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# Evaluation of the Geothermal Potential in Morocco: A Northeastern Morocco Case Study

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## ABSTRACT

As a state agency, ONHYM (National Office of Hydrocarbons and Mines) is in charge of developing geothermal energy exploration in Morocco. In a framework that ONHYM has been conducting since 2012, various programs of evaluation and overall synthesis were completed by compiling all existing geoscience data (Sadki, 2012; Berkat et al., 2017). This allowed defining two large areas with prospective high geothermal potential: northeastern Morocco and the South Atlantic margin of the country. This paper presents the main results of an evaluation of geothermal potential in northeastern Morocco, where surface geothermal features have been reported and studied since the first decade of the 20th century. This part of the country is characterized by recent widespread volcanic activity (14.6 to 0.3 Ma), thin crust and lithosphere, geothermal gradient and heat flow that exceeds 40°C/km and 110 mW/m$^2$, respectively. As part of this project, ONHYM carried out a surface exploration program consisting of detailed geology mapping, a geochemistry survey over the superficial index, and thermal loggings in shallow and deep boreholes. The results of this program allowed identifying and selecting five areas with geothermal resource potential. A road map was proposed to develop this energy in the coming years for direct use as well as for electricity production using a binary system. This program states clearly that pilot geothermal projects either in direct use or power generation are in accordance with the new mining law that integrated in 2015 for geothermal exploration and exploitation licenses.

## 1. INTRODUCTION

Morocco is an energy-dependent country, producing small volumes of oil and natural gas. More than 50% of the national energy demand is imported. To overcome this energy shortage, the country has focused on developing renewables such as solar, wind, biomass, hydropower and geothermal energies. The energy plan aims to exceed 52% of the national electricity mix by 2030 from renewable energy. The geothermal energy subsidiary can participate in the energy mix to fill the gap and supply this energy plan.
Moroccan estimated energetic potential is 25,000 MW for wind power in onshore, 250,000 MW for wind power in offshore and 20,000 MW for solar power. Currently, only 3,700 MW of renewable energy capacity or 35% in the electricity mix is reached (Ouhmid, 2019).

Conscious about the importance of geothermal energy as an affordable and sustainable solution to reduce dependence on fossil fuels, as well as a way of reducing global warming risks, the National Office of Hydrocarbons and Mines (ONHYM) as a state-owned company lunched several new studies in order to evaluate and develop Moroccan geothermal potential. These studies allowed ONHYM to delineate the potential zones in the country. The purpose of this paper is to characterize the geothermal province of northeastern Morocco using a modeling approach. The founding results, concerning the high geothermal gradient, can act as a stimulus for future deep geothermal investigation.

## 2. GEOTHERMAL POTENTIAL

Located at the northwestern part of the African plate, Morocco is the site of lithospheric shortening related to the Africa-Europe convergence. The large number of hot springs, and recent volcanism in northeastern Morocco have drawn several geothermal studies (e.g., Facca 1968; Alsac et al., 1969; Rimi and Lucazeau 1987; Zarhloule 1999; Rimi et al., 2012, Barkaoui, 2014; Barkaoui et al., 2015, Berkat et al., 2017). Northeastern Morocco, from Eastern Rif and the Middle Atlas towards northwestern Algeria shows a heat flow range of 80 to 110 mW/m$^2$ (Zarhloule et al., 2015). This part of the country is characterized also by high geothermal gradient values reaching 50°C.km$^{-1}$ (Rimi 1999, Zarhloule et al., 2001, 2015).

In the sedimentary basins of northeastern Morocco, the deep circulation of geothermal fluids (water and gas) is facilitated by the presence of complex fracture systems (Rimi, 1999; Zarhloule, 1999, 2015). The Liasic aquifer is considered the prominent geothermal reservoir in the eastern part of the country. More than 25 hot springs, whose surface temperatures range from 26 to 54 °C and flow rate sometimes exceeds 40 L/s, are connected to this reservoir. Some boreholes show high heat flow and high geothermal gradients, like well 1624/7 where the measured temperature at 470 m is equal to 50 °C and the geothermal gradient begins to increase at 300 m depth from 29 to 127 °C km$^{-1}$ (Zarhloule et al., 2015). In this well, Barkaoui (2014) estimated the bottom temperature to about 120 °C.

## 3. GEOGRAPHIC AND GEOLOGICAL FRAMEWORKS OF THE STUDY AREA

Geographically, the study area is located between the following coordinates: 32°88'N to 35°80'N and 01°11'W to 03°87'W (Fig. 1). It extends over almost the entire northeastern region of Morocco, and is limited to the North by the Mediterranean Sea, to the West by a watershed called Oued Sebou, to the East by Algeria and to the South by the Eastern Atlas. The orography is mainly guided by the vast plateau of the eastern Meseta to the East and two large mountain ranges: the Rifain Arc to the Northwest, and the chain of Atlas to the West, the South and the Southwest. Northeastern Morocco consists of two large contrasting areas: a mosaic of small units of mountains, plains and corridors in the northern part, and huge steppe and sub-desert areas in the southern part.

Structurally, northeastern Morocco is divided into two large domains: the eastern Rif to the North, and the Atlas domain to the South. The Atlas Domain includes different structural units which are: High plateaus, Taourirt-Oujda corridor, Horsts Chain, Beni Snassen-Beni Bouyahi massif and Triffa plain, and Middle Moulouya (Fig. 2).

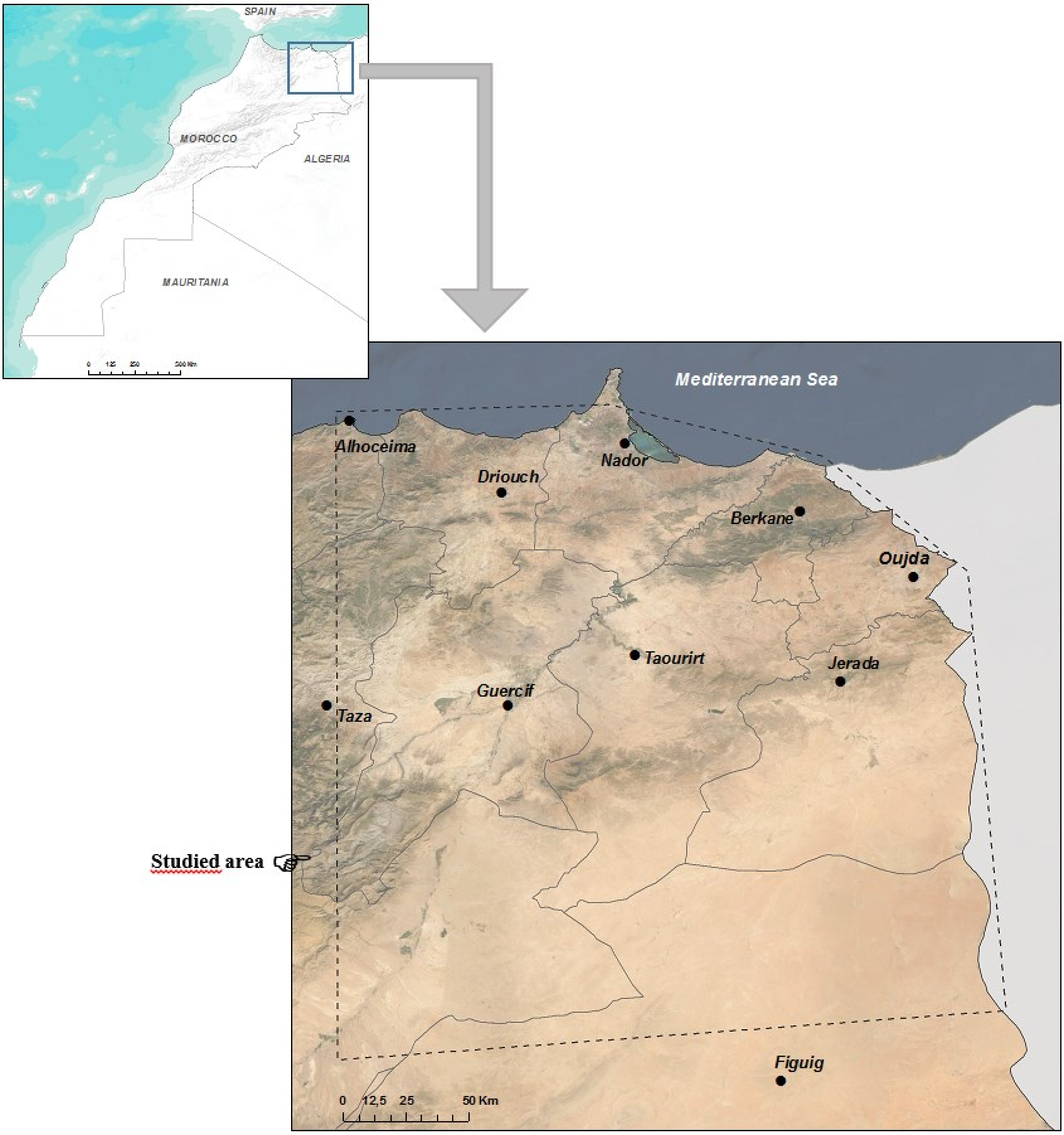
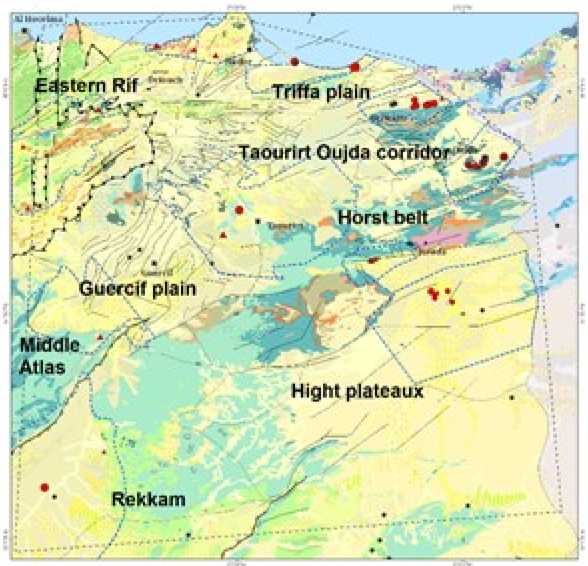



**Figure 1: Location map of the study area.**




| | Period | Stratigraphic ages | Thickness | Main Lithology |
|---|---|---|---|---|
| IV | | | 0 - 800m | Conglomerate, sandstone, alluvium, Sand….. |
| III | | Miocene | 10 - 2000m | Marl |
| | | Oligocene | 30 - 100m | Conglomerate, limestone |
| | Cretaceous | Senonian | 300m | Limestone, Marl |
| | | Turonian | 0 - 150m | Limestone |
| | | Infraceno-Cenomanian | 0 - 300m | Marl, sandy limestone |
| II | Jurassic | Kimm-Porth | 10 - 760m | Limestone -dolomite |
| | | Callovian-Oxfordian | 100 - 1400m | Sandstone |
| | | Battonian | 100 - 850m | Marl, sandstone |
| | | Middle to upper Bajocian | 30m | Limestone |
| | | Low Aalenian Upper Bajocian | 20 - 2020m | Limestone, Marl |
| | | Low Toarcian-Aalenian | 20 - 1946m | Marl, limestone |
| | | Lias | 50 - 1600m | Limestone, dolomite |
| | Trias | | 40 - 2200m | Clay, salliferous clays, sandstone, Granit, basalt |
| I | | | | Schists, Clay, Sandstone, Limestone … |

**Figure 2 : Simplified geological map of northeastern Morocco with the different morphological units, and synthetic stratigraphic log of the study area (Zarhloule, 1999).**

## 3. GEOTHERMAL FRAMEWORK OF THE STUDY AREA

The project area is characterized by recent widespread volcanic activity (14.6 – 0.3 Ma), a thinned crust and lithosphere, geothermal gradients and a heat flow exceeding 40°C/km and 110 mW/m$^2$, respectively. This area is located on a major SW-NE trend, called the Morocco Hot Line (MHL), that extends from the Canary Islands in the Southwest through the Middle Atlas and northeastern Morocco in the Northeast, and continues into the Alboran Sea, southeastern Spain and eastern Algeria (Fig. 3) (Frizon de Lamotte et al., 2009).

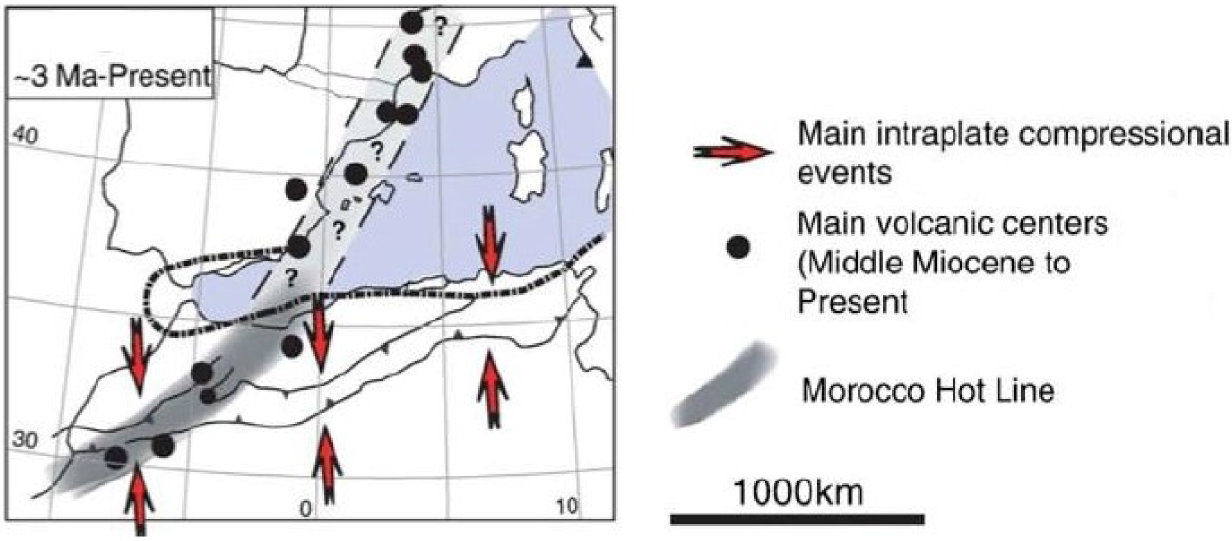



**Figure 3: Moroccan hot line (MHL) (in gray), in its recent regional geodynamic framework (Frizon de Lamotte et al., 2009). Along this narrow and elongated zone, the lithosphere is less than 100 km thick**

## 4. IDENTIFICATION OF GEOTHERMAL RESERVOIRS AND PRIORITY AREAS

The assessment of the hydrogeothermal resources in the study area involved integrating geological and geophysical data, as well as evaluating the temperature distribution, hydrodynamic petrophysical and chemical characteristics of the reservoirs. Thermal water inventory points out 40 springs and boreholes with temperatures higher than 25 °C (the minimum threshold to define thermal groundwater). The average temperature is 32.4 °C, with a maximum of 54 °C recorded at the Ben Kachour well (Table 1 and Fig. 4). Twenty-six groundwater points show a temperature below 30 °C, five between 30 °C and 40 °C and nine whose temperature exceeds 40 °C.

The location of these water points and their geological environments revealed limestone and dolomite Liasic as a hot continuous water reservoir in different hydrogeothermal basins of the Atlas domain. In the Pre-Rif domain, where the geology is more complex, springs are located in Neogene volcanic formations or Mesozoic to Cenozoic sedimentary rocks (Zarhloul, 1999; Berkaoui 2014).

**Table 1: Springs and boreholes inventory.**

| N° | Nom | Nature | T (°C) | Latitude | Longitude | Elevation |
|---|---|---|---|---|---|---|
| **1** | Berkanin | Borehole | 39,6 | -2,4820000 | 35,0890000 | 120,0 |
| **2** | Puits Yadim 2 | Borehole | 42,0 | -2,4752430 | 35,0892050 | 70,0 |
| **3** | Puits Yadim 1 | Borehole | 43,0 | -2,4746680 | 35,0931860 | 70,0 |
| **4** | Kariat Arekman | Borehole | 42,0 | -2,7431090 | 35,1135150 | 2,0 |
| **5** | Hammam Chaâbi jdid (1598/6) | Spring | 34,0 | -3,3486800 | 35,1851660 | 0,0 |
| **6** | Hammam Chaâbi bali (1599/6) | Spring | 32,8 | -3,3529370 | 35,1866680 | 56,0 |
| **7** | Haddou au Amar (1604/6) | Spring | 29,0 | -3,0919670 | 35,1450280 | 122,0 |
| **8** | El Hammam 2 | Spring | 32,1 | -3,1874140 | 35,1695700 | 84,0 |
| **9** | Ain Hommam 1 | Spring | 27,0 | -3,1898280 | 35,1678990 | 84,0 |
| **10** | Hajra Safra | Spring | 26,0 | -3,9205660 | 34,4682410 | 855,0 |
| **11** | Ain Hamra | Spring | 24,0 | -3,9432070 | 34,7397270 | 1200,0 |
| **12** | Ain Chifa | Spring | 32,0 | -3,6112460 | 34,9039460 | 514,0 |
| **13** | Forage 208/31 | Borehole | 48,0 | -3,8480500 | 33,2316690 | 820,0 |
| **14** | Ain Tissaf | Spring | 27,4 | -3,5855950 | 33,3901630 | 1341,0 |
| **15** | Zouaïd | Borehole | 26,8 | -2,0662940 | 34,1011650 | 905,0 |
| **16** | Sehb Abd Alwad | Spring | 27,6 | -2,1133920 | 34,0943510 | 906,0 |
| **17** | Forage Sehb Abd Alwad (UES) | Borehole | 25,9 | -2,1240140 | 34,0821510 | 915,0 |
| **18** | Forage Sehb Lghar | Borehole | 30,1 | -2,1394980 | 34,0988860 | 919,0 |
| **19** | Forage Mrabou | Borehole | 26,6 | -2,1235190 | 34,0702650 | 930,0 |
| **20** | Ain Rayan (299/18) | Borehole | 24,7 | -2,0468930 | 34,0531160 | 916,0 |
| **21** | Ain Moussa Ben Hemmim | Spring | 25,7 | -2,4031350 | 34,2389550 | 779,0 |
| **22** | Ain Khales | Spring | 24,8 | -2,3844830 | 34,2437230 | 810,0 |
| **23** | Ain Ellah | Spring | 25,5 | -2,4070510 | 34,2362610 | 759,0 |
| **24** | Ain Cheffa | Spring | 25,5 | -2,4080710 | 34,2394330 | 804,0 |
| **25** | Ain Bouisseden | Spring | 25,6 | -2,3847060 | 34,2432500 | 830,0 |
| **26** | Bou Rached | Spring | 32,0 | -3,6007620 | 33,8983500 | 971,0 |
| **27** | Ain Goutitir (sidi chafi) | Spring | 45,0 | -3,0597910 | 34,3514700 | 380,0 |
| **28** | Forage 1212/11 | Borehole | 42,6 | -2,9879960 | 34,4577490 | 343,0 |
| **29** | Oued Nachef IV | Borehole | 33,0 | -1,9418210 | 34,6529890 | 597,0 |
| **30** | Beni Oukil | Borehole | 35,7 | 0,0000000 | 0,0000000 | 2150,0 |
| **31** | Forage 2952/12 | Borehole | 47,0 | -1,8199220 | 34,6944230 | 560,0 |
| **32** | Ben Kachour (159/12) | Borehole | 54,0 | -1,9094470 | 34,6680640 | 562,0 |
| **33** | Tercha (777/7) | Borehole | 28,0 | -2,2202340 | 34,9139250 | 275,0 |
| **34** | Sidi Rahmoun | Borehole | 29,2 | -2,1257920 | 34,9313770 | 268,0 |
| **35** | Forage 1624/7 | Borehole | 53,0 | 0,0000000 | 0,0000000 | 0,0 |
| **36** | Fezouane 3 (1672/7) | Borehole | 37,0 | -2,2128410 | 34,9450050 | 252,0 |
| **37** | Fezouane 2 (1331/7) | Borehole | 37,0 | -2,2057580 | 34,9204960 | 252,0 |
| **38** | Fezaoune 1 (1268/7) | Borehole | 37,0 | -2,2057880 | 34,9196940 | 256,0 |
| **39** | Ain Kiss | Spring | 25,4 | -2,0923360 | 34,9516830 | 901,0 |
| **40** | Aichoun 2 | Borehole | 29,0 | -2,1614260 | 34,9211280 | 310,0 |
| **41** | Aichoun 1 (1279/7) | Borehole | 29,0 | -2,1463490 | 34,9266580 | 273,0 |
| **N°** | Nom | Nature | T (°C) | X | Y | Z |

Considering the thermal water points distribution, hydrogeological basin continuity, geothermal gradient evaluation, and the occurrence of recent volcanism and major faults, 10 geothermal areas were selected: 7 are located in the Atlas domain and 3 are in the Pre-Rif domain. Those 10 areas were selected for direct use and power generation by means of an analytical method based on different weighted parameters: resource level, socio-economic, institutional and environmental conditions (Fig. 5 and 6).

The five highest-ranking zones, regarded as the most promising are Berkane/Fezouane, Gourougou/Driouch, Arekman/Ras El Ma, Oujda/ Angads, and Ain Goutitir/Taourirt zones. The Pre-Rif to Meso-Rif zone, which takes seventh place owing to less favorable socio-economic conditions, was however included in later stages of the analysis as the presence of free-phase gas could be linked to an interesting geothermal potential (Figs. 6, 7).

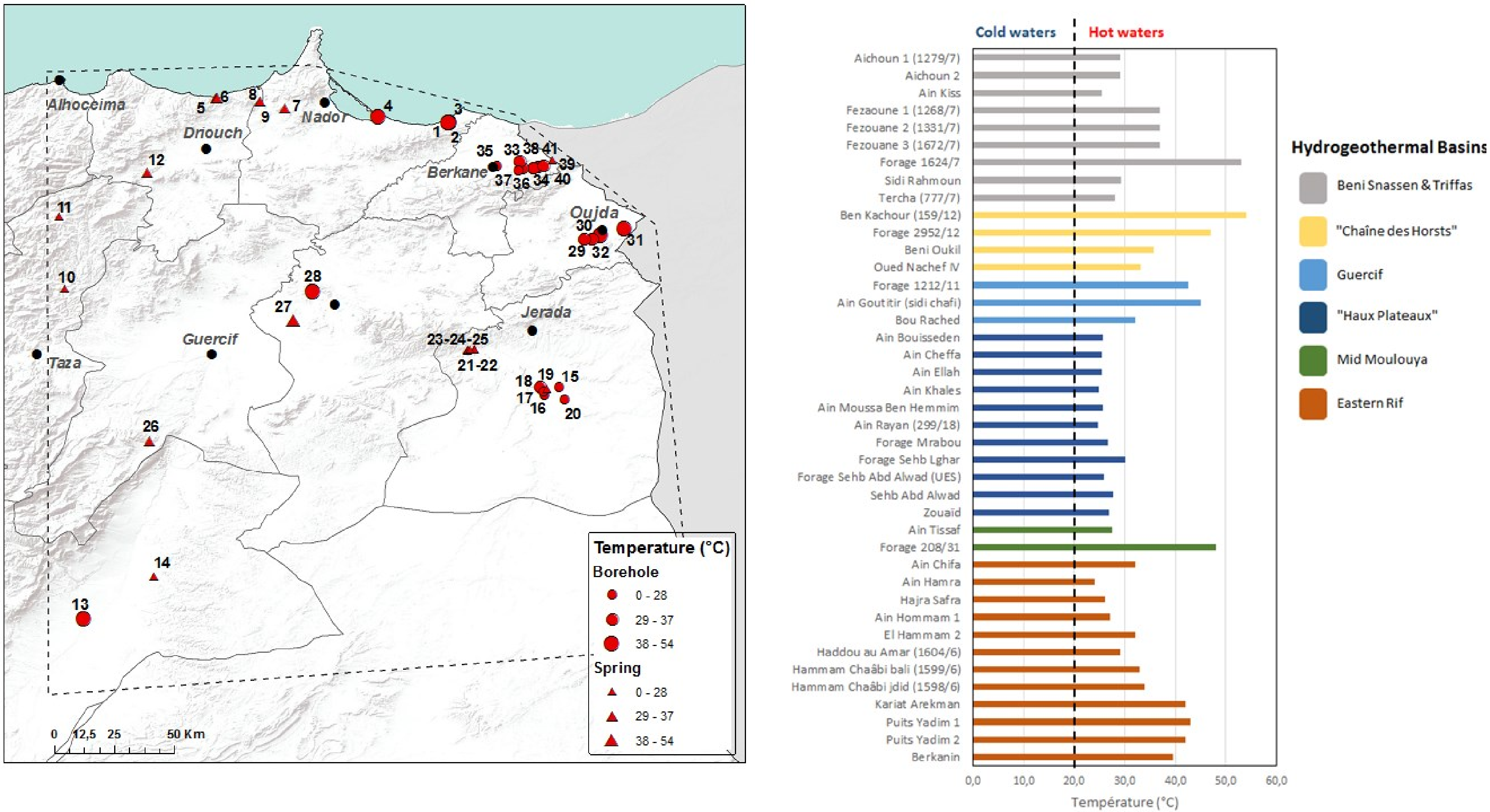



**Figure 4 : Location of thermal water points sorted by type (borehole/spring), and water point temperature levels versus hydrothermal basins.**

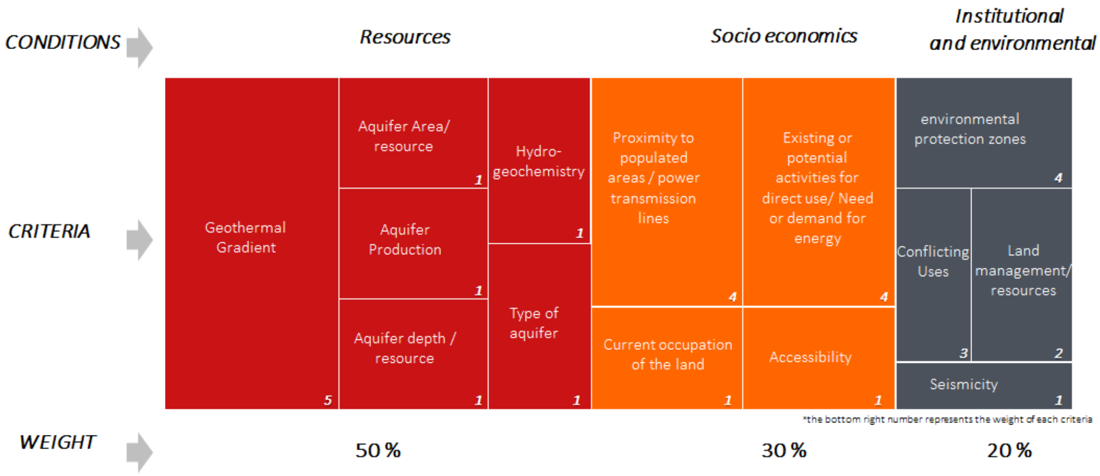



**Figure 5: Ranking criteria applied on the selected geothermal areas.**

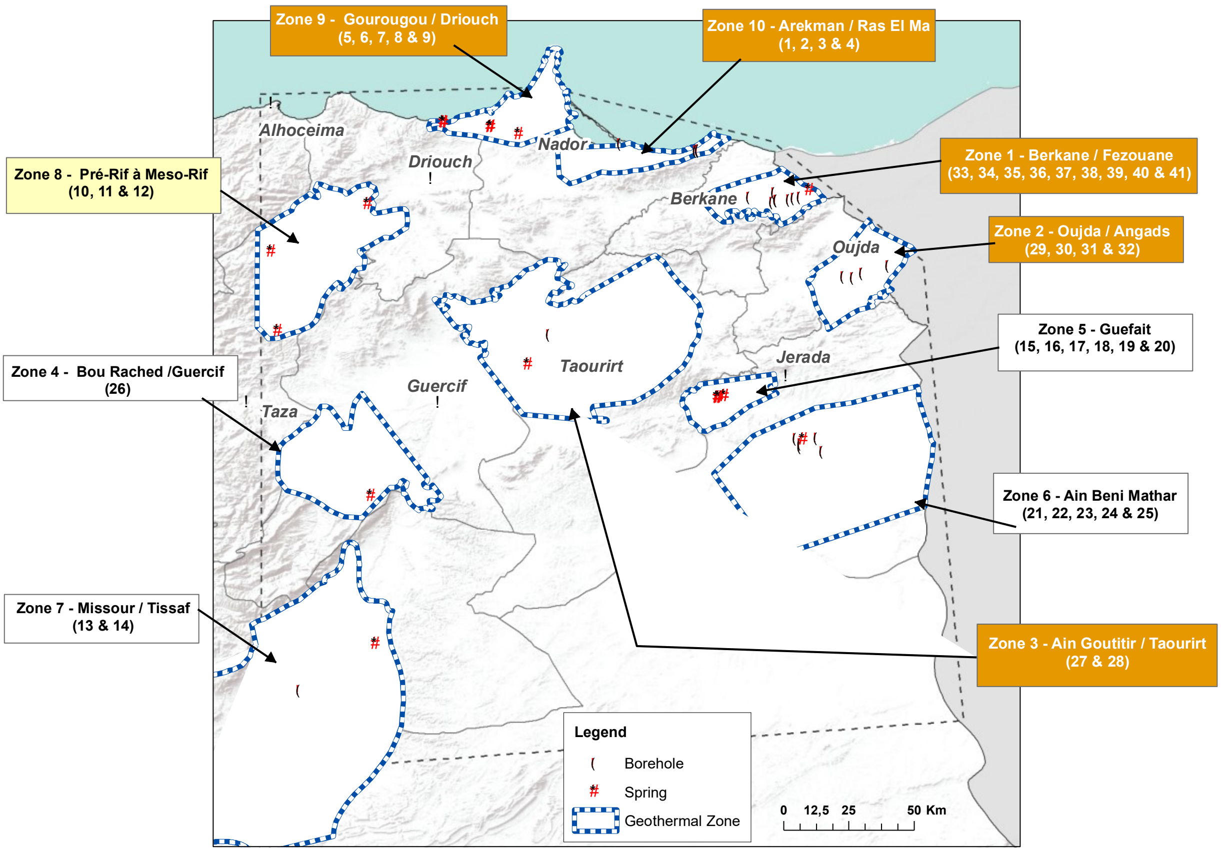
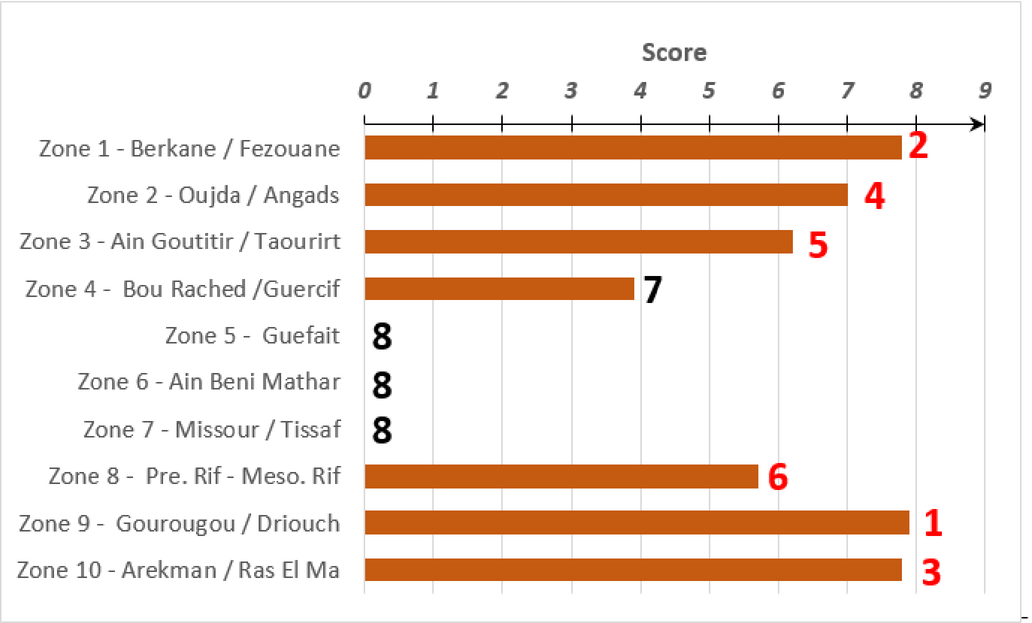



**Figure 6: Selected geothermal areas in northeastern Morocco**

☞ **For Electric generation :**




☞ **For Direct uses :**

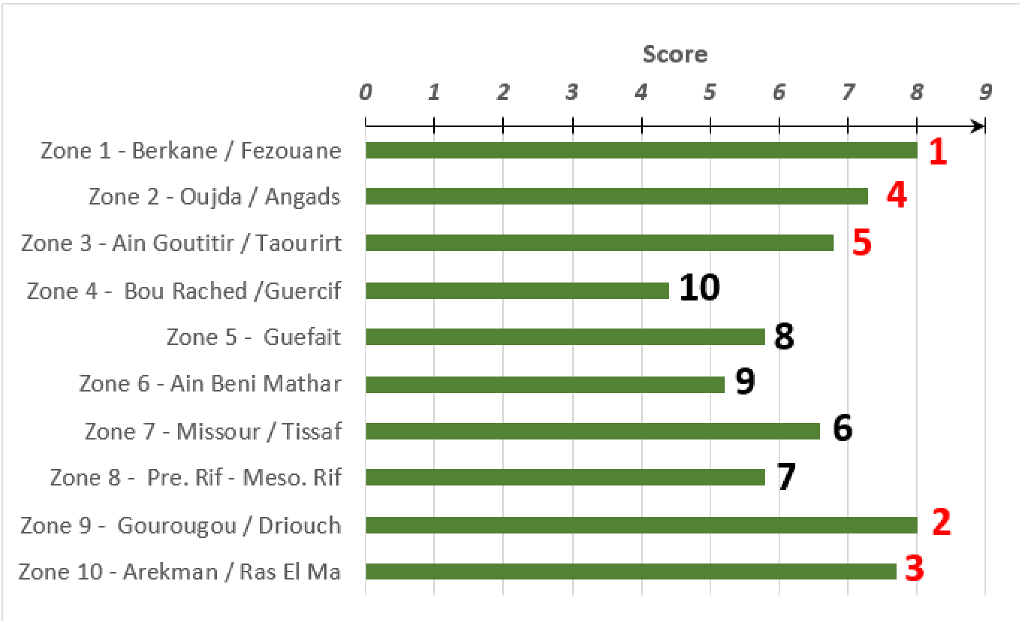



**Figure 7: Final score and ranking of geothermal areas. The numbers after the score bar show the ranking. The most promising targets [red rank] are compared to less promising targets [black rank].**

## 5. GEOCHEMISTRY

The six selected target zones were the subject of the following fieldwork:

- measuring physico-chemical parameters (pH, Eh, TDS temperature), and temperature logging in seven boreholes;
- chemical and isotopic analysis of 128 groundwater and gas samples collected at 27 sites (Fig. 8);
- and 23 rock samples for laboratory measurements of thermal conductivity and concentration of natural radioactive elements (uranium, thorium and potassium).

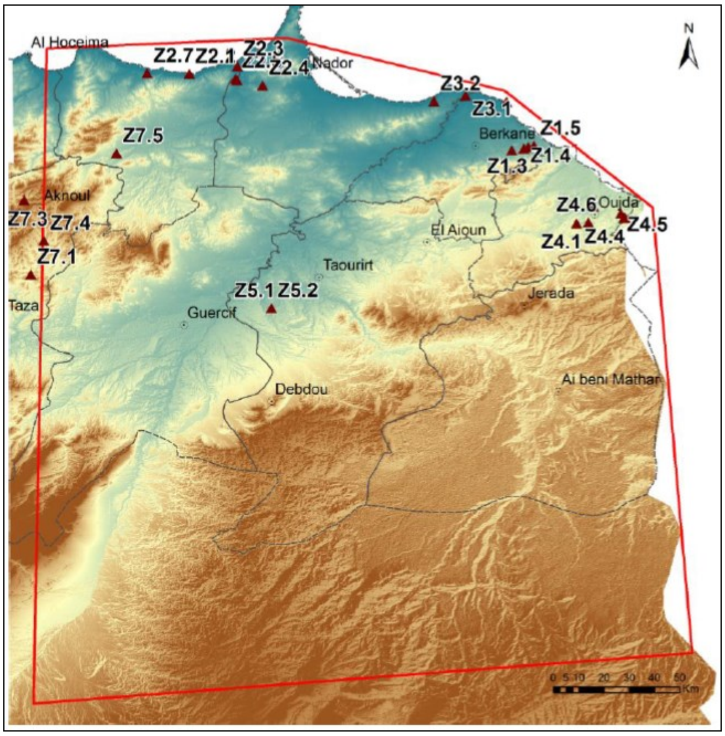



**Figure 8: Location of collected water samples in the study area.**

All sampled geothermal groundwater is of a calcium bicarbonate or sodium chloride type (Fig. 9). Groundwater from Gourougou/Driouch, Arekman/Ras El Ma and Ain Goutitir/Taourirt zones shows high mineralization traces by mixing with seawater or contact with evaporitic formations. The water from Berkane/Fezouane and Oujda/Angad zones appears less mineralized.

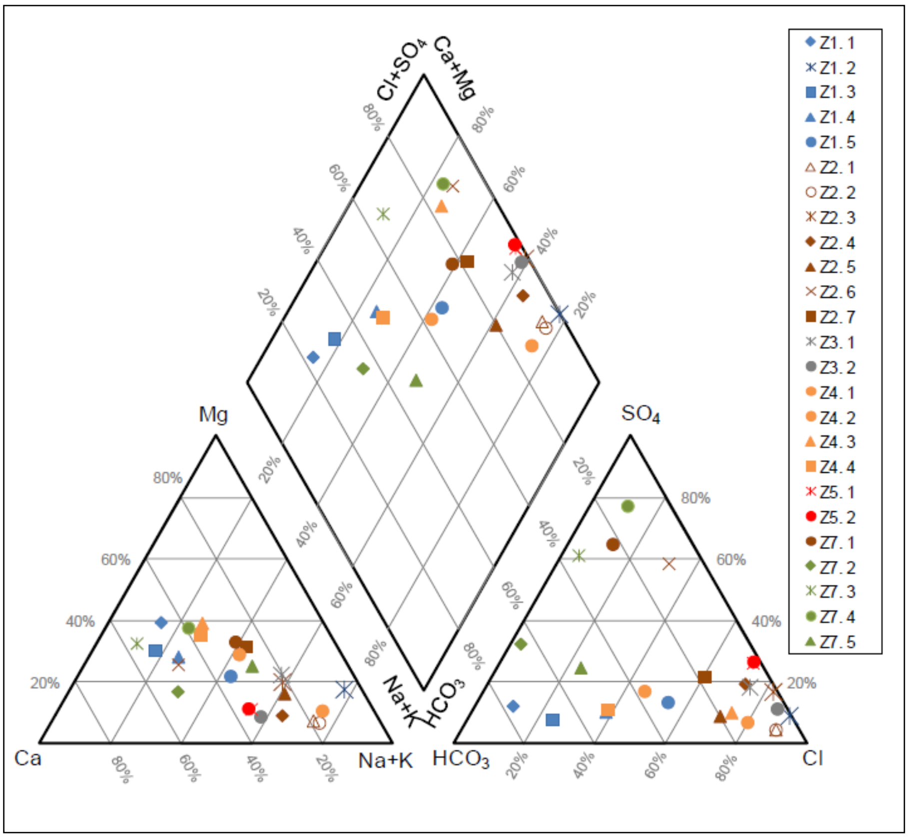



**Figure 9: Major elements Piper diagram of NE Morocco waters.**

Samples collected in Gourougou/Driouch and Pre-Rif to Meso-Rif zones contain a free-gas phase, indicating partial magmatic or crustal contribution and major deep geothermal component (Fig. 10 A). The $^3He/^4He$ ratio shows that the gas phase of Gourougou/Driouch zone has a magmatic component, whereas Pre-Rif to Meso-Rif zone has a crustal component (Fig. 10 B).

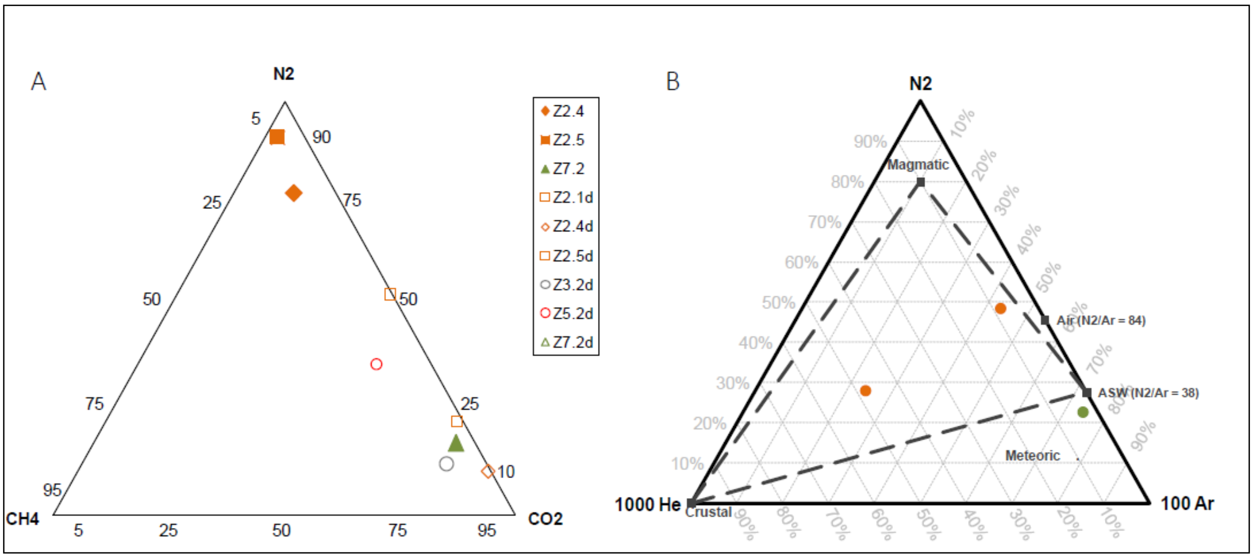



**Figure 10: (A) Triangular diagram for the CO2-CH4-N2 projection of free and dissolved gases (d) sampled. (B) Projection of free gas on a triangular diagram of Ar-N2-He (orange color zone 2, green color zone 7).**

Thermal groundwater of northeastern Morocco has very low Rn content that does not exceed 565.2 Bq/L, with the highest values in Gourougou/Driouch zone, suggesting that the gases can easily reach the surface through high permeability fracture.
The relation $\delta^{18}O$ <u>vs</u> $\delta^{2}H$ shows that hot water aquifers in the region are recharged at high topographic levels, mainly from meteoric water (Fig. 11). The recharging altitudes are less than 250 m for Gourougou/Driouch and Arekman/Ras El Ma zones, 700 to 750 m for Ain Goutitir/Taourirt zone and more than 1000 m for Pre-Rif to Meso-Rif zone.

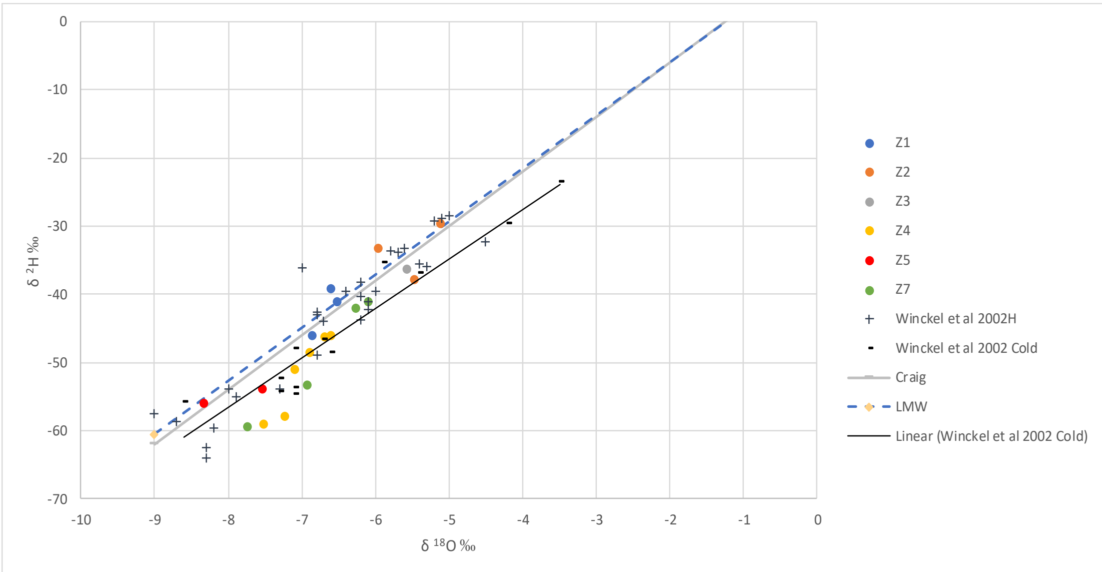



**Figure 11: Isotopic ratios of sampled waters, δ2H vs δ18O (Craig, 1961), and local meteoric water line (LMW) according to Cidu and Bahaj (2000). Isotopic composition projection of some mineral waters (+) and cold waters (-) according to Winckel (2002) and Winckel et al. (2002).**

## 6. HEAT FLOW DENSITY MEASUREMENTS

In addition to previous mining and groundwater wells logs, seven new temperature logs were carried out. The bottom hole temperatures from oil exploration boreholes were processed and interpreted, after thermal conductivity and heat production on rock samples were measured. That made it possible to estimate the values of the geothermal gradient and the heat flow density in each geothermal zone.

All target areas show positive anomalies, with the geothermal gradient average ranging from 45 to 50 °C $km^{-1}$ in Ain Goutitir/Taourirt, Oujda/Angads and Berkane/ Fezouane zones, with higher values around 80 °C $km^{-1}$ observed in the northern zones of Arekman/Ras El Ma and Gourougou/ Driouch.

The surface heat flow density values range between 80 and 90 mW $m^{-2}$ in the South (for instance in Ain Goutitir/Taourirt zone), to around 120 mW $m^{-2}$ in Gourougou/Driouch zone (Fig. 12). These values are clearly higher than the global average of 60 mW $m^{-2}$.

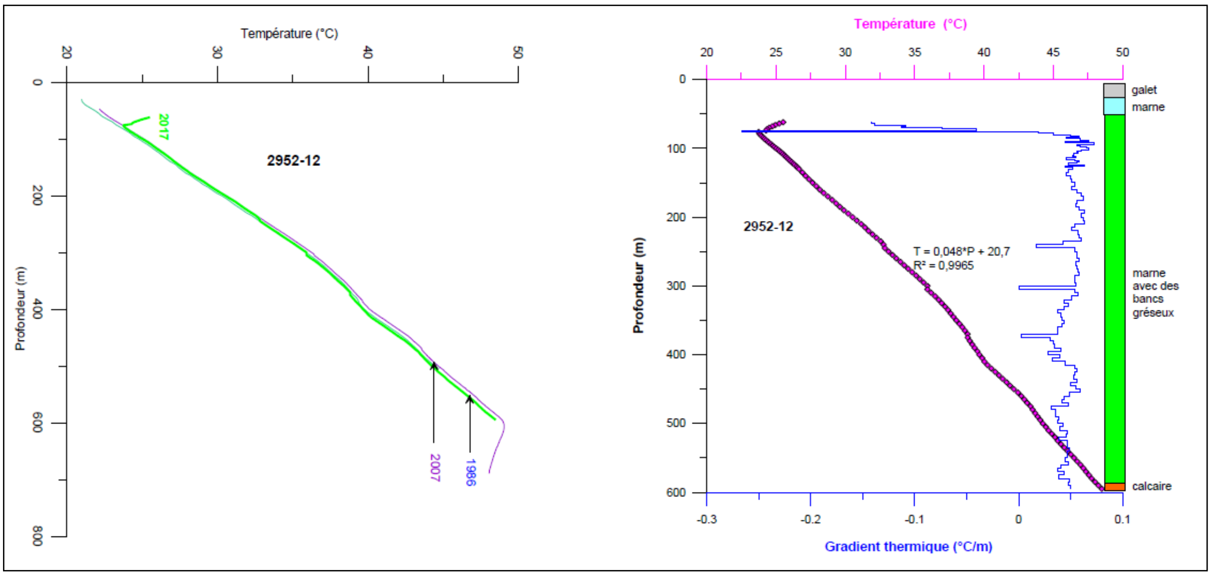



**Figure 12: Example of temperature profile and geothermal gradient determination in borehole 2952/12 (Oujda/Angads area).**

### 7. GEOTHERMOMETRY

Geothermal exploration is based on the knowledge of the actual temperature versus depth, as surface temperatures rarely reflect those of deep groundwater and the condition in the reservoir. For this purpose, two types of geochemical methods are routinely applied using temperature-indicating elements, such as qualitative and quantitative geothermometers.

The estimation of temperature using silica geothermometers gave the most reliable result especially for quartz, which appears to be the most suitable geothermometer for such geothermal systems in sedimentary basins (Table 2).

**Table 2: Temperature and reservoir depth estimates.**

| Zone | Reservoir temperature by Geothermometer | | | Reservoir | | | geothermal gradient (°C/km) (in brackets) |
|---|---|---|---|---|---|---|---|
| | Silica | Cation | multi-mineral | Formation/ Age | Depth min (m) | Depth max (m) | |
| **Berkane/ Fezouane** | <75°C | <70°C | 60°C to 75°C | Forage 1624/7, Limestone and dolomite /Lias | 896 | 1228 | 1631-7 (45.2) |
| **Gourougou/ Driouch** | <180-185°C | <200°C | <175°C | Jurassic of the Temsamane massif | 653 | 1829 | (85) according to the gradient map of the figure 14 |
| **Arekman/ Ras El Ma** | <100°C | <100°C | 75°C to 100°C | Arekman/Lias | 694 1463 | 1006 - 2073 | Nador1 (41) Arekman (80) |
| **Oujda/ Angads** | 90°C | -- | 75°C to 125°C | Limestone and dolomite /Lias | 1156 | 1960 - 2664 | 2952-12 (48)/ |
| **Ain Goutitir/ Taourirt** | <106°C | <100°C | 80°C to 110°C | Limestone and dolomite /Lias | 1729 | 2586 | MSD1, GRF1, KDH1 (35) |
| **Pré-Rif to Méso-Rif** | 100-125°C | <120°C | >100 to150°C | Limestone and dolomite /Lias | 1635 | 2446 | AKL101, ATM1 (37) |

The highest reservoir temperatures were estimated in northern zones, with maximum temperatures ranging from 180-185 °C in Gourougou/Driouch and up to 125 °C in the Pre-Rif to Meso-Rif. The Atlas domain zones show reservoir temperature less than 100 °C, although they can be slightly higher in Ain Goutirir/Taourirt. It should be noted, however, that in Berkane/Fezouane the collected samples are not representative of the deepest parts of the aquifer, where temperatures could reach about 120-125 °C. In Arekman/Ras El Ma, although geothermometers indicate maximum temperatures of 100 °C, the samples were collected only in the eastern segment of the zone. The western segment (around the Kariat Arekman village) is expected to have reservoir temperatures similar to those of the Gourougou/Driouch reservoir, with which it is limited to the West.

Data analysis for reservoir temperature and heat flow density made it possible to estimate the depth to the reservoirs. The shallowest reservoirs appear to be those located furthest North of the study area, with depths estimated from 650 m to a maximum of about 1850 m for reservoirs in Gourougou/Driouch, Arekman/Ras El Ma and Berkane/Fezouane. It should be noted that in the first two cases, water flow occurs mainly along fractures, which increases the uncertainty of the estimates.

In the remaining zones, the estimated depths of the reservoirs are always higher than 1000 m, with maximum values around 2500 m.
The combination of these data allows highlighting the various possibilities of use of the geothermal resource (generation of electricity by binary cycle systems, which requires a reservoir temperature greater than 90 °C, or direct use, for lower temperatures).

## 8. CONCEPTUAL MODELS

The study shows that in northeastern Morocco, two types of geothermal systems are distinguishable, and thus two distinct conceptual models have to be considered: a model for Atlas domain (Fig. 13) and another for Pre-Rif domain (Fig. 14). Atlas domain, which covers Berkane/Fezouane, Oujda/Angad Ain Goutirir/Taourirt zones, is characterized by conventional sedimentary geothermal systems, where heat is mainly transferred by convection in porous aquifers. Sometimes, advection along faults allows resurgence of thermal water at the surface (springs). The temperature is mainly a function of the structure of the reservoir formations: the geothermal potential increases to the northern part of these zones due to the sedimentary sequence dipping in the same direction.

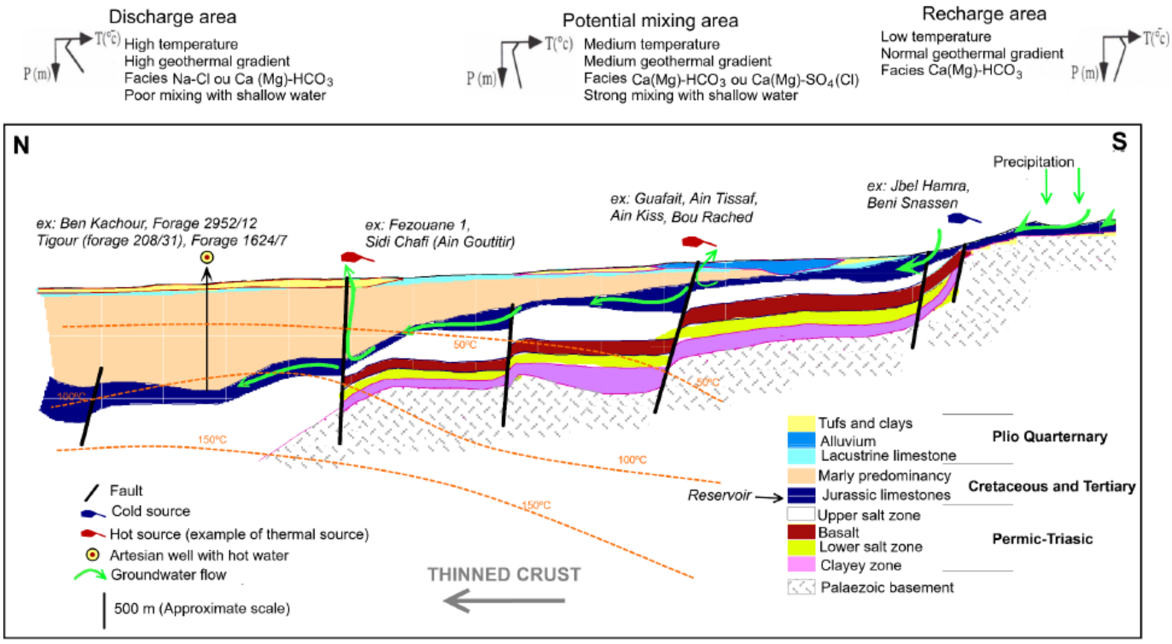



**Figure 13: Conceptual model of the Atlas Domain of northeastern Morocco: Relation between hydrodynamics, temperature, chemistry, and topography (schematic cross-section).**

In the conceptual model of Pre-Rif domain, which includes the Gourougou/Driouch, Arekman/Ras El Ma and Pre-rif to Meso-Rif areas, the geothermal system is characterized by the presence of volcanic rock reservoirs and by flow along faults and fractures, as demonstrated by the presence of free-phase gas and Radon concentration. The abundance of springs, particularly in the Gourougou/Driouch zone, whose isotopic analysis denotes magmatic sources of gases and the discontinuous nature of the rock formations of the region, indicates the predominance of convection as a heat transfer mechanism.

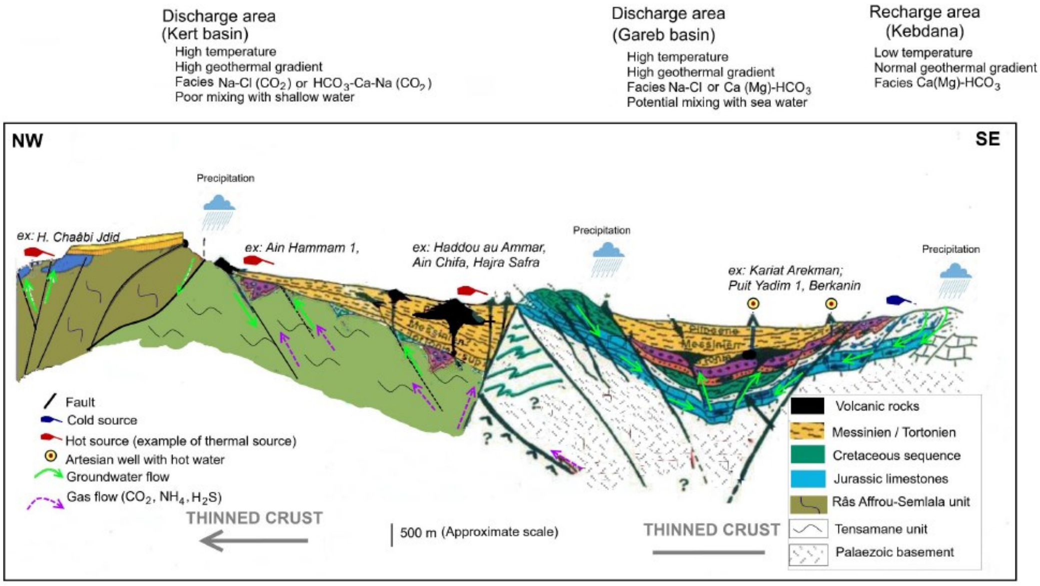



**Figure 14: Conceptual model of the Pre-Rif Domain of northeastern Morocco: Relation between hydrodynamics, temperature, chemistry, and topography (schematic cross-section).**

## 9. MODELING OF RESOURCES AND RESERVES

The conceptual models defined for each zone served as a basis to quantify heat-in-place and recoverable heat. This quantification was performed using a volumetric method, implemented as stochastic modeling with the @RISK7.6 software, which provided estimates of proven, probable, and possible reserves for each of the five selected areas, for both direct use and power generation scenarios (Table 3).

**Table 3: Probable reserves, equivalent to the P50 cumulative probability.**

| Zone | Power production | | Direct Use | |
|---|---|---|---|---|
| | Heat in Place ($Twh_{th}$) | Power (MW) | Heat in Place ($Twh_{th}$) | Recoverable heat ($Twh_{th}$) |
| Berkane/Fezouane | 131.5 | 3.9 | 371.0 | 46.7 |
| Gourougou/Driouch | 2575.0 | 38.9 | 3878.0 | 195.0 |
| Arekman/Ras El Ma | 636.6 | 8.2 | 1159.0 | 58.1 |
| Oujda/Angads | 152.5 | 4.3 | 655.3 | 83.1 |
| Ain Goutitir Taourirt | - | - | 1436.5 | 182.8 |

Gourougou/Driouch zone contains probable reserves for electricity production capacity of about 40 MWe. Arekman/Ras El Ma area also seems promising for power production up to 8 MWe. However, the lack of deep drilling in both areas, particularly Gourougou/Driouch, recommends further geophysical surveys and drilling to confirm the estimated potential (Fig. 15).

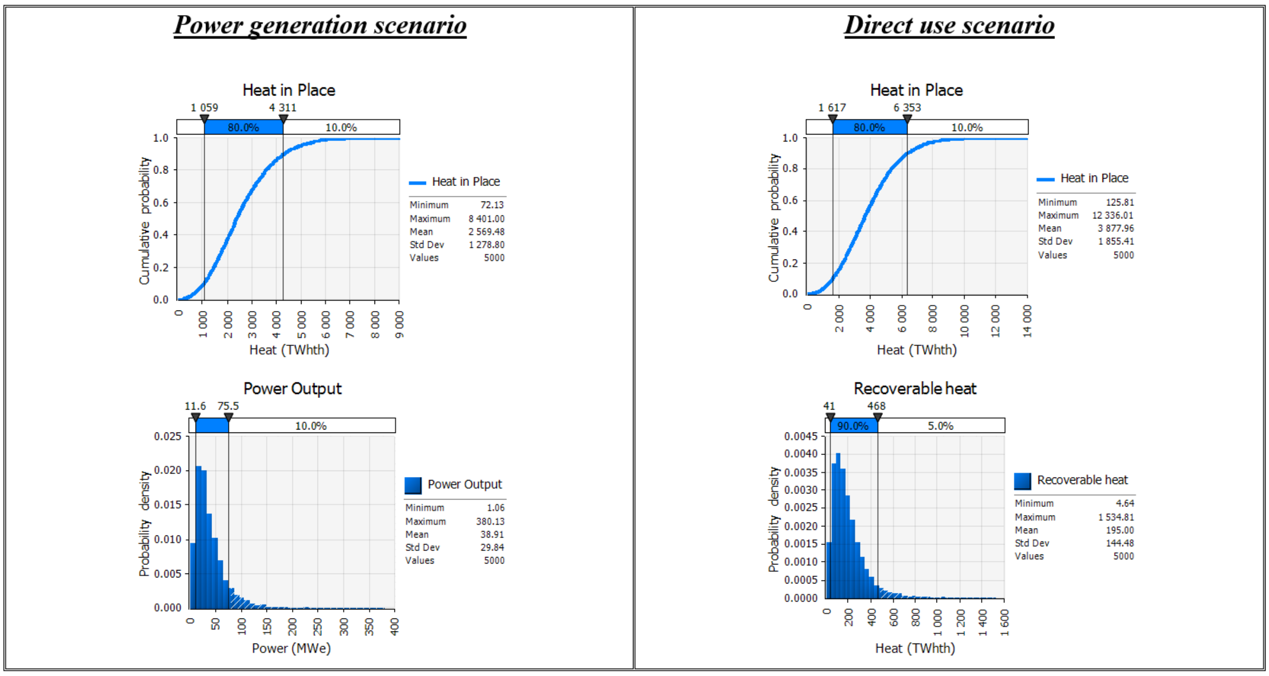



**Figure 15: Cumulative probability of heat in place and power distribution for power generation and direct use scenarios in Gourougou/Driouch area.**

## 10. CONCLUSIONS AND RECOMMENDATIONS:

Given the energy supply and climate change mitigation challenges that Morocco will face in the coming decades, it is advisable to bring geothermal energy into the mix of renewable energies that will shape the future of the country. This study has shown that northeastern Morocco has significant geothermal reserves for direct use and possibly, along the coastal region, for power generation in binary cycle power plants.

Oujda/Angads and Berkane/Fezouane areas present similar values, but about half of the energy available and the power estimated is in Arekman/Ras El Ma. Compared to the previous zones, this part of northeastern Morocco is the most favorable for direct use, and recoverable heat reserves range from 47 $TW/h_{th}$ in Berkane/ Fezouane, up to 83 $TW/h_{th}$ in Oujda/Angads.

Considering socio-economic activities in northeastern Morocco, the agricultural sector appears to be the most interesting for direct use of the geothermal water. A case study of vegetable oil refining was simulated by Pinch Analysis to illustrate the potential for energy savings. The analysis shows that integration of geothermal heat reduces the energy consumption of the hot process to 563 kW. Although this is just one example, it illustrates that energy savings are achievable both for the agricultural and the industrial sectors.

The analysis of all gathered information is summed up in a series of proposals and recommendations incorporated in a roadmap for the exploitation of geothermal resources in northeastern Morocco, including, in addition to other activities, action plans for each of the priority zones of intervention. This Roadmap presents a set of measures to be implemented until the end of 2025 that include:

- Integration of geothermal energy into the regional development strategies for tourism, agriculture, industry and energy sectors;
- Integration of geothermal energy into the national climate change mitigation strategy, namely in the Nationally Determined Intended Contributions (INDC); the stated objectives include raising US $ 45 billion in international funds that could be used to finance geothermal projects;
- Implementation of the existing mining law, which regulates geothermal activities, to allow local, national or international investors to have an interest in exploitation and use of geothermal resources of Morocco;
- Setting up mechanisms to support investment in the sector to cope with risks during the resource exploration phases;
- ONHYM has to play a main role in the dissemination and public promotion of the technology, including conducting workshops with local communities and demonstrating the technology in a small-scale pilot project.

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