lisi and Isbil areas, which represent part of the volcanic activity that characterizes the recent Dhamar-Rada volcanic field. 4) Preliminary geothermal evidence provided by previous studies in Al lisi and Isbil in the early eighties indicated that it is the most promising for drilling geothermal exploration wells. 5) Scientific and technical support provided by some foreign scientific organizations in geothermal exploration in Yemen in the eighties. Therefore, the cooperation between local and international experts was also discussed, in particular, how it would be possible to launch geothermal development in Yemen by learning from other countries that have a geothermal expertise and developments, such as Italy, Iceland and USA.

The outcome of the debate was the establishment of the GDP by an official decision of the former Minister of Oil and Minerals, under the supervision of the Geological Survey and Mineral Resources Board. Based on the objectives that were set for the GDP, the project management communicates and coordinates with scientific organizations and bodies in some of the European countries to visit Yemen. Subsequently, these efforts succeeded, and a number of cooperation agreements and memoranda of understanding were signed to support and implement the work of the project from its inception date until the present day. The most important of these Institutions involved in supporting the GDP developments are:

Local authorities such as: Geological Survey and Mineral Resources Board (GSMRB) in the Ministry of Oil and Minerals (MOM), Ministry of Water and Environment (MWE), Ministry of Electricity and Energy (MEE) and Yemen Tourism Promotion Board (YTPB), because they are the beneficial ministries in terms of utilization in the future. International Institutions include The Italian University of Florence (UNIFI), National Research Center and the Institute of Geosciences and Earth Resources (CNR - IGG), German Institute for Geosciences and Natural Resources (BGR), United Nations University - Geothermal Training Program in Iceland (GRO-GTP), the Icelandic Ministry of the Environment, Energy and Climate and Global Environment Facility (GEF/UNEB).

2. MAIN OBJECTIVES OF THIS STUDY

The Yemeni Geothermal Development Project (GDP) mission is to develop not only the geothermal energy as a sustainable, environmentally friendly, and economically competitive resource, but also obtain geothermal expertise and make the society aware, in order to be involved in the contribution to the energy requirements in Yemen. In this paper, the achievements of the project and all the geothermal work executed during the last two decades (2000 - 2022) will be summarized. The overall situation of the project will be introduced, and the status of the geothermal exploration and team training will be highlighted; publication of research (papers, reports, books and presentations) by the project team will be introduced as well.

3. PREVIOUS GEOTHERMAL EXPLORATION IN YEMEN

Previous studies provided estimations about the geothermal potential in Yemen, which are considered courageous at the current expertise. First studies were published during the 1980s, when several organizations developed strategies to explore geothermal energy sources in Yemen (e.g., BRGM, ELC and EXXON). Nevertheless, the planned activities rarely exceeded a preliminary planning level as the following:

The first program of the preliminary studies accomplished in 1980 under the international cooperation activity with the French geological survey (BRGM), which recommended Dhamar area as a high priority geothermal target and suggested other geothermal zone in the southern part of Yemen as medium and low enthalpy prospects (BRGM 1980). The second phase of the preliminary surface geothermal investigation in Yemen was achieved in 1981 by the Italian Electroconsult company (ELC) and funded by the Yemen Mineral and Oil Company in Dhamar volcanic field, southwest of Yemen. The geothermal exploration included regional volcanology, geological studies, and geophysical (vertical electrical soundings), hydrogeological, water chemistry and geochemistry exploration in Al lisi and Isbil area, Dhamar, southwest of the country. The general objective was to evaluate the possible geothermal potential in the area. The main result of the ELC study indicated that there are more than two anomalous zones of geothermal interest at the E-SE of Al lisi volcano and south of Maram village. The study recommended drilling two initial geothermal exploratory boreholes to 1200 m depth on the sites of the study area where are the anomalous zones of geothermal interest.

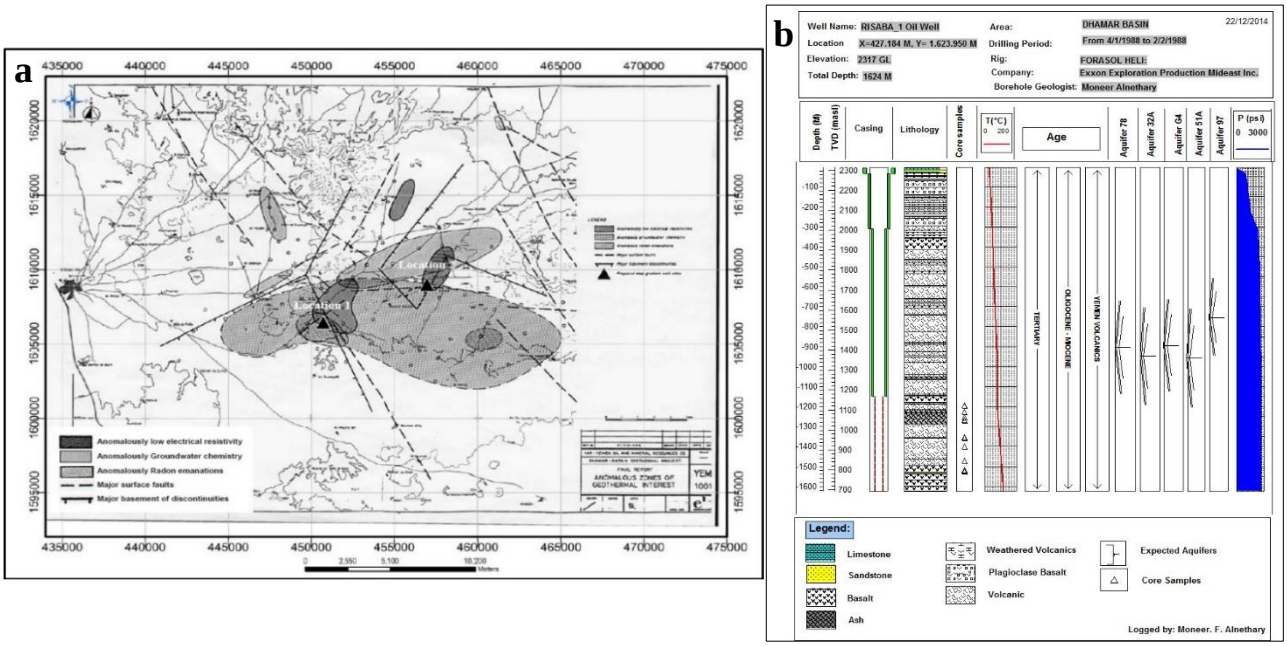

Figure 1: a. Map of anomalous zone of geothermal interest (ELC 1982); and b. Lithology of the Oil well, drilled in 1988 in Risabah area in the geothermal region by Exxon (Source is Exploration Production Mideast Company and GSMRB 1989).

The first well location was supposed to be in the intersection of three anomalous zones (low resistivity, groundwater chemistry, and radon emanation anomaly) as shown in Fig 1a, while the second location settled in the intersection of two anomalous zones (low resistivity and anomaly in the ground water chemistry). The hydrogeological and geochemistry studies of ELC suggested that a deep Cretaceous sandstone reservoir exists at 1200 m depth with high water flow direction from east toward west and temperature around 200°C (ELC 1982). The third phase of the geothermal related exploration was drilling several oil and gas exploration wells in Dhamar and the western red sea coastal area in 1988 by Exxon (Exploration Production Mideast Company). The first oil exploration and production well, was drilled in 1988 in Risabah area (Dhamar) which was planned to the depth of 2743 m in order to obtain a brief information about the lithology, as shown in Fig 1b (lithology diagram was replotted by Alnethary, 2014). It was expected from the

seismic survey to find sedimentary rocks (sandstone or limestone) for hydrocarbon source, but volcanic rocks instead were found, which was the reason to stop drilling at 1625 m depth, as it was not a promising result for oil.

Because Yemen is an oil producing country, several studies focused on oil exploration in the recent volcanic field in western and the Red Sea. Nevertheless, the collected data was used later to help the GDP to figure out the geothermal potential. Electric logs and temperature profiles performed by Schlumberger Company showed the bottom temperature recorded was 105°C and the extrapolated equilibrium bottom hole temperature was 115°C, which indicated a high thermal gradient and heat flow (GSMRB 1989). After the previous work in Yemen in 1988, geothermal exploration stopped due to political barriers until 2000 when the GDP was founded.

4. HISTORY OF THE GEOTHERMAL DEVELOPMENT PROJECT IN YEMEN (GDP)

The GDP contributes to the improvement of the geothermal industry in Yemen and the rest of the Arabian countries, especially because it was the first geothermal project of its kind in the Arabian country and Middle East at that time. As this project was created for the development of geothermal studies in different places in Yemen, some activities were relevant during the twenty years and positioned GDP as the main reference for scientific exploration, education and dissemination knowledge and work with society.

4.1 Establishment of GDP

The Geothermal Development Project (GDP) consists of an independent department that follows the leadership of the Geological Survey and Mineral Resources Board (GSMRB) and falls within the organizational and administrative structure of the authority according to the decision of the former Minister of Oil and Minerals, Rashid Barba, issued in 2003. GDP began operations by May 2000, as a result of a group of scientists, including M. Mattash, interested in creating a research center that could address critical and scientific topics that have been neglected by local and international authorities, despite the fact of having one of the largest untapped geothermal potentials in Yemen.

Mattash, among other scientists, has made many contributions to the GDP in Yemen since the early stage of the establishment. He was in charge of a number of important geothermal research, projects, communication between the Yemeni geothermal community and international institutions. He played a key role especially in the founding of the geothermal industry in Yemen by pointing out the GDP in international forums, when he clarified the importance of the Yemen location to the African rift valley through his presentations, especially during the ARGeo-C1 in Ethiopia 2006. Consequently, that was the first step to invite international expertise (Italian, Icelandic, and Germans) to visit the geothermal manifestations in the country.

GDP was awarded the first fund from MOM to implement the geology and geothermal investigation for the whole country and produced the first geothermal map, called Physiotherapic and Hot Water Spring Tourist map of Yemen at scale 1:1,250.000 in 2003, as seen in Fig 2. GDP team in cooperation and supervision by the GSMRB produced it. The map shows the location of all known thermal manifestations as hot springs and fumaroles in Yemen, including their superficial temperature and pH measurements as well as the detailed description of each hot spring, fumarole, or gas vents with relevant photos.

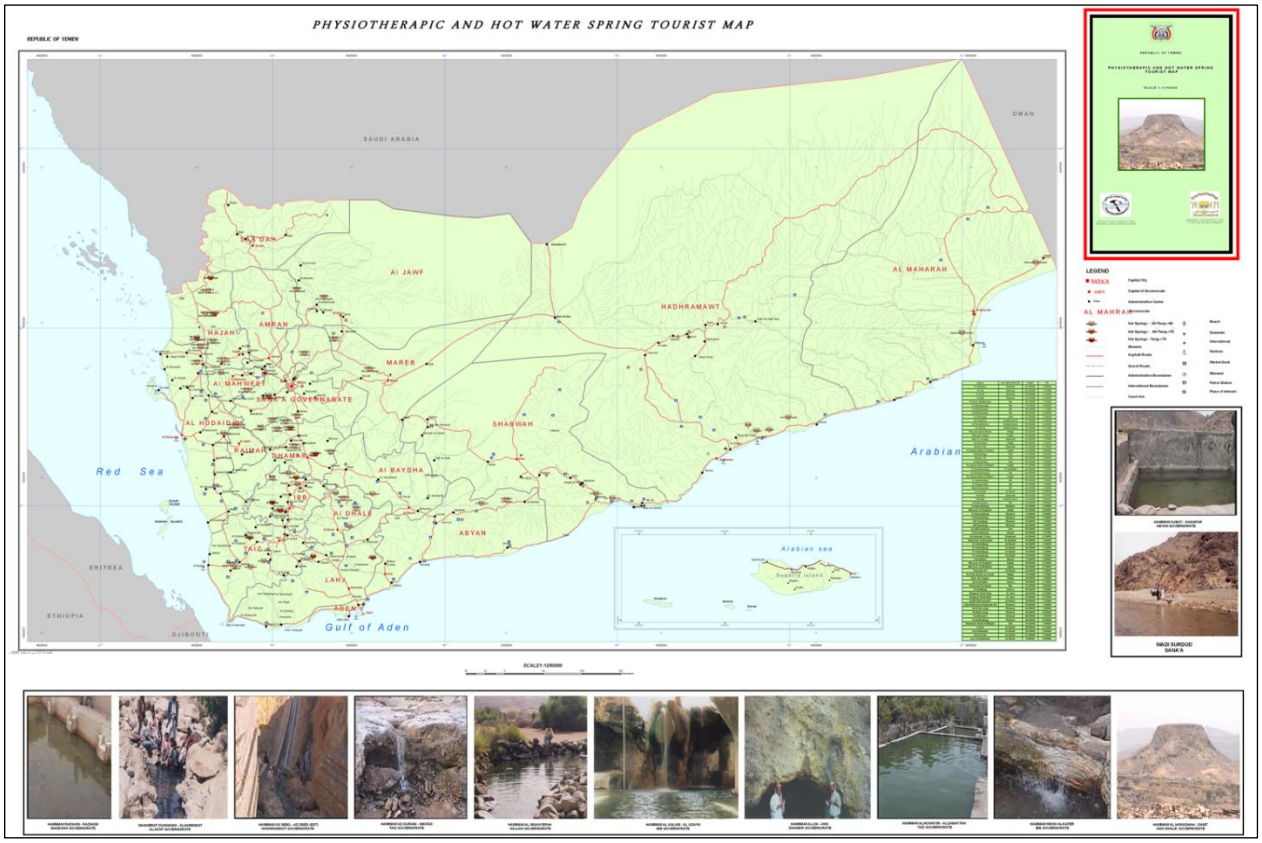

Figure 2: Physiotherapic and Hot Water Spring Tourist Map in Yemen with scale of 1:250, 000 (Original title in Arabic: خارطة السياحة العلاجية ومصادر الطاقة الحرارية في اليمن). Source GSMRB.

After positive international evaluation of this work and hot spring map production, the CNR supported the GDP for the period of 2003 - 2009 to carry out geochemistry studies in the western of Yemen. Therefore, the GDP works in two main strategic lines as the following:

4.1.1. Detailed geothermal exploration and development.

The exploration goals were focused on establishing comprehensive geothermal studies and developments for geothermal systems in Yemen, addressing different case studies in each geothermal field including all the geothermal aspects of the studies: a) Geothermal surface exploration (geothermal mapping), b) Geochemistry studies, c) Geophysical studies, d) Environmental assessment and e) Drilling process. Each of this exploration lines have been working on specific scientific aspects and interdisciplinary project for both high enthalpy system in Al lisi and Isbil geothermal, Al Qafr and Damt field for power generation, and moderate to low enthalpy systems in Red Sea and Taiz geothermal fields. The latter projects were developed with the aim to promote geothermal direct uses in society. After ten years of hard work (2000 - 2010), the GDP is considered as an internationally well-reputed research project. Fig. 3 shows some of the GDP activities during the years.

Figure 3: Geothermal manifestations (hot springs, fumaroles, steam vents, hydrothermal alterations, and volcanic recent eruption), different views of the Geothermal Development Project (GDP) activities and Bir Ali Quaternary volcanic crater (in the centre) in Yemen.

4.1.2. High level research (training, education, and networking)

Another major highlight of the GDP in those years was a training center for scientists and students. The fellows who finished taking courses abroad applied for their work and studies immediately after returning home, by delivering their experience to the staff of GDP. Therefore, almost three professionals worked in the project (center) since 2003, and more than 18 scientists joined the project later, who were trained by the older professional scientists in the project. Moreover, undergraduate, and postgraduate students (MSc and PhD level) from different Yemeni universities developed their thesis and research in the GDP center. Thus, it is one of the most relevant centers for training and capacity building in the region. Numerous scientific papers and presentations in national and international congress were presented and published by GDP scientists, which in turns have a high impact on the dissemination of geothermal knowledge.

5. HUMAN RESOURCES AND FINANCIAL SUPPORT

5.1 Growing the GDP staff member (team)

The workforce in GDP increased gradually during the last twenty years. There were only three geologists in the project at the beginning, but after the establishment in 2000 the number of geologists increased respectively in 2003, 2007, 2008, and 2009 and became 5, 8, 9, 10, and in 2012 reached the maximum of 21 scientists and geologist. They came from various disciplines including geology, geophysics, geological engineering, environmental scientist, and GIS. Likewise, the GDP work started in one office room with only one computer in 2001, which extended with time to three office rooms as seen in Fig. 4, six computers, printers, and pH and ELC instruments for field measurements. The facilities include archives with more than 112 previous geothermal reports of different regions in Yemen that were donated to the project in both Arabic and English language, and also all the recent geothermal reports that have been written during the twenty years of work in the GDP.

Figure 4: Geothermal Development Project offices in GSMRB

The management personnel of GDP are the project manager and coordinator, deputy manager and geologists with different specialties as shown in Fig. 5. The different responsibilities of the GDP team are the Management Director and deputy responsible for the management of GDP and relationships with the geothermal industry. Project Consultant: Contribute his technical expertise and collaborate to develop project plans, assign project tasks and resources as well as supervising the geothermal research. Project Focal Point: Representative of GDP and acting as a bridge between national and international expertise. Financial Officer: In charge of overseeing the financial transactions and preparing financial reports. Scientists and geologists: Composed of five outstanding scientists and specialists (geologist, borehole geologist, geochemists, geophysicists, and environment specialists) who are involved in geothermal and geological exploration and development. Project Secretary: Responsibilities are maintaining diaries, arranging appointments, organizing, and managing databases.

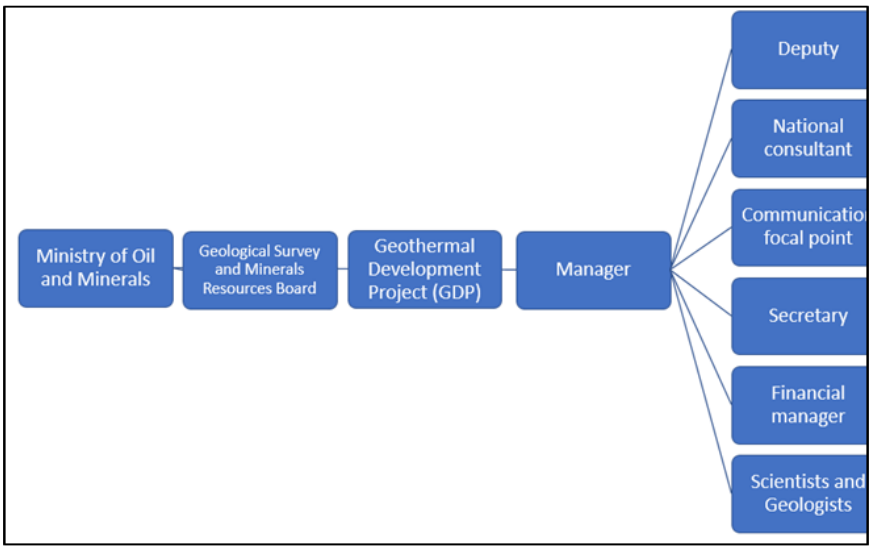

Figure 5: Management system of the GDP for the period 2000 - 2013

Thus, the GDP has a solid team integrated by young researchers. This group works under the supervision of the GSMRB chairman, a governmental institution under the Ministry of Oil and Minerals (MOM) in Yemen and continued working on an already existing project and developed a new one (drilling project in Al lisi - Isbil) for the near future. The GDP team has consolidated as a national and international reference for developing geothermal resources in local industries and organized communities.

5.2 Financial support

Since the establishment in 2000, the GDP has financed exploration projects in different areas within the country, such as geology and geothermal mapping, geochemistry, geophysical and environmental studies. Other goals of the GDP are the formation of advanced human capital, establishment of national and international cooperation networks, and dissemination of research results to the scientific

community and society. Grants came from local authorities and international institutions to provide and generate high–impact scientific research. Most of the Yemeni fund comes as an operating budget provided annually by the Ministry of Oil and Minerals via GSMRB, while international funds came from the Italian University of Florence, the National Research Center and the Italian Institute of Science and Earth Resources (CNR - IGG), and partly from the German Institute of Resources and Geosciences (BGR) for the geothermal exploration. The GRO – GTP has highly contributed to the geothermal workforce build-up in Yemen by inviting Yemeni fellows to be trained on geothermal specialties in Iceland. Reykjavik Energy Invest (REI) signed an agreement in 2008 for technical assessment of the project, but the company went bankrupt during the financial crisis. Additionally, the GEF fund for the prospective geothermal drilling well in Al lisi - Isbil geothermal field approved in 2008 and was ready to start at the end of 2010. The target was set at 1500 m depth, where temperatures above 200 °C were expected to be found. The financial support to GDP increased gradually from 2000 - 2013 in line with the workforce development, geothermal explorations, team publications and team training in GDP as mentioned above (Fig 6).

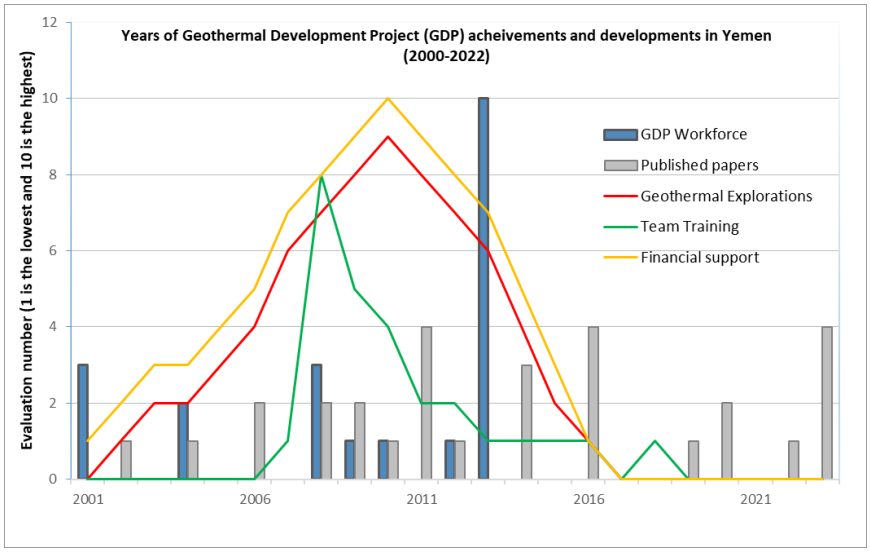

Figure 6: Growth rate of the activities (geothermal explorations, team training, financial support, publication, and workforce) of GDP during the last twenty years

6. ACHIEVEMENTS AND OUTPUTS OF GDP

There are several objectives achieved through the various work of the project, the most important of which are: 1. Initially seeking to find an alternative source of renewable and clean energy sources to contribute to cover part of the high shortage of electricity in Yemen through geothermal utilizations. That started by recording and mapping all the geothermal manifestations and resources in the whole country (hot water springs, steam vents and fumaroles) and classifying the scientific reasons that led to their formation (geology and tectonics). 2. Seeking to explore high and low to moderate temperatures fields to contribute to cover part of the shortage of electricity in the country. 3. Seeking to develop medical tourism in Yemen to contribute to support the public treasury. 4. Team training and skills development of the GDP. 5. Dissemination knowledge and raising public awareness about their geothermal resources. The work progress of the GDP was in full capacity from 2000 until 2013. During this period, the geothermal development and exploration, publication of scientific papers, and giving presentations via conferences or workshops have greatly increased as seen in Fig 6, which indicates the high-speed development and achievements of the GDP. Five geothermal fields have been primarily identified: Al lisi and Isbil, Al Qafr, Damt, Taiz and Red Sea coast geothermal fields. Al lisi - Isbil is the most promising geothermal field for electricity generation, and other fields have good potential for low and moderate enthalpy resources (further information about each field in detail can be found in (Alnethary. M 2021).

6.1 Geothermal explorations in Yemen

Geothermal surface exploration started in the 1980s but in more detail in 2000 by the GDP team in Yemen, with more focus on the western part where the thermal manifestations and Quaternary volcanoes are widely distributed. To overall evaluate the geothermal potential in the country, geological and geothermal studies were carried out as the first steps for more than one hundred manifestations in the form of hot springs, fumaroles, and intensive alteration surfaces as well as domestic hot wells. The geothermal areas in Yemen are unique and exceptional geothermal sources of research and with this purpose in mind the main research lines were defined: (1) General exploration of the geothermal areas (geology and geothermal mapping); (2) Geochemical study; (3) Hydrological Studies; (4) Geophysical study; (4) Drilling, as shown in table 1.

Table 1: Geothermal detailed studies in Yemen (Alnethary. M 2021)

Table 1: Geothermal detailed studies in Yemen (Alnethary. M 2021)

No.	Study	Al lisi and Isbil	Al Qafer	Damt	Red Sea	Taiz
1	Geological and Geothermal mapping	✓	✓	✓	✓	✓
2	Geochemical study	✓	✓	✓		
3	Hydrological study	✓	✓	✓		
4	Geophysical study	✓				
5	Environmental study	✓				
6	Temperature gradient	✓			✓	
7	Well location and site prepation	✓				
8	Drilling					

6.1.1 Geology and geothermal study

Extensive geothermal fieldworks and water/gas samplings were carried out initially for hundred thermal springs and domestic wells. The purpose was to assess the geothermal potential for the whole country. Detailed geological and geothermal investigations were done later based on that work with more focus on the western part of Yemen which is one of the most active areas in the Arabian plate boundaries. Manifestations as hot springs, fumaroles and intensive rock alteration surfaces widely occurred and mapped in the country by the GDP team. Five geological and geothermal maps were produced for the main geothermal fields at scale 1:50,000, which illustrate hot springs, fumaroles, alteration surfaces and Tertiary and Quaternary volcanic areas as well as the relationship between geothermal activities, tectonic setting, and structural patterns (Fig 7).

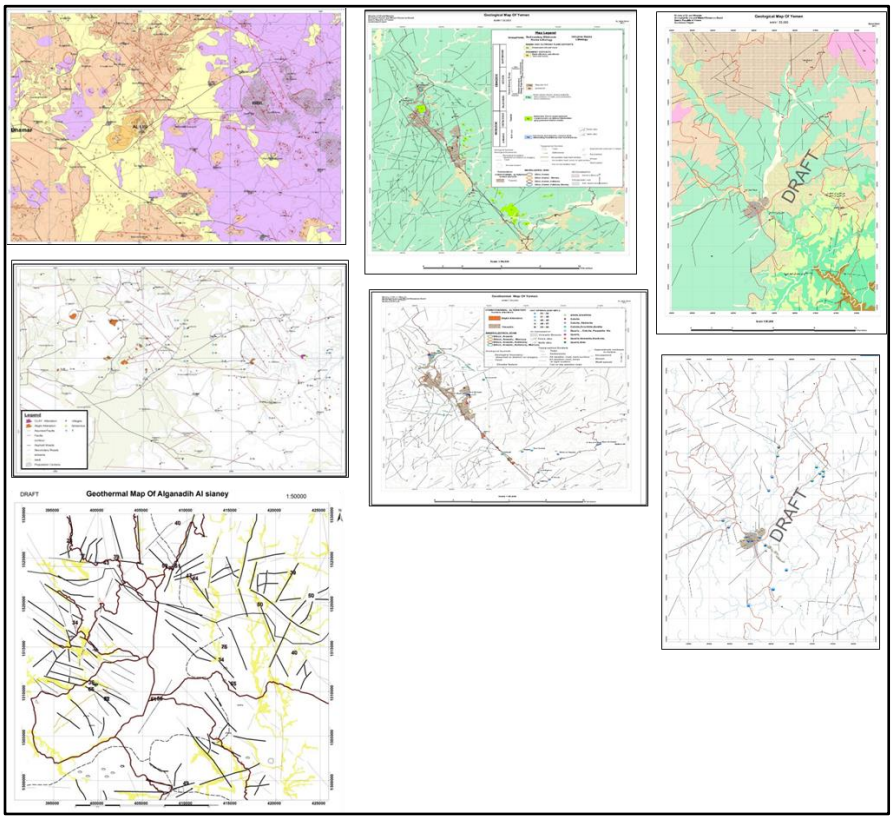

Figure 7: Geological and geothermal maps for (Al lisi – Isbil, Al Qafr, Damt and Taiz geothermal fields in western part of Yemen), the maps produced by GDP.

6.1.2 Geochemical studies

Geochemical studies accomplished by the GDP team in cooperation with international scientific CNR started in 2001 and with BGR in 2006. Hundred thermal and cold springs all around the country were selected to be sampled in Italian and German laboratories (Minissale, Mattash, et al. 2007). Based on this sampling, extensive geochemical work and additional field trips were done later during (2001 - 2012) by the GDP and the Italian Council for Research at the Institute of Geosciences and Earth Resources CNR and Department of Earth Sciences at the university of Florence UNIFI, to obtain more accurate details of the western region of Yemen including Al Qafr and Damt and practically around the Quaternary volcanic area (Al lisi - Isbil). The main purpose was to select the

best thermal anomalous area to drill an exploratory well for further development of geothermal generation in Yemen. Surface temperature, pH, electrical conductivity, ammonia, and silica concentrations were directly measured in a larger number of wells. The analysis of samples included major, minor, trace components and isotopic ratios at the laboratories of UNIFI and CNR in Italy and some of them in Germany. Some of the results are shown in Fig 8.

The analysis results indicate that thermal anomaly discovered in this area is mainly caused by local high conductive heat flow, which undoubtedly is related to the presence of cooling magma associated with the Quaternary volcanoes, which in turn have possibly generated an active hydrothermal system in the volcanic sequences (YTS). In addition, this shows that the most reasonable area for drilling the first geothermal well in Yemen is between the two Quaternary volcanoes of Al lisi and Isbil at the central part of Yemen volcanic Plateau (YVP), where the expected temperature gradient is greater than 150 °C/km (Minissale, Vaselli , et al. 2013). In addition, BGR study included a brief geochemical comparison between the three geothermal fields (Al lisi - Isbil, Al Qafr and Damt) in 2007. The main findings indicated some similarities in terms of geological setting and geothermal manifestations. High enthalpy and potential geothermal resource occur in all the three areas, where the Tawilah aquifer is the major thermal aquifer. Therefore, it is expected that the same heat source is feeding all three geothermal sites possibly due to the same aquifer. The thermal water springs are cropping out from Tawilah sandstone in Damt as well as where the active fault systems are cutting the Tawilah aquifer in Al Qafr, while the mixing of thermal and cold groundwater in Al lisi - Isbil area likely occurs along this fault zones. Despite of thermal manifestations are restricted to fumaroles and steam vents in Al lisi - Isbil, the area is the recommended geothermal site for further exploration activities (Frank. W 2007).

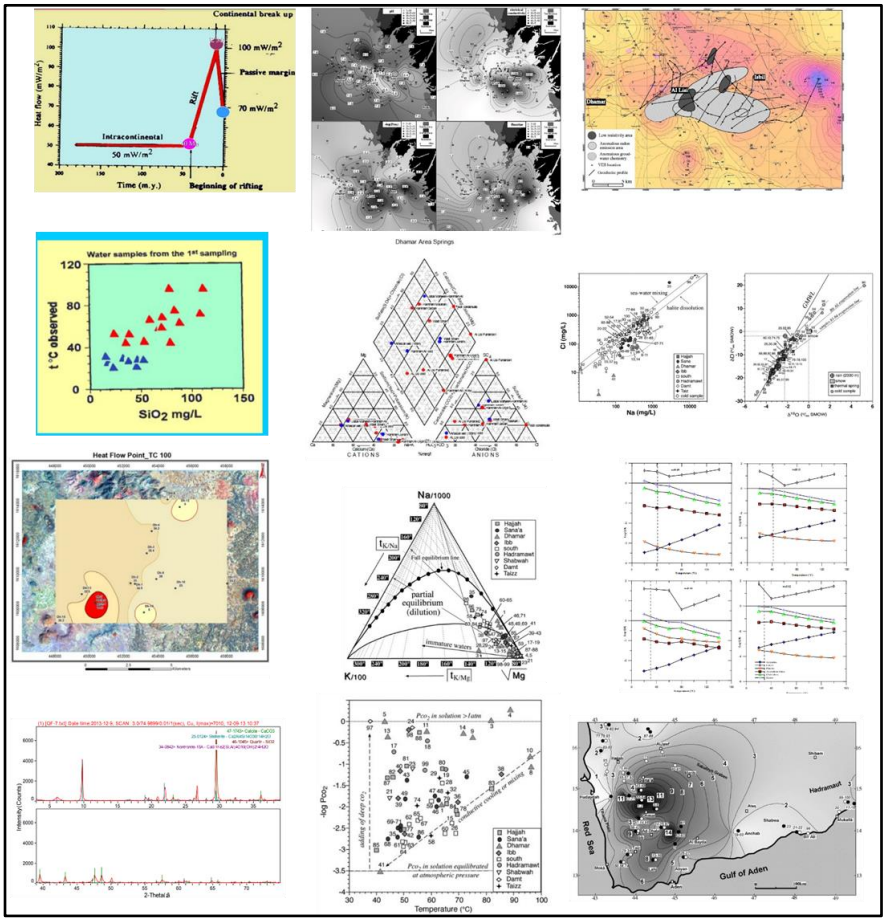

Figure 8: Some of the results of geochemistry analysis in various geothermal fields in Yemen

6.1.3 Hydrological studies

Hydrogeological studies implemented in three geothermal areas in Yemen, Al lisi and Isbil, Al Qafr and Damt, in order to prepare the water resources assessment plan with focus on the areas with potential for geothermal energy generation. The National Water Resources Association (NWRA), not the GDP, did these studies, and therefore they are not further discussed here.

6.1.4 Geophysical study for Al lisi and Isbil geothermal field

Geological Survey and Mineral Resources Board (GSMRB) executed the geophysical exploration for Al lisi and Isbil geothermal field in 2010 in cooperation and with financial support from the Federal Institute for Geosciences and Natural Resources (BGR). According to (Al Qubatee and Kalpercamp 2010), the study aimed to reinterpret the previous geophysical survey in Al lisi and Isbil to delineate the best location for drilling an exploratory geothermal borehole. Two previous geophysical surveys were reinterpreted: (1) the geothermal exploration study (ELC 1982), which includes 83 vertical electric sounding in Schlumberger array with half

electrode spacing (AB/2) between 1000 m and 3000 m; (2) the geophysical study (GSMRB & BGR in 2007) including 5 vertical electric sounding in Schlumberger array with half electrode spacing (AB/2) of 2000 m as seen in Fig 9. The study recommends drilling an exploratory deep geothermal gradient well, to about 1250 m below soil surface, in one of the three selected locations. The three locations matched with five vertical electrical soundings (VES) with the lowest electrical resistivity.

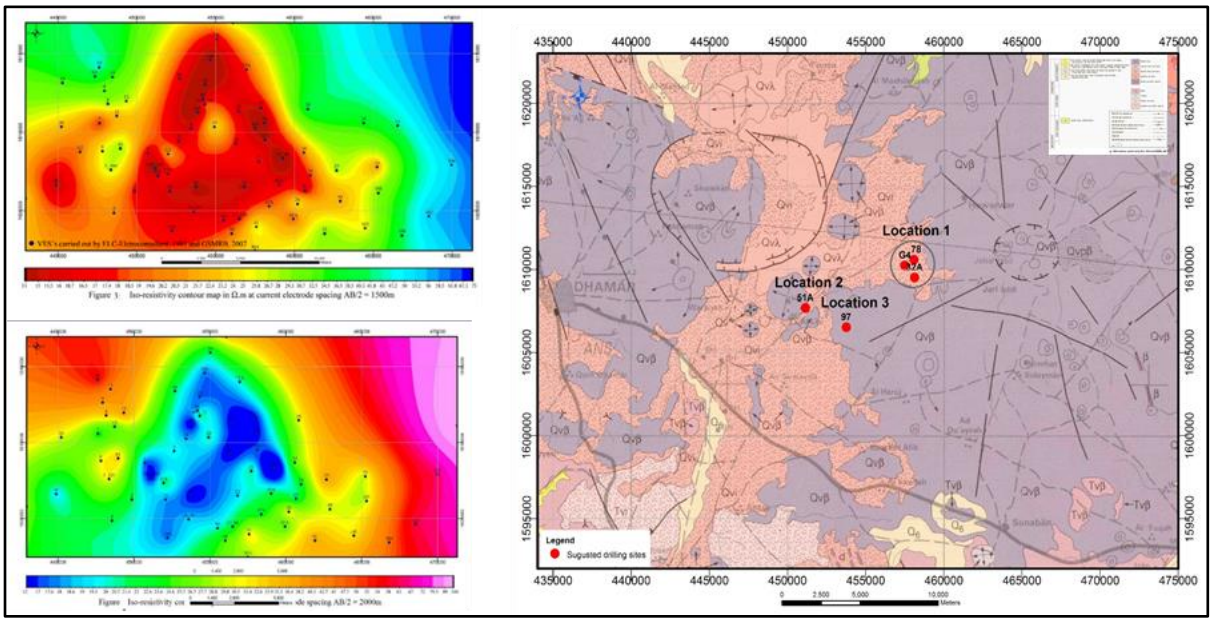

Figure 9: Geophysical studies in Al lisi and Isbil geothermal area (Al Qubatee and Kalpercamp 2010) and the geological map of the study area (Robertson 1991) including the recommended sites for drilling an exploratory deep geothermal gradient well.

6.2 Team training and capacity building

From 2000 to 2005 only five scientists were working in the GDP, with different geological backgrounds (geology, geochemistry, geological engineering, and GIS) and no geothermal knowledge. Some of the GDP team trained later in different geothermal courses and programs. In 2006 Mattash presented the Yemeni geothermal studies in the African Rift Geothermal Conference (ARGeo-C1) held in Ethiopia, and as a consequence the UNU-GTP chairman, Ludvik S. Georgsson, was invited at the same year to visit the geothermal manifestations in Yemen. He and several Icelandic geothermal scientists came to Yemen in 2007 and signed an agreement with GDP for technical assessment in 2008. The assessment included training the GDP members in short geothermal courses in Kenya and in the six-months course in GRO-GTP and master's degree in the University of Iceland. Up to 2009, 29 Yemeni fellows participated in various geothermal training courses in Kenya, in which 4 of the fellows (Al Dukhain 2008), (Al Kohlani 2008), (A. Al Sabri 2009) and (Alnethary 2010) attended the six months training in Iceland and 1 fellow (Alnethary 2018) has obtained his fellowship to do MSc degree at the University of Iceland in 2015 after completed his six month training course in 2010. Whereas other 14 Yemeni scientists participated in short courses in Kenya, 7 participated in geothermal training courses at the university of Florence, and 3 participated in the ARGeo conferences. The GDP is where all the fellows came from but none of the fellows was a female and that unfortunately is due to the lack of female geologists in the project.

The Yemeni scientists attending those courses and trainings played very important roles in the geothermal exploration of Yemen, especially in the development of the geothermal fields of Al lisi and Isbil, as well as in the development of other moderate to low enthalpy fields. Almost all the Yemeni scientists returned to their position in GDP after completing training, and applied their studies, shared their expertise, and became leaders in their specialties. These meet the increased needs of the geothermal workforce in Yemen until 2013.

6.3 Dissemination of geothermal knowledge (publications)

The output of the GDP is not limited to the exploration and development of the geothermal resources in Yemen but also building up a very experienced staff and well-trained team. Eventually the results, they wrote and published numerous scientific papers, reports, and presentations (mainly in English and some in Arabic languages) in national and international geothermal events. Publication of scientific papers by the GDP staff increased remarkably during the twenty years of the project shown in Fig 6. On the other hand, several other Yemeni scientists published papers based on the data obtained from the GDP database, as it is considered the main source of geothermal database source in Yemen. The GDP team also presented the geothermal work in local and international scientific forums, workshops, and congresses. Furthermore, the GDP team gave short courses about geothermal energy resources in the petroleum training center (PTC), which included geothermal exploration, mapping, geochemistry, geophysics, GIS, and environmental impact assessment. This course aims to give hope and opportunity to the next working generation, offering them the prospect of rewarding jobs in a new sustainable industry. Geothermal Symposiums were organized by the GDP at the Ministry of Oil and Minerals, in which all the stakeholders in Yemen were invited.

6.3.1 Geothermal Publications (papers, reports, books) and presentations or lectures.

Yemeni geothermal research and studies were published in the form of peer reviewed papers and reports, such as the ones published between 2001 - 2023 which are included in the references. The most common papers are the Yemeni-Italian papers which approached the geochemistry studies for example (Mattash, Al-Ganad, et al. 2001), (Mattash. M. and Al Ganad 2003), (Mattash. M 2005), (Minissale, Mattash, et al. 2007), (Minissale, Vaselli , et al. 2013) and (Mattash, Pinarelli, et al. 2013). Also, the Yemeni-German papers which introduced the geophysical studies of Al lisi and Isbil (Al Qubatee and Kalpercamp 2010) and another important geochemical paper which briefly compared between Al lisi and Isbil, Al Qafr and Damt geothermal fields in Yemen (Frank. W 2007).

The GDP team published several geothermal papers via various conferences sorting out the work accomplished, and work implemented reports which are written in Arabic after each field work, which assist the society to understand about the geothermal resources in the country, and their importance for indirect and direct utilization. These papers and reports include; (Al Dukhain 2008), (Al Kohlani 2008), (Al Kohlani 2010), (Al Kohlani. T 2015), (A. Al Sabri 2009), (Al Sabri, et al. 2015), (Al Sabri. A 2022), (Alnethary 2010), (Alnethary 2015), (Alnethary 2018) (Alnethary 2019), (Alnethary. M 2021), (Alnethary and Mattash 2022), (Alnethary M. Mattash. M 2022) (Alnethary. M Mattash. M 2023), (Al Kubati 2005), (Al Kubati. M 2015), (M. F. Al Kubati 2017). In the meanwhile, other authors published reports and master thesis related to geothermal with the GDP assistance and/or based on GDP geothermal database such as A master thesis (Al Kubati 2005), (Jazem, et al. 2011), (Motahar. A 2011) and (Al-Fakih 2018).

On the other hand, participation in international organizations, meetings, conferences, and workshops are well known in scientific communities. In a country like Yemen, geothermal experts often be asked to give lectures to promote the public knowledge of geothermal sciences. Therefore, lectures and presentations are presented in various local workshops and international conferences to show the accomplished work, discuss the findings and future plans for the project. That included annual presentations, introduction presentations as well as short geothermal courses at the petroleum-training center (PTC) and at several universities across the country.

Moreover, during the GDP's early days, Mohammed Mattash, one of the founders of the GDP, as mentioned before, wrote an Arabic textbook called Thermal Springs in Yemen that was published by GSMRB at the Ministry of Oil and Minerals in Yemen in early 2003. This textbook was the first attempt to present in a single and an easy text the geothermal resources in Yemen and how it could be exploited. The book is an amazing piece of work and quite an inspiration for the outreach unit in the GDP and was the only reference to the Yemenis hydrothermal water and geothermal resources at the time. The book includes a detailed description of the thermal springs within the whole country and based on those data the Yemeni thermal springs map, at scale 1:250,000 was produced in 2003 (Fig 10 shows the book cover and the map of the hot springs in Yemen). The book discusses the geography and geological setting of Yemen, water resources (surface water, groundwater, and thermal springs), the physical and chemical properties of the thermal water and the fundamentals of geothermal energy in Yemen.

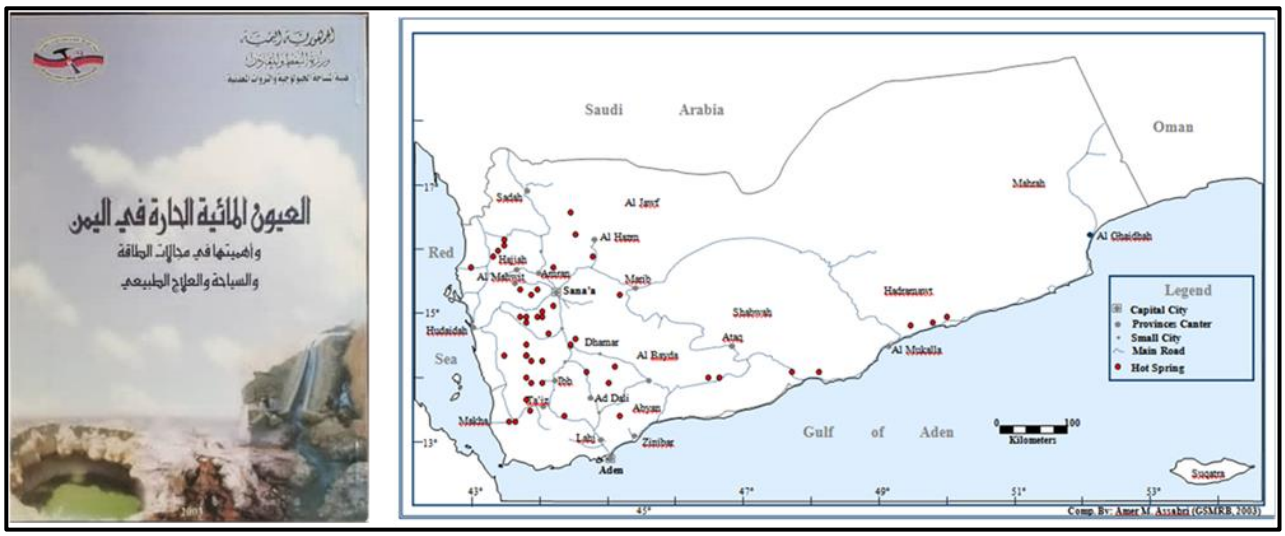

Figure 10: Book cover of Thermal Springs in Yemen (original title in Arabic: العيون المائية الحارة في اليمن) and Hot Spring Map of Yemen (1:1000,000).

6.3.2 Geothermal database sources

A collection of data and information about geothermal in Yemen was organized and arranged by GDP for rapid search and retrieval by a computer. Two types of data were collected: paper based and electronic based data, including paper documents, reports, annual reports and geothermal maps, This Archive offers a unique opportunity to do research based upon previous and recent studies and made accessible for scientists. The archiving process was carried out by the GDP team in 2007 and contains about 112 local and international reports classified according to author name, report title, and published year.

6.3.3 Society outreach and geothermal education

The GDP provides reliable and objective information about geothermal resources in general and exploration and development in particular to the public, in order to bring people closer to geothermal science and inspire the younger scientists to create a sustainable geothermal industry for the country. Thus, the GDP has produced printed material, books and brochures, magazine articles as well as

documentary films about geothermal in Yemen, broadcasted on local channels. Public response to the GDP has increased during the last ten years, which helped to pave the way for the future of the project.

6.4 Other related geothermal, volcanology and mineralogy work by GDP

6.4.1 Jabal Altair recent volcano in Yemen

As a result of the volcanic activity on Jabal Altair Island in September 2007, the GDP (represented by Mattash and GDP team) was among the technical monitoring team who consisted of mineral experts from GSMRB and Sana'a University, volcanologists from CNR, and geophysics from the Seismic Monitoring Centre in Yemen. The aim of the study was carrying out the necessary scientific studies, including determination of the type of gases emitted, the type of volcano, and rock sampling to define the geochemical composition and isotopic studies, including Radon emissions. The main conclusions are the following.

Jabal Altair Island is located 100 km to the northwest of Hodeida city, western of Yemen. The Island is an almost oval-shaped island with more than 10 km^2, which consists of relatively thin basalt lava. Volcanic recent eruptions began on Jabal Altair Island in Yemen in Sep. 2007, and were active until the re-eruption in Dec. 2007. The lava flowed to about 1 km from the northern part of the island through two newly formed craters. There were no serious civilian or environmental risks because the island is relatively remote.

Jabal Altair volcano is the most recent active volcano in the Red Sea. The activity of the volcano is represented by the flow of basaltic lava, which is mostly of a ropy lava (Pahoehoe) with different colors and appearances. The thickness ranges from 1 m to 3 m. In addition, there is another type (Aa), which flows over the older yellowish sedimentary volcanic materials as shown in Fig 11. The volcano released vapors and steam, sulfur dioxide gases, and minor carbon dioxide gases.

Two types of cracks were observed on the Island. Radial cracks in different directions, but most of them parallel to the main direction of the Red Sea. Newly formed cracks parallel to each other, which have a north-south direction and are exposed in the northern part of the Island. The width of these cracks' ranges from centimeters to more than a meter. Altair volcano is of Strombolian type.

The chemical composition of basaltic lava is sub-alkaline with a silica content ranging from 49 to 51%, which is similar in composition to the bottom rocks of the southern Red Sea. The mineral components are plagioclase, clinopyroxene, olivine and opaque minerals.

Figure 11: General view of the current activity of Jabal Altair Volcano including the eruption event, gas emissions and the size of lava flow (Pahoehoe and Aa) with dark grey colour covers most of the Island.

6.4.2 Thamar Drilling well in Al lisi geothermal field

The Thamar well is located 7 km to the west of Al lisi mountain (geothermal area) in Dhamar province, western part of Yemen. It was drilled by GDP and GSMRB in 2008. The well is vertically drilled to a total measured depth of 289 m. The objective was to define the subsurface stratigraphy, mineral conditions (gold potential), hydrothermal alteration and chemistry characteristics of the study area. For this purpose, several analyses were undertaken, including analysis of more than 96 cutting samples from the core samples of the well. The length of the core samples is almost 220 m and about 70 individual cores (Fig 12).

The methods used for analyses included ME-ICP41, ME-MS81 and AU-ICP21 for trace elements and gold analyses, carried out in Italy. The analysis result indicated that the stratigraphy of Thamar is formed by two main stratigraphic units, early felsic and later intermediate to mafic rocks. This division was also observed in the hydrothermal alteration and mineralization patterns. Hydrothermal alteration has been observed with progressive depth. The most common hydrothermal alterations are clay and silica alteration (argillization and silicification) which related to felsic rhyolite domes in the study area; biotite as secondary mineral was identified in Waragah.

Chemical results of trace elements indicated that gold was found in sub-economic grades (from 111 ppb through 188 ppb and up to 235 ppb Au) in several stratigraphic levels in association with felsic domes and silicic alteration. Associated anomalous trace elements are silver, arsenic and molybdenum. The relatively high epithermal trace elements values in drill samples of the silicic tuff breccia (Ag 38 ppm, Zn 647 ppm, Pb 269 ppm, As 464 ppm) support this possibility for a nearby epithermal vent (Mattash M. 1998).

The above brief descriptions of alteration and mineralization are based on the previous extensive field survey carried out by ELC-Electroconsult company (ELC 1982) and Odyssey Company (Strachan D 1997) at Thamar, Al Alanah, and Waraqah areas (Tertiary volcanic in western Yemen), which identified several alteration anomalies from satellite and prospecting data. Gangue minerals were either quartz, calcite, or clay. Opalite indicates near-surface epithermal conditions and sometimes barren or contained low levels of gold.

Further exploration was carried out based on digital satellite TM (Thematic maps) imagery, identifying anomalous clay and iron oxide accumulations, structural features, and geology. These anomalies had revealed significant hydrothermal alteration at Waraqah, Al Alanah and Thamar prospects (Workman A 1993) and (Mattash, Al-Ganad, et al. 2001).

Figure 12: Drill core from Thamar well in Al lisi geothermal field (by GDP and GSMRB).

7. OBSTACLE FOR THE GDP IN YEMEN

The unstable annual financial support for the work of the GDP and the ignorance of decision-makers about this vital and important geothermal resource, obstructed and delayed many of the technical work entrusted to the project, especially in the promising areas. The failure of some local partners to play their role toward the GDP also led to obstruction and delay that influenced the GDP. For example, the financial support from the electricity ministry as a co-financial never arrived as promised. Some foreign organizations also failed to fulfill their obligations towards the project, according to the agreements, for instance in the preparation of the drilling of the first geothermal well in Al lisi - Isbil field, as was the case of the German friends (BGR), which in turn hampered the implementation of many technical works in the project plan. Furthermore, political instability generated obstacles, and lack of policy and regulatory framework of geothermal development which influenced the mutual comprehension of geothermal science.

Therefore, the continuity of GDP beyond March 2018, when the grant by GEF to drill the first geothermal well was canceled, might not be possible. Without local and international financial support, all the work and achievements of the GDP during the last years dramatically interrupted, in accordance with the history of geothermal development of the country.

8. UTILIZATION OF GEOTHERMAL RESOURCES IN YEMEN

The oldest evidence of the geothermal utilization in Yemen was during the ancient times. Thermal water was used for curative effects and recreational purposes in the form of balneology and bathing. The best hot springs known in Yemen are called Hammam Ali (Ali's bath), name given simultaneously for many hot springs that were mainly used to take baths for relaxation and recovery.

Geothermal springs located in areas of tourist attraction have become an important source of local and regional tourism. The overall potential capacity is estimated to be 600 MWt (Al shetwi. A 2021) and a geothermal energy study estimated that 2900 MW of power might be available from geothermal sources. However, the utilization of the resources is still limited to direct applications by private tourism activities for entertainment and balneology, with an estimated use of 1 MWt and 15 TJ/year in 2000 (Davidson 2000). Today, the use of geothermal resources in tourism activities has increased due to the building of more hotels and recreational facilities in several areas, and so the estimation is 5.0 MWt and 100 TJ/yr (Lund and Toth 2021).

The GDP suggests to use geothermal resources in Yemen for power generation, particularly in the area between Al lisi and Isbil volcanoes, whose exploration and drilling was stopped in 2010 (Alnethary and Mattash 2022). Swimming facilities can also be developed to be within the framework of the international standard bathhouses based on their flow rate and water geochemistry or geothermometric characteristics. Moreover, according to a study by (Chandrasekharam D 2016) and (Minissale A 2019), the geothermal energy from Damt geothermal field can be utilized for irrigation purposes by generating freshwater through desalination of seawater from the Red Sea, where this field was shortlisted in 2008 for establishing 1 MWe with financial assistance from UNDP. There might also be a chance if we could focus on an existing industry such as fish farms or some kind of crop production which could use a shallow well or a flowing hot spring that we could use for drying produce.

9. CONCLUSIONS

The GDP is a scientific research project concerned with studying the resources of geothermal energy in Yemen which falls within various branches of earth sciences and its components such as exploratory geological, geothermal mapping, hydrogeological, geophysical studies and drilling as well as periodic measurements and monitoring of the physical and chemical properties of the

elements that make up the resource. GDP began operations in 2000 under the supervision of the Geological Survey and Mineral Resources Board in Yemen GSMRB and worked to generate and improve geothermal knowledge in Yemen via training and improving the geothermal skills for the staff and society.

Exploration for the geothermal resources in Yemen carried out by GDP resulted in the identification five main geothermal fields: Al lisi - Isbil, Al Qafr, Damt, Red Sea Coast and Taiz. Al lisi – Isbil has potential for electricity generation, so it's recommended to drill an exploration well at 1500 m depth where temperatures above 250 °C are expected. Other geothermal fields with interesting potential for moderate to low enthalpy resources have also been studied by GDP.

GDP comprises a team of researchers from several earth science faculties in Yemen, with Yemeni scientists from international faculties. The Yemeni fellows are playing a very important role in the geothermal development, which assist the society to understand about the geothermal resources in the country, and their importance for indirect utilization (electricity generation) and direct utilization (greenhouses, fish farms, crop production and drying produce).

The workforce increased observed through the local and internationally scientific papers, books, and presentations by the GDP team, providing reliable data of geothermal in Yemen. The financial support for GDP came locally from the Ministry of Oil and Minerals (MOM) through the Geological Survey and Mineral Resources Board (GSMRB), and from some international institutions like CNR, BGR and GEF/UNEP.

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