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# The geological controls of geothermal groundwater sources in Lebanon

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**Abstract**
Lebanon is a country that is relatively rich in water resources, as compared to its neighboring states in the Middle East. Several water sources are issuing on the surface or subsurface, including nonconventional water sources as the geothermal groundwater. This aspect of water sources exists in Lebanon in several localities, as springs or in deep boreholes. To the present little attention has been given to these resources and their geological setting is still unidentified. The preliminary geological field surveys revealed that they mainly occur in the vicinity of the basalt outcrops. Therefore, understanding their geological controls will help in exploring their origin, and thus giving insights into their economical exploitation. This can be investigated by applying advanced detection techniques, field surveys along with detailed geochemical analysis. This study aims at assessing the geographic distribution of the geothermal water in Lebanon with respect to the different geological settings and controls that govern their hydrogeologic regimes. It will introduce an approach for an integrated water resources management which became of utmost significance for the country.


**Keywords:** Hot water; Basalt; Renewable energy; Thermal detection; Lebanon.

## 1. Introduction

Water resources occur in different aspects and dimensions, which implies multiple uses. Water for domestic use is the most important, seconded by irrigation, which is a supplementary exploitation for human needs. The miscellany of other uses, as industrial and recreational, depends on the water quality and available supply. Warm water, also referred to as "*geothermal water*" is another feature of groundwater. It exists in several regions in the world, where it is exploited for different purposes, mainly energy. The American Energy Commission [1] estimated that geothermal resources can supply the world's need of energy for the next 100000 years. While, the New Energy Foundation [2] reported the increasing implementation of the geothermal resources in the generation of electricity: Japan relies on 16 geothermal power plants with approximately 530 MW production, covering 0.2% of its power capacity. At present, 24 countries generate electricity from geothermal resources, among which the leading five are USA, Philippines, Indonesia, Mexico and Italy [3].

The geothermal heat pumps currently occupy up to approximately ¾ of the total installed capacity use. Other uses, by decreasing order, include bathing and swimming, space heating, greenhouse heating, aquaculture pond heating, cooling/snow melting and agricultural drying [4]. Kenya, as an example relies on geothermal energy for greenhouses heating, warming swimming pools, and drying pyrethrum products among other beneficial uses [5]. Therefore, the exploitation of geothermal water can be of considerable economical value. This allows for a variety of applications, owing to the wide array of temperatures that it can have ranging from room temperature to over 300°C.

The majority of geothermal waters fall into two major categories: The hot (or warm) groundwater, and the hot springs. Both have almost the similar hydrogeological mechanism (e.g. contact with igneous bodies, flow regime and storage), they differ however, mainly in the volume of water reserve and the discharge continuity. In this respect hot groundwater can be used for electrical power generation and considered almost as an alternative energy source [6]. While, hot springs can be exploited for medical purposes as recreational and touristic resorts, as in Slovenia, Tunisia, Iceland and Japan.

The temperature of geothermal water increases as the depth of burial of groundwater reservoir (i.e. aquifers) increases, due to the geothermal gradient, which is a natural increase in the temperature with depth. Hence, it is utmost important to understand the hydrgeological setting and the related geological controls of the hot groundwater reservoirs, which is the scope of this study. This will help exploring the geothermal water, which has a different concept than the exploration of fresh groundwater, and thus it considers the fractures in igneous rocks with high temperature [7]. Accordingly, the exploitation procedure implies drilling wells into the rocks, and thus penetrating the reservoirs of the temperate rocks.

The chemistry of the geothermal water differs significantly than fresh water as it contains large concentrations of dissolved minerals, such as sodium, calcium, sulfate, chloride, or iron. These ions have been dissolved from the minerals in rocks that compose the geothermal reservoirs and vary as the mineral composition of the rocks varies. Especially aggressive, are hot water from volcanically active regions, these brines contain carbonic acid, hydrogen sulfide, salts and heavy metals, which renders them very corrosive to well casing and toxic due to the waste water, besides emissions of hydrogen sulfide and to a lesser extent carbon dioxide [8]. This necessitates detailed geochemical analysis of the waters in question.

In Lebanon, the country with abundant freshwater resources, there are several evidences on the existence of hot water, either as hot springs or in aquifers at depth. Nevertheless, they were discovered unintentionally, at sites where the water flowed naturally to the surface. These geothermal water sources occur in, or at proximity of the basaltic rocks. Yet, no proper attention has been given to these sources, either in terms of investigating their hydrological mechanism, or investment projects.

Lebanon is considered as an energy dependent country, where oil products are still the principal sources. They comprise about 93.5% of energy sources [9]. Lebanon imports around $500 million worth of fuel annually to generate the electricity needs [10]. This shows the urgent need for alternative sources of energy, as being optimized recently for the exploration of oil and gas in Lebanon. Therefore, if the geothermal water is properly investigated, it might however fulfill an integral part of the energy needed.

There are few previous studies on the geothermal water in Lebanon, these are rather prospects and hypothesis on the subject, such as those by [6, 10, 11]; in addition there are limited researches by graduate students. In order however, to assess the geothermal water of Lebanon, the studies must be performed at different institutional levels. Amongst which, an accurate understanding of the geological setting of the geothermal water, chemical analysis for this nonconventional water, as well as the advanced exploration techniques (e.g. remote sensing).

This study focuses on diagnosing the geological setting, and more certainly the controls of the issuing water from the hot sources in Lebanon. It also presents a systematic approach to delineate the geothermal potentials.

## 2. Aspects of geothermal water

### *2.1 Geology of geothermal water*

Geothermal water often flows, discharges and is stored in almost similar hydrogeological regimes similar to freshwater, except that it must be in a direct or indirect contact with igneous rock masses at different depths and aspects of contact. Thus, geothermal waters can be issuing on the surface as springs or seepages, and they can be also subsurface sources such as the case in deep groundwater. Therefore, the geology of geothermal water along with the controlling factors should be well identified. This will help estimating the regime of discharge, the chemistry and the sustainability of the resource.

Heating groundwater follows different hydrologic mechanisms, therefore presenting numerous aspects. The main ones can be described as follows:

 

1. Direct contact between deep groundwater and hot magmatic rocks where molten materials heat up the water which is mostly stored at considerable depth in the confined aquifers (Figure 1a). This groundwater usually has high temperatures that may exceed 300°C.
2. Contact between the sedimentary aquifers and hot igneous rock bodies. This is well pronounced in porous and permeable sedimentary lithologies which overly hot igneous rocks (Figure 1b). The temperature of this groundwater is almost moderate and may reach 150-200°C; however, this mainly depends on several influencing factors, such as the proximity to the sources of heat.
3. Flowing of geothermal water under the effect of pressure and heat, along fracture systems and conduits, which are connected with molten materials or hot igneous bodies and open at unidentified spots where the geothermal water discharges as springs or seepages (Figures 1c and 1d). The temperature of this geothermal water is usually moderate to low and it does not normally exceed 100°C.
4. Dissipating hot gases along fractures and conduits, similar to geothermal water that circulates along fractures, but the flow is mostly hot steam (i.e. gas). This setting is observed not only on-land but also in the sea floor (Figures 1c and 1d).

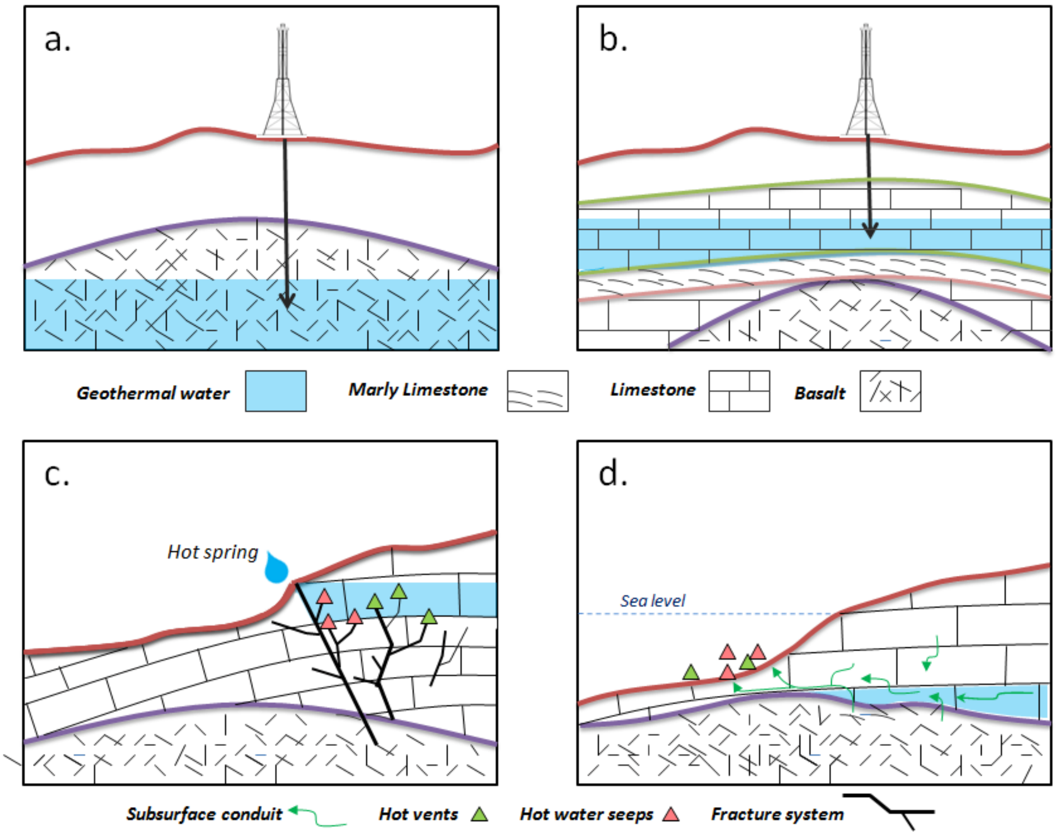


Figure 1. Examples on the flow mechanism of geothermal water

Accordingly, the hydrologic mechanisms and the resulting aspects imply a number of geologic factors that govern the dimensions, water temperature and quality of the geothermal water. The proximity of contact between the molten materials or the hot rock masses with respect to groundwater is equally a determining factor. These settings also control the flow regime of hot water among different lithologies, whether in lateral or vertical directions. Therefore, in the presence of heat sources, the majority of these factors can be summarized as follows:

1. Geologic structures: This almost includes the linear rock breaks of different sets. It can be as fissures, joints, conduits and faults which connect the heat source to the water-bearing stratum or water outlet localities. The geothermal water can move according to the predominant alignments of these breaks. In the presence of fissures and joints, the hot water flows with low energy for relatively limited distances. Nevertheless, along fault alignments, the water is transported for long distances with high energy.

This factor has a variety of aspects and dimensions which play a role in the occurrence of geothermal water on the surface or subsurface. For example, fissures can expose geothermal water on the land surface as patches of seeping hot water; faults almost result in hot springs with remarkable flow, but at a unique locality; grabens, on the other hand, result in multiple sources, once the hot water sources exists.

2. Volcanic exposures: This represents the major component of geothermal water factors. The volcanic rocks on the land surface are usually connected with subsurface and hidden igneous rock masses, which in principle have hydrologic linkages with deep heat sources, such as magma and molten materials.
3. Heat proximity: The closer to the magma source the more probable is the connection with heat channels and contacts.

The volcanic rocks in contact with magma and molten materials will convey the heat through these rocks and then to the overlying sedimentary sequences. But if these sources are at considerable depth, the heat will not be effective in producing geothermal sources.

4. Rock boundaries: The rock boundaries might play a negative role in transporting hot water or heat in case these boundaries (i.e. stratigraphic contacts) are wide enough to separate the vertical heat and water flow, the heat/water can though be conveyed in lateral directions.
5. Rock mineralogy: Normally the mineralogy of the rocks has an essential role in transporting heat, notably when the contact is directly with igneous rock. Thus, the included minerals can either act in transporting or blocking the heat flow. For example, rocks with high metallic minerals (e.g. iron, copper, etc) have higher heat connectivity than the non-metallic ones (e.g. silicates, etc).
6. Rock permeability: As a major physical property the permeability of rocks is the major factor in controlling the heat and liquid flows through the different rock types. Consequently, impermeable rocks usually act as cap rocks that reserve heat and water flow. Hence, in the case of geothermal water, these rocks almost confine the water at depth.
7. Igneous activity: It represents the generating factor of geothermal water sources. Nevertheless, many igneous rocks are not molten enough to produce heat and this usually depends on the thickness of the rock masses as well as the mobilization, activity and energy of the molten materials.

*2.2 Geothermal water sources in Lebanon*

Indicators of geothermal sources are well known in Lebanon. They can be related to geologic evidences (i.e. geologic structures and lithologies). Otherwise they are spotted as hot/or warm water sources and sometimes hot gas vents.

The geologic indicators do not assure that the geothermal waters occur, whilst hot and warm waters are direct evidence for these sources. In Lebanon, several geological evidences are correlated with the geothermal sources. These include the volcanic rocks as basalts and tuff materials, outcropping at different levels of the geological sequence [12]. In fact, most geothermal waters and vents found in Lebanon are in the proximity of these rocks. In addition, there are many surface ring geomorphologic features that are attributed to geothermal sources, where volcanic bodies exist or might have erupted in the geologic past [13].

The geothermal water and vents in Lebanon are however the concrete evidence of the geothermal sources existence, and since they occur where igneous bodies are located, it can be anticipated that other potential sources might exist in other localities, in the vicinity of volcanic rocks exposures. The spotted sources occur as surface water or are drilled in a subsurface stratum, yet they are both of groundwater origin. They can be classified as:

*2.2.1 Surface geothermal sources*

These sources appear as issuing springs and seeps on the land surface, specifically where basalt rocks occur. The hot/or warm water discharges almost at low rates (i.e. <1l/sec) and at relatively low temperatures. A number of these springs and seeps are known in Akkar region, north Lebanon, where as anticipated, there are several exposures of basaltic rock in the mountainous areas. However, many of them have dried up lately as a result of the overexploitation of the groundwater reservoirs. Moreover, due to the lack of awareness on the importance of these sources, many are not protected. They are on the contrary covered by soil and wastes.

Ayoun es-Samak is the most known hot spring in this region. It is located at the geographic coordinates: 34°37'05" N& 35°57'59" E (Figure 2). The discharges are more than 1l/sec on average. The Field tests show average temperatures ranging between 50-65 °C depending on the time period; higher temperatures and low discharges occur in the dry seasons [7]. The estimated Total Dissolved Solids (TDS) in the spring was about 21000mg/kg and with pH of 8.3.

Based on the controlling geological factors, some water springs and gases have been detected in the marine environment. These geothermal sources are well known to the fishermen along the Lebanese coastal zone. They are clearly identified in three localities as follows:

- Along the southern coast beside Sour at the geographic coordinates: 33°15'33" N & 35°11'32"E (Figure 2). It is represented by several submarine hot vents in the sea floor at a distance of about 300 m from the coast and at a depth of about 30m. These vents are originated from holes in the seafloor (Figure 3).
- Beside Chekka area along the northern coast at the geographic coordinates: 34°19'24" N & 35°43'21"E (Figure 2). This site is represented by a number of small bubbles and vents of tens of centimeters in diameter. They were detected during an airborne Thermal Infrared survey applied by [14]. The temperature of these clusters was about 38°C while the surrounding temperature of water was about 26°C. The estimated TDS was about 18500mg/kg and with pH of 7.7.
- Facing Al-Abdeh city along the upper northern coast of Lebanon at the geographic coordinates: 34°31'37" N & 35°59'07"E (Figure 2). This spot equally exists as a number of small bubbles of warm water, identified by the airborne Thermal Infrared survey carried out by [14]. The temperature of these clusters was about 38°C while the surrounding temperature of water was about 22.5°C.

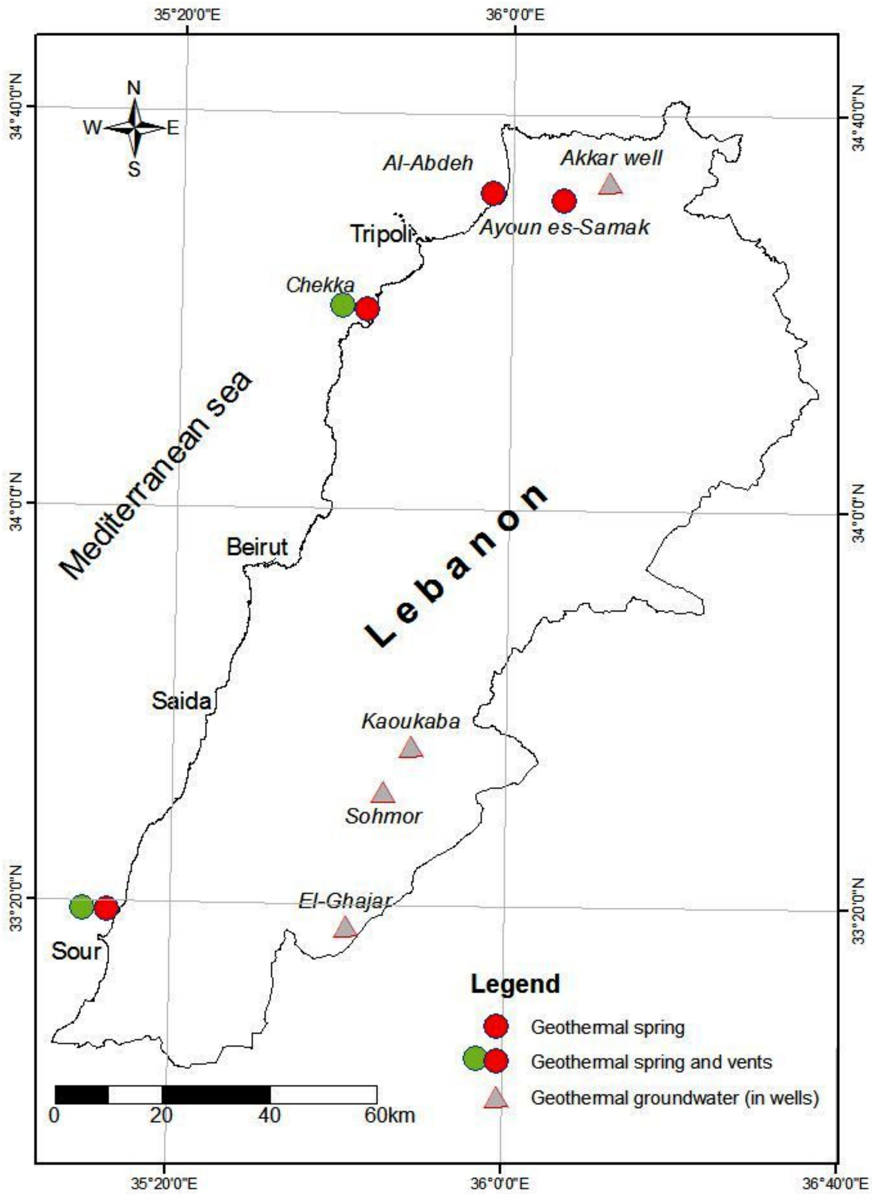


Figure 2. Localities of geothermal sources in Lebanon

 

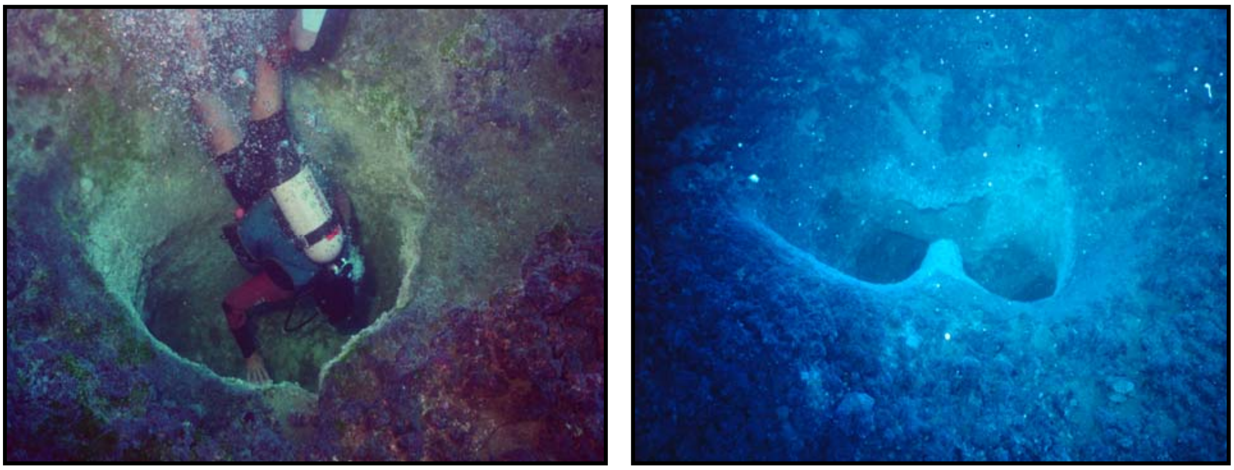

Figure 3. Submarine hot springs and vent beside Sour coast [15]

*2.2.2 Subsurface geothermal sources*

From the hydrogeologic point of view, the majority of geothermal water is mainly in deep rock stratum where they can be in large amounts. Nevertheless, this water remained unknown in porous rocks unless boreholes are dug, or they are overflow on terrain surface along weak surfaces (e.g., faults, conduits, veins, etc) as mentioned previously. Therefore, geothermal groundwater often appears in drilled wells at different depths. These sources are not supposed to exist only where igneous rocks are exposed, but they may found also in sedimentary rocks which are hydrogeologically connected to hot igneous bodies.

This is the case in Lebanon, where hot water and gases have been observed in several drilled boreholes. However, all of them were ignored and left unexplored. These waters are observed in several localities in the north of the country, in Akkar region. They were encountered at variable depths and displayed different physical characteristics. The most known well in this region was drilled in the 1970s in the fractured basalt rocks to about 550m depth. The water from the well was injected to about 30m above ground due to the high piezometric pressure. It had temperatures of about 70°C and high sulfur content [10]. Many other observations have been encountered in southern localities (Figure 2), as in the village of Sohmor, where warm water has been noticed in a well at a depth of more than 800m [16]; in Kaoukaba village, a drilled well discharged warm water with estimated TDS content of 16000mg/kg and a pH of 7.2; Similarly, warm water was reported in El-Ghajar village along with many other wells that showed similar phenomena.

## 3. Prospection methods

Prospecting for geothermal resources should follow systematic approaches. It is not only dependant on surface waters observations or drilling boreholes as was the case in Lebanon. The investigations should include geological mapping, thermal detection, either directly on the ground surface or by using airborne or spacecraft shuttles, geophysical prospecting (e.g. electrical and magnetic), drilling and observation wells. The chemistry of water should also be determined as it represents an important aspect in determining the suitability of the resource use, rather than the temperature itself.

However, in all cases a preliminary investigation can be obtained by studying the geological maps for the volcanic rocks as basalt, since the majority of the geothermal waters occur in contact with hot rocks.

In this study, the applicable approaches to identify geothermal water sources in Lebanon will be illustrated depending on the available data sources, as well as in consistency with the exposed geothermal sources mentioned previously in this study.

*3.1 Geologic investigation*

The eight traced geothermal sources in Lebanon should be investigated for their lithological facies, geological controls and heating mechanism. Correlations with similar geological settings can help inducing the existence of new geothermal sources. The geological maps scaled at 1:50.000 by [12], were analyzed and field reconnaissance followed. Direct temperatures measurements were taken, when possible. The land owners were addressed, to inquire about their knowledge on the existence of geothermal water/gases and ascertain to a certain degree their presence in the drilled boreholes. In this

respect, many inhabitants witnessed observing warm water; especially near areas of basalts of the Pliocene age, which are distributed in four domains (i.e. Akkar, Hinayder, Kaoukaba and El-Ghajar) as shown in Figure 4. These sources were categorized according to the geological controls (Table 1).
In the field survey, a number of geological considerations were accounted for, depending on the characteristics of each locality. These include:

1. Measuring the dip and strike of the exposed formations, and thus presuming the alignments of rocks, notably along the igneous/sedimentary contacts.
2. Measuring the fractures and joint systems and the number of sets for each. This helps inducing the density of fissuring, which increases the heating rate.
3. Delineating the alignment and dimensions of faults.
4. Constructing stratigraphic cross-sections and illustrations of rock successions, as needed.
5. Identifying the characteristics of aquifeours strata and the hydrogeologic setting of the springs.
6. In principle field testing is applied *in-situ*, and primarily water temperatures measurements, in addition to collecting samples for further chemical and physical analysis in the laboratory. For this purpose, specified probes can be taken to determine directly these parameters, at different time intervals and at variable depth.

*3.2 Geothermal detection*

*3.2.1 In-situ temperatures measurements*

Thermometers are simply use to determine the temperature of the spring or boreholes water. It is also easily practicable to monitor the temperature variations over different time periods. However, more sophisticated thermal detectors (or digital thermometers) are currently in use. These can detect temperatures at higher rates (i.e. several hundreds of degree Celsius), being portable devices, they can also help to measure the temperature gradient at different depths and to determine equally the gases and vapor temperatures.

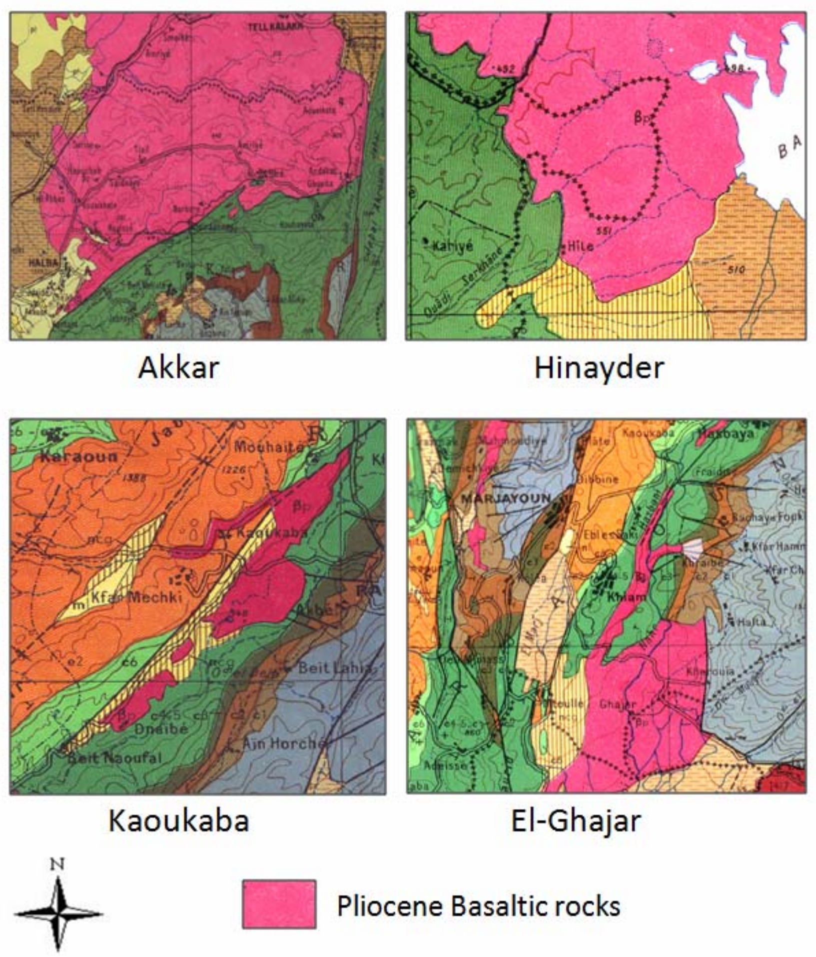


Figure 4. The major basaltic domains in Lebanon as appear on the geologic maps

Table 1. Major geological characteristics of the known geothermal sources in Lebanon

| Geothermal source | Source type | Dominant lithology* | Geologic deformation* | Mechanism of heat flow |
|---|---|---|---|---|
| Ayoun es-Samak | Terrestrial spring | Basalt and tuffs covered by alluviums | Fractured terrain, low-land topography | Heat transfer along the fractured basalt where the groundwater level is exposed in the low-land |
| Al-Abdeh | Submarine spring | Alluvial deposits and sand terraces | Fissured and tilted bedding planes | Seepages of heated water along fissures from igneous rock masses on Akkar plateau |
| Chekka | | Limestone with marly facies | Faulting exists plus fissure rocks | Joints and fissures, as well as faults work as heat transfer routes, but the source is still unknown |
| Sour | | Carbonate rocks mixed with marly limestone | Relatively large-scale fault alignment | |
| Akkar | Borehole (groundwater) | Basalt and tuff | Normally fissured basalt rocks | Direct contact between groundwater and hot rock masses at depth |
| Kaoukaba | | Basalt rock masses | Jointed and fissured rocks | |
| Sohmor | | Chalky and marly limestone, and basalt exposures in the proximity | Faulting and lithological boundaries exist | Faulting acts in heat transfer between groundwater and hot rock masses |
| El-Ghajar | | Basalt rock masses | Jointed and fissured rocks | Direct contact between groundwater and hot rock masses at depth |

* *As determined in the field reconnaissance*

The following points must be taken into account while using thermal detectors to measure temperature of water sources:

1. The increase in temperature of water or vapor is an ordinary phenomenon that is controlled by several physical factors, notably the seasonal climatic variations, as well as the depth of water column. However, normally the background values are considered in order to presume the temperature increases in any media, and this was applied in the field reconnaissance which was carried out on the existing geothermal sources in Lebanon.
2. The sensor of the thermal detector should be totally immersed into the water body or in the discharged water at the middle point of water column; the immersion should last for few minutes before the readings are taken.
3. In the case of water seeps, showing dissipated water outlets, the temperatures measurements should be taken on the sources of water eruption and not where water spreads.

*3.2.2 Surveying thermal sources*

Considering the case of Lebanon; it is becoming obvious that most geothermal sources are found in the context of basalt rocks. Therefore, it is possible to apply ground investigations in terrains where the basalt is exposed. This can be applied in two geological settings: First, when the basalt is covered by sediments and no dominant fractures can be observed. Second, when the basalt rocks with dominant fracture systems are not covered by sediments or any surface materials. Hence, two detection approaches can be applied as follows:

1. Drilling observation boreholes following the grid classification, where the spacing between the different boreholes will be constant. This approach can be carried out in both of the cases mentioned above. The boreholes will be drilled until the groundwater reservoir is reached. Then the temperatures can be measured at different depth. As a result, a geothermal map can be drawn (Figure 5).
2. From this map the concentration of the geothermal sources can be identified, and thus the geological illustrations will be obtained (e.g. cross-sections, such as AA′ and BB′ in Figure 5).

 

3. Drilling observation boreholes on the existing rock structures and more certainly along faults alignments or fracture systems that are encountered on the basalt rock masses (Figure 6). This method can be applied when the basalt rock masses are outcropping at the surface and not covered by overlying sediments. Hence the distribution of the observation boreholes will be totally controlled by the existing geologic structures.

In this method, at some instances a tracing approach is applied, in which the boreholes with increased temperature will be followed. In other words, if the geothermal sources are detected along the fault alignment, thus drilling more boreholes can be continued along the same direction of this alignment unless the temperature becomes normal and vise versa.

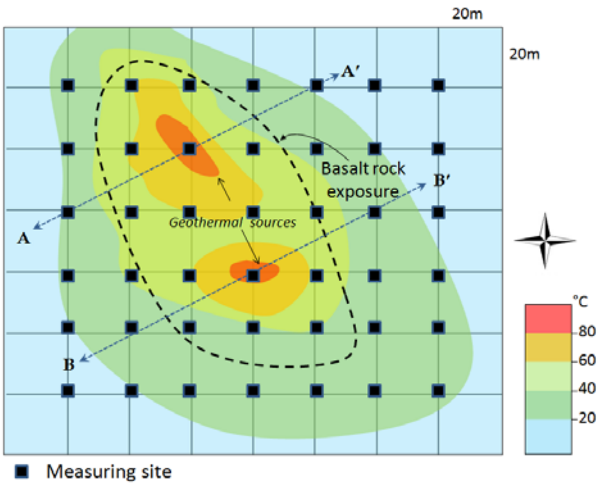


Figure 5. Example on the Grid method to detect thermal sources

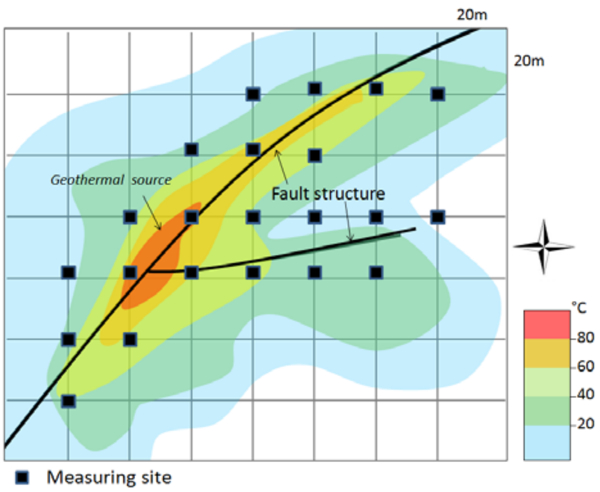


Figure 6. Example on the drilling of observatory boreholes along fault alignment to detect thermal sources

**4. Results and discussion**

To the present, no systematic approaches have been applied to explore the geothermal resources in Lebanon. Yet this study introduces an inventory on the geological controls that govern the existence of these resources. It introduces the first-hand information on where these resources can be found and how they are to be explored. Therefore, considering the existing indications of the geothermal resources can assist, in this respect, in finding new locations with similar conditions. Three major geological settings are associated with the present geothermal sources:

1. Four of the eight sources in Lebanon are directly located in areas dominant with basalt rock exposures. These are the sources of: Ayoun es-Samak, Akkar, Kaoukaba and El-Ghajar.
2. Two sources are in the proximity or basalt rock masses and they are covered by sedimentary materials (e.g. alluviums and soils), such as Al-Abdeh and Sohmor.
3. Two sources are not located in the proximity of the basalt rocks, but there are existing faults, that are presumed to provide routes transferring heat to the sedimentary rocks.

Therefore, by integrating the above three indicative outcomes of the geothermal resources in Lebanon, it can be clear that these resources are mainly located in areas with basalt rocks, and more precisely the basalt of the Pliocene age. Additionally, the basalt rock masses with fault systems are considered as more promising localities for geothermal resources whether in the form of water or gas. These are the most abundant hydrologic phenomena worldwide, similar to those occurring in Turkey and having analogous characteristics to those in Lebanon [17]. Nevertheless, potential sites are also sedimentary deposits that have a lithological contact with igneous rock bodies.

The geological settings in Lebanon with its evidenced geothermal resources allow applying different methods of geothermal detection in order to explore the potential sites in the different territories. Thus, boreholes can be dug to delineate the geothermal parameters and their dimensions can be measured in order to have insights into their exploitation and implement economical investment plans.

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