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3D Geologic Model and Energy Potential Estimation of UAE Geothermal Systems Mubazzarah-Ain Faidha and Ain-Khatt

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ABSTRACT

In the United Arab Emirates (UAE) there exist several groups of hot springs classified as low-enthalpy. In this study, multiple geophysical and numerical investigations have been applied to better understand the geologic controls, depth and reservoir temperature, energy potential and future possible applications of the geothermal systems identified by these hot springs.

The low-enthalpy geothermal systems were examined using densely spaced gravity and magnetic surveys to study the subsurface structure and geology. We have estimated the correlation between the density and the magnetic inversion results at the studied geothermal fields using a neural network trained estimation algorithm. Results from neural network classification helped to draft an initial geological structure showing that these geothermal manifestations are structurally controlled.

The thermal waters of the hot springs were sampled and tested for geochemical signatures indicating fluid origin and reservoir temperature. The thermal fluids are rich in Na and Cl with temperatures at surface discharge ranging from 32 ^{o}C to 49 ^{o}C. The geochemical and isotopic signature of the water suggests a meteoric origin. The reservoir temperatures of the sampled waters were estimated using cation geothermometers and showed values ranging from 56 ^{o}C to 87 ^{o}C.

A 3D geothermal numerical simulation was developed using the geophysical and hydrochemical understanding in an attempt to reproduce these geothermal manifestations.

The geothermal electricity potential was calculated for the main low-enthalpy geothermal fields in UAE using a stochastic Monte Carlo simulation and showed a value of 320.62 kWe for 25 years and 162.54 kWe for 50 years.

These geothermal manifestations can be utilized for direct utilization and hybrid systems.

1. INTRODUCTION

United Arab Emirates (UAE) is located on the southern side of the Arabian Gulf, at the northeastern edge of the Arabian Plate. Although large areas of the country are covered in Quaternary sediments (Figure 1), the bedrock geology is well exposed in the Hajar Mountains, the Musandam Peninsula of the eastern UAE, and along the southern side of the Arabian Gulf west of Abu Dhabi. Geology of the Emirates can be divided into nine main components:

- Late Cretaceous UAE-Oman ophiolite.
- A Middle Permian to Upper Cretaceous carbonate platform sequence, exposed in the northern UAE (the Hajar Supergroup).
- A deformed sequence of thin limestone and associated deep-water sediments, with volcanic rocks and mélanges,w that occur in the Dibba and Hatta Zones.
- A ploydeformed sequence of metamorphic rocks, seen in the Masafi – Ismah and Bani Hamid areas.
- A younger, Late Cretaceous to Palaeogene cover sequence exposed in a foreland basin along the western edge of the Hajar Mountains.
- An extensive suite of Quaternary fluvial gravels and coalesced alluvial fans extending out from the Hajar Mountains.
- A sequence of Late Miocene sedimentary rocks exposed in the western Emirates.
- A number of salt domes forming islands in the Arabian Gulf characterized by complex dissolution breccias with a varied clast suite of mainly Neoproterozoic (Ediacaran) sedimentary and volcanic rocks.
- A suite of Holocene marine and near-shore carbonate and evaporate deposits along the southern side of the Arabian Gulf forming the classic Abu Dhabi sabkhas and Extensive Quaternary to recent aeolian sand dunes which underlie the bulk of Abu Dhabi Emirate.

The two main geothermal fields Ain Khatt in Ras Al Kheimah emirate (north of UAE) and Mubazzarah – Ain Faidha hot springs in Al-Ain (Abu Dhabi emirate, eastern UAE) are hosted by carbonate rocks and overlain by limestone and sedimentary Quaternary cover.

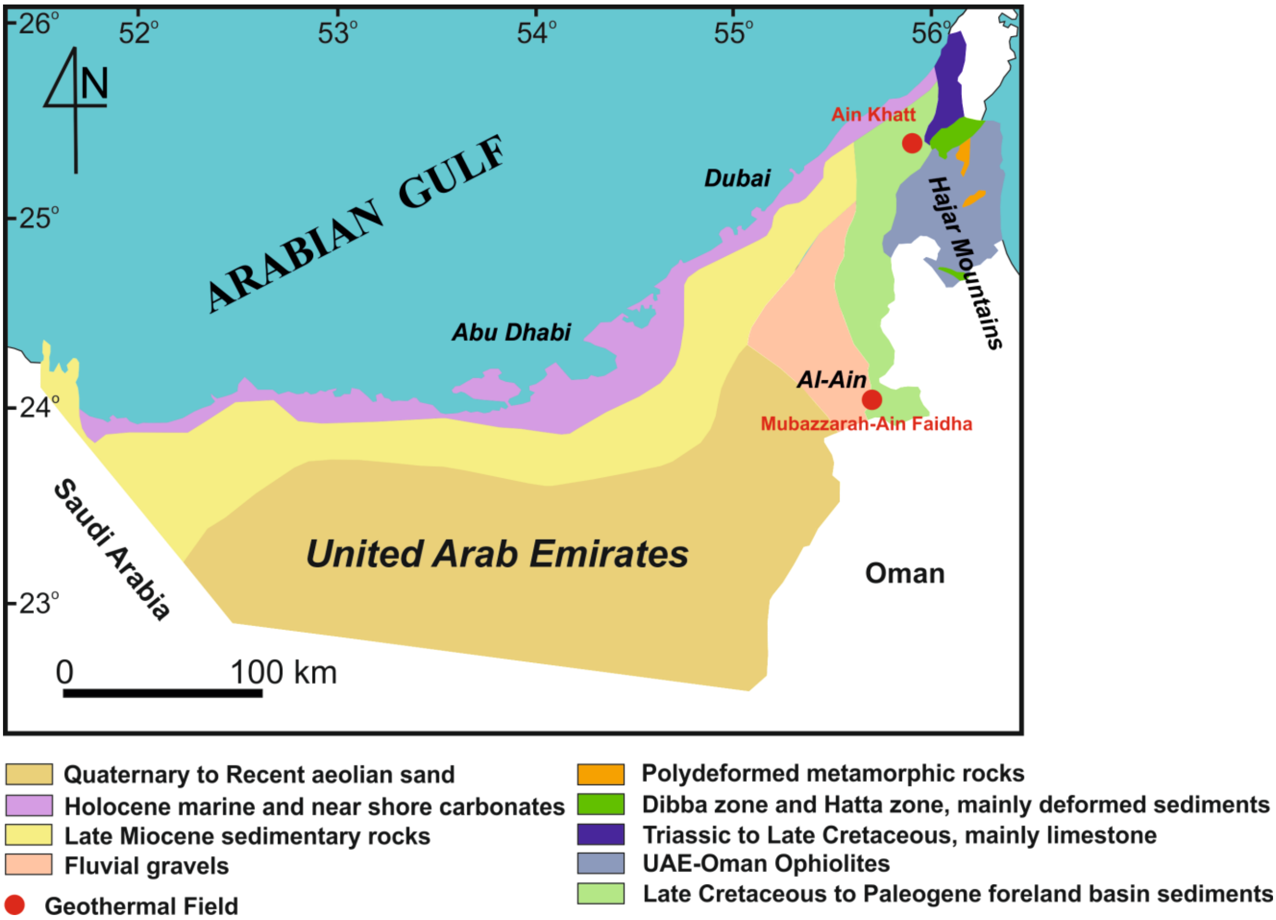

Figure 1: Geological map of UAE showing the location of the two main geothermal fields.

2. POTENTIAL FIELD DATA

2.1 Potential field data (inversion and neural network analyses) in Mubazzarah and Ain Faidha hot springs

The Al-Ain region was covered by magnetic and gravity surveys during 2017 and 2018. The coverage was dense around the geothermal manifestations in order to understand the subsurface structure regionally and locally. There were more than 600 magnetic stations in these surveys. The details on the magnetic data acquisition and processing analyses are presented in Saibi et al. (2019a). The details on the gravity data acquisition and 2D and 3D interpretation are published by Saibi et al. (2019b). Figure 2 shows the RTP map of the total magnetic field data from Al-Ain. The RTP magnetic data values range from 43189 nT to 43865 nT. The two main geothermal springs Mubazzarah and Ain Faidha are located at boundaries between high and low magnetic values on the RTP map. This location proves that the geothermal manifestations in Al-Ain are structurally controlled. A three-dimensional (3D) magnetic inversion was developed to understand the relationship between subsurface structures and geothermal manifestations (Figure 3). Here, the 3D magnetic inversion also shows that the hot springs are located on the surface at boundaries between high and low magnetic densities. The subsurface anomalies of magnetic densities are located from ground surface to around 400m (beneath ground level) (Figure 3). This observation is another proof that hot springs in Al-Ain are structurally controlled.

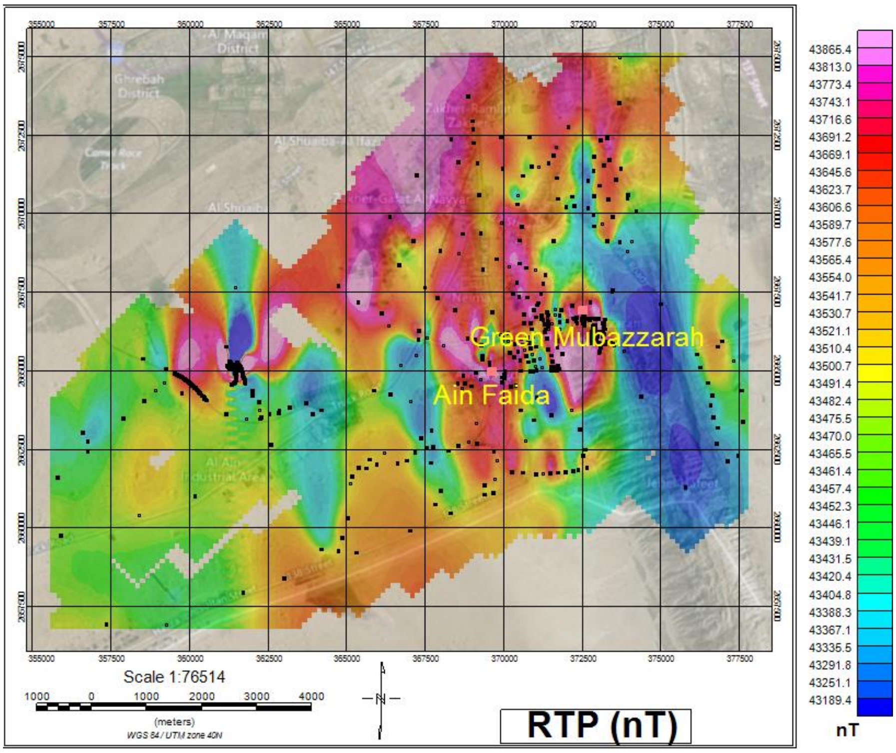

Figure 2: Reduced to the pole total magnetic field in Al-Ain. The hot springs in Al-Ain are located at boundary between high and low magnetic field values.

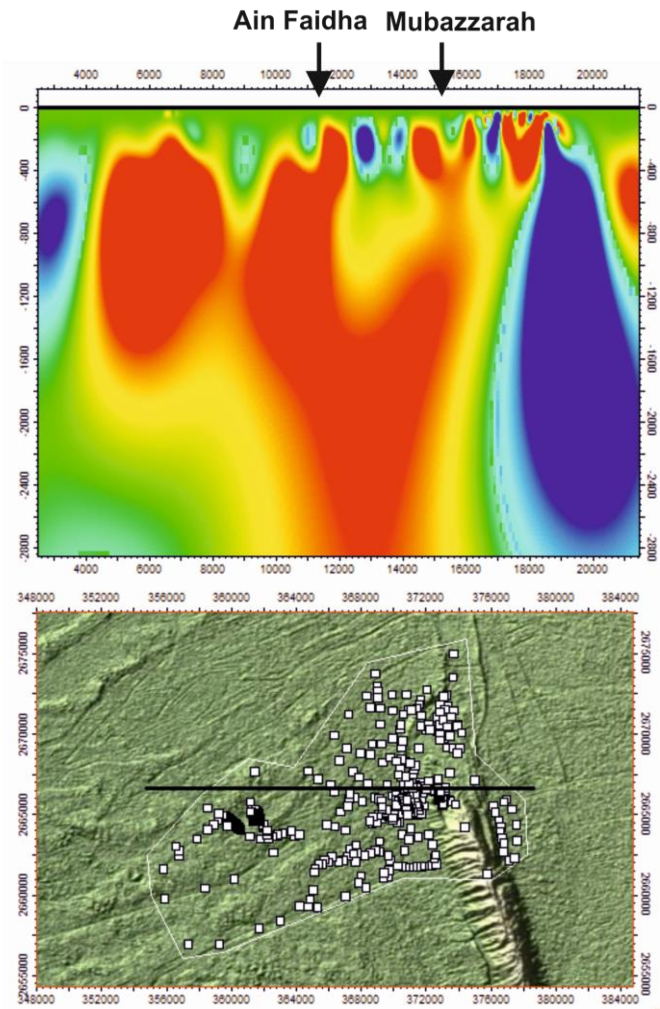

Figure 3: Cross-section of 3D inverted magnetic field from Al-Ain data and profile location map. The two hot springs in Al-Ain emerge at a boundary between areas of high and low magnetic density.

To retrieve an adequate structural model from both gravity and magnetic data inversion results, we used a neural network-based algorithm to help automatic delineation of the subsurface structure. Artificial neural-network (ANN) is a powerful tool for data classification that can be used for classifications of geological variables. The results of the ANN are presented in Figures 4 and 5. Figure 4 shows the Neural-network relative error function from 300 runs applied for gravity and magnetic data from Mubazzarah and Ain Faidha.

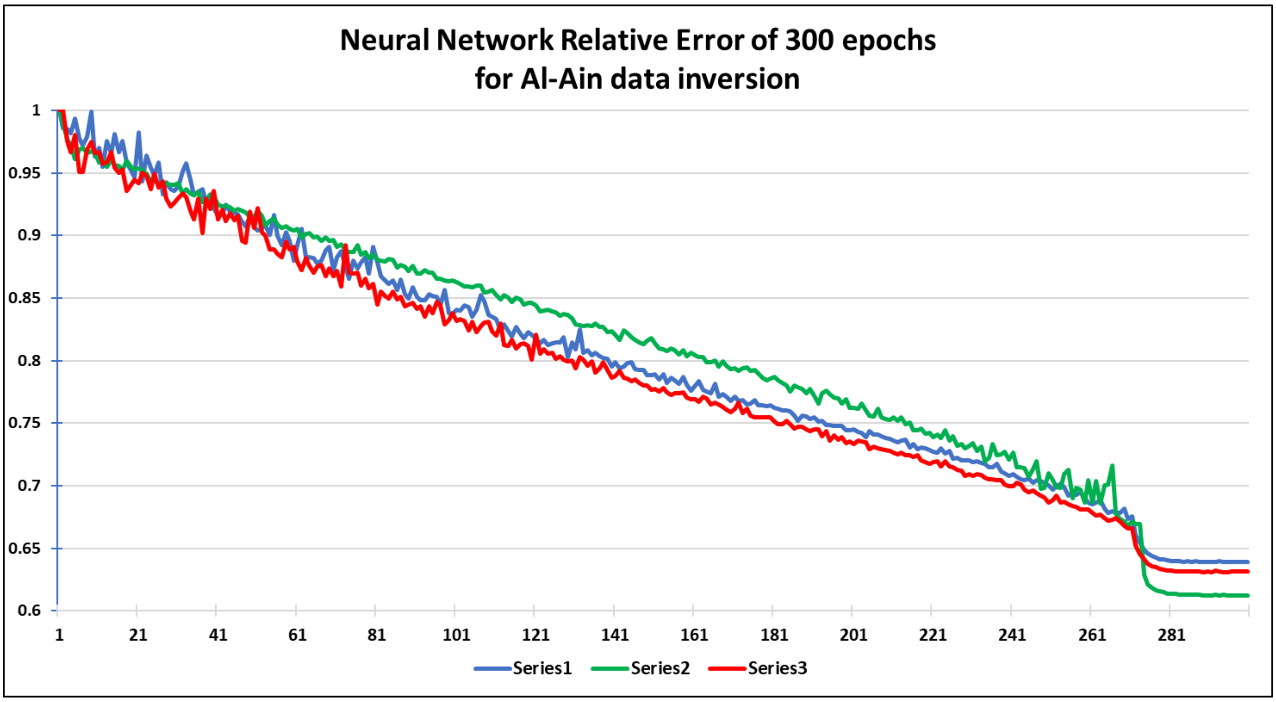

Figure 4: The applied Artificial Intelligence Neural Net to both gravity and magnetic data from Mubazzarah – Ain Faidha.

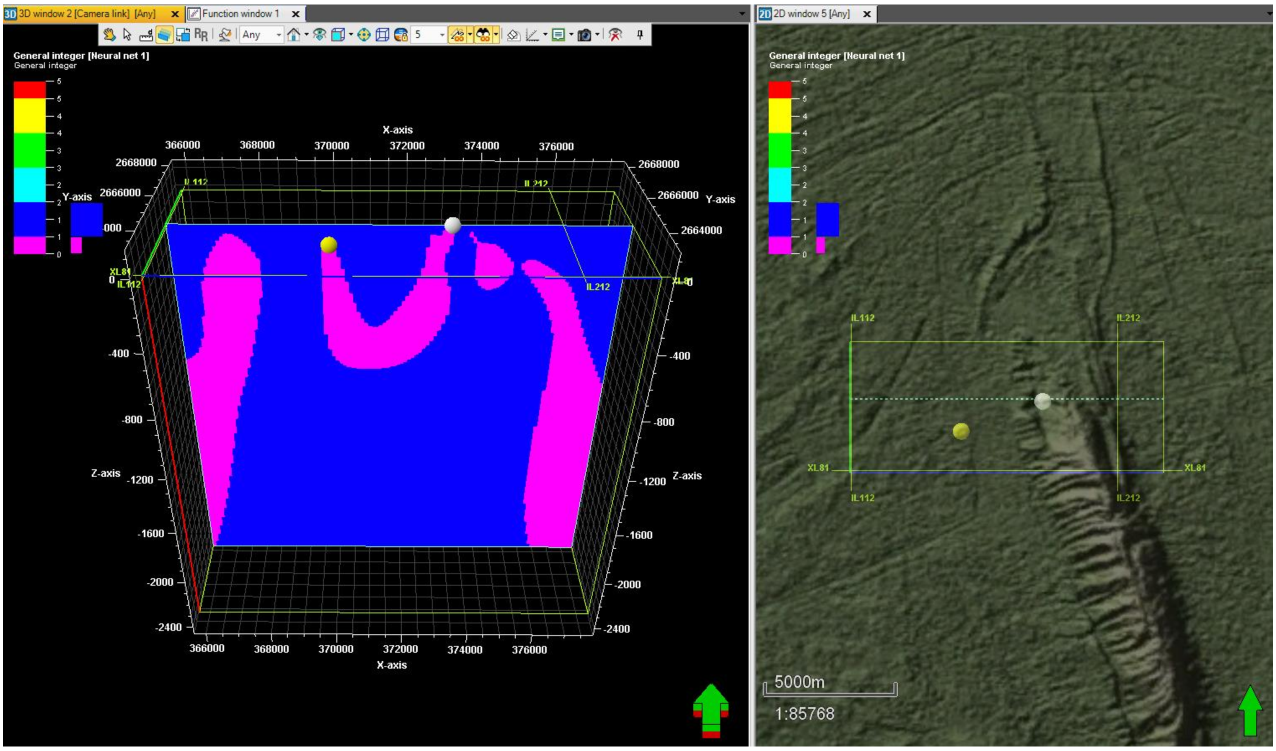

Figure 5: The applied Artificial Intelligence Neural Net to both gravity and magnetic data from Al-Ain automatically highlighted the "U" shape structure connecting the main two hot springs Mubazzarah and Ain Faidha.

2.2 Potential field data (inversion and neural network analyses) in Ain Khatt hot spring

Ain Khatt hot spring was surveyed with magnetics and gravity. A total number of 109 stations are shown in Figure 6) below. These surveys were run in order to understand the geological conditions beneath Ain Khatt hot spring. Figure 6 shows the RTP map of the total magnetic field data around Ain Khatt hot spring. The RTP magnetic data ranges from 43993 nT to 44522 nT. Ain Khatt thermal spring is located at boundary between low and high RTP magnetic values. This observation suggests that Ain Khatt hot spring is also controlled by subsurface geological structures like Mubazzarah and Ain Faidha springs. The 3D magnetic inversion at Ain Khatt hot spring shows that the two main hot springs in Ain Khatt KT1 and KT2 emerge at boundaries between high and low magnetic densities, which have depth ranging from ground level to around 300m depth (Figure 7).

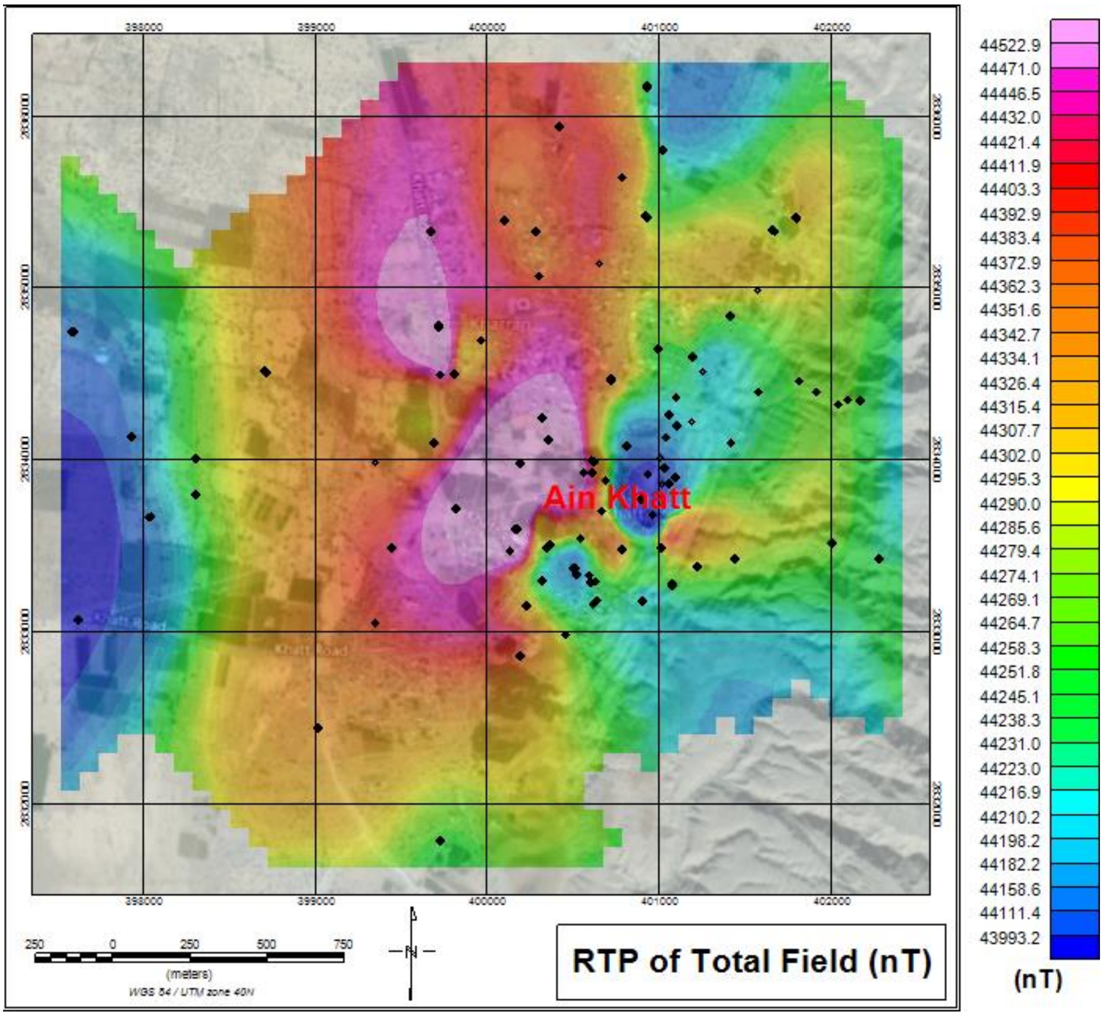

Figure 6: Reduced to the pole total magnetic field in Ain Khatt. Ain Khatt. The hot spring is located at a boundary between high and low magnetic field values.

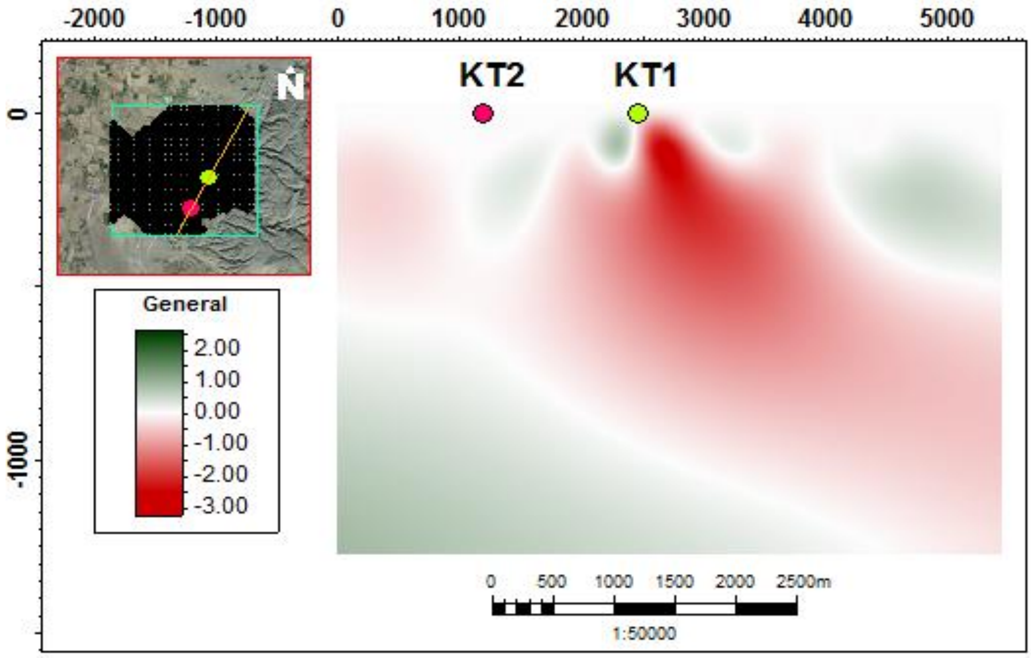

Figure 7: Cross-section of 3D inverted magnetic field from Ain Khatt data. KT1 and KT2, the two hot springs from Ain Khatt geothermal field.

We trained the neural network algorithm for 300 iterations to generate a synthetic model clustered into 4 unsupervised classes and repeated the process three times to avoid deficiency of physical interpretation.

Plotting of the error function against iterations in Figure 8a shows that the algorithm reaches its least misfit at around 280 epochs, where it stabilizes at its best value. Average models from 3 classifications are combined in the cross section illustrated in Figure 8b.

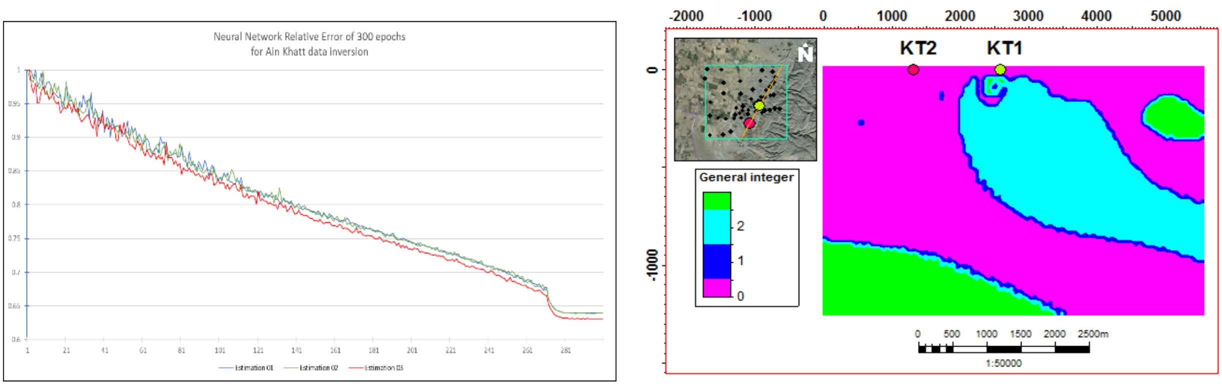

Figure 8: The applied Artificial Intelligence Neural Net to both gravity and magnetic data from Ain Khatt.

(a) Neural-network relative error functions from 300 runs.

(b) Neural-network classification using density and magnetic inversion results.

3. HYDROCHEMISTRY

Nineteen water samples were taken from the hot springs (Mubazzarah, Ain Faidha and Ain Khatt) and also of sea water during 2017 (Saibi et al., 2019c). The majority of water samples belong to the Na-Cl water group as plotted in the Piper diagram (Figure 9). The temperature of the samples varied from 32.5 °C to 49 °C. The results using cation geothermometers give reservoir temperatures between 56 °C and 87 °C (Saibi et al., 2019c). The location of the samples in the immature waters zone in the Na-K-Mg trinary diagram of Giggenbach (1988) (Figure 10) is explained by the mixing of hot waters with shallow groundwaters.

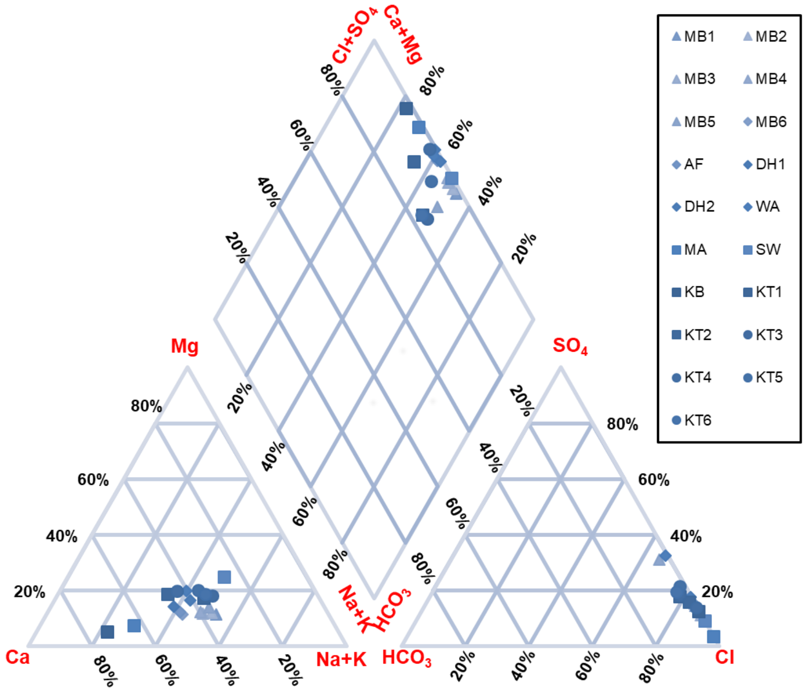

Figure 9: Piper diagram of hot and cold waters sampled from different places in UAE.

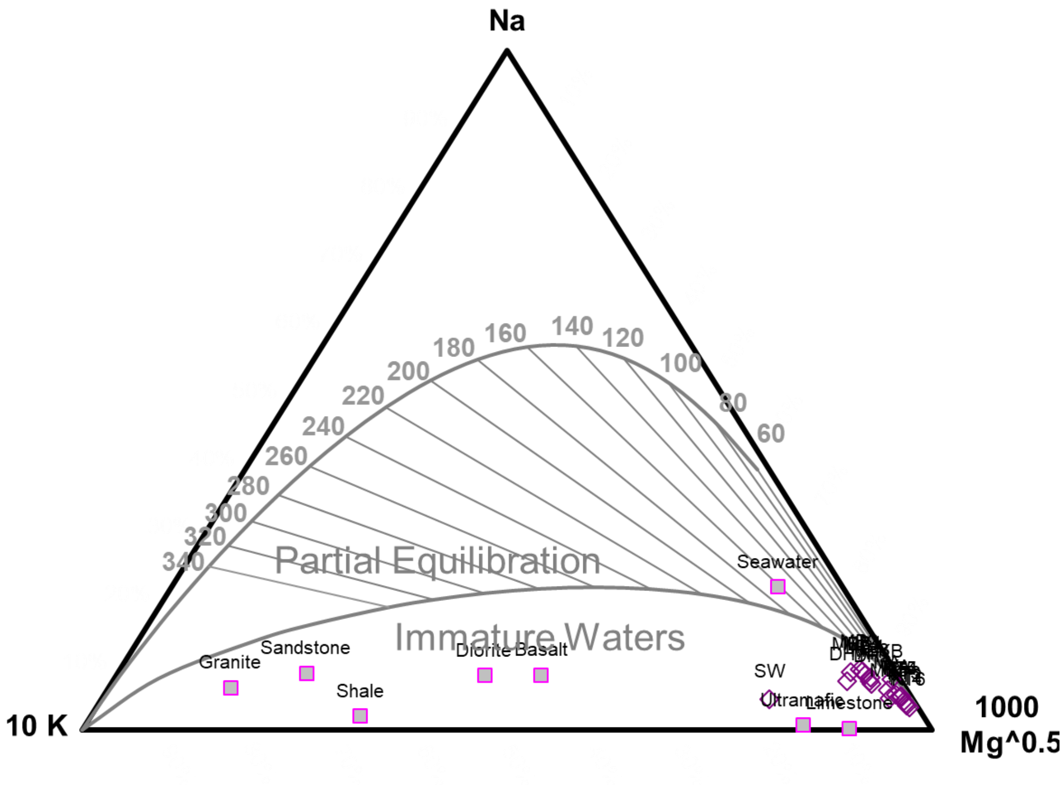

Figure 10: The Na-K-Mg ternary diagram of hot and cold waters sampled from different places in UAE.

3. GEOTHERMAL NUMERICAL MODELS

A 3D numerical geothermal model was developed using Petrasim software (Figure 11). This study focused on the Mubazzarah – Ain Faidha geothermal system. A conceptual model was created based on previous geological, geophysical and geochemical data from this study area. The geothermal reservoir is located at around 1 km depth and the upflow of hot waters is developed through deep fractured structures existing in this area. This type of geothermal system is mainly developed by conduction. The source zone of this geothermal system is from the east (Oman side) with water flow coming from Oman mountains and then reaching this zone. The physical parameters of each geological layer were assigned: such physical values were not measured in the laboratory, but taken from literature at this stage.

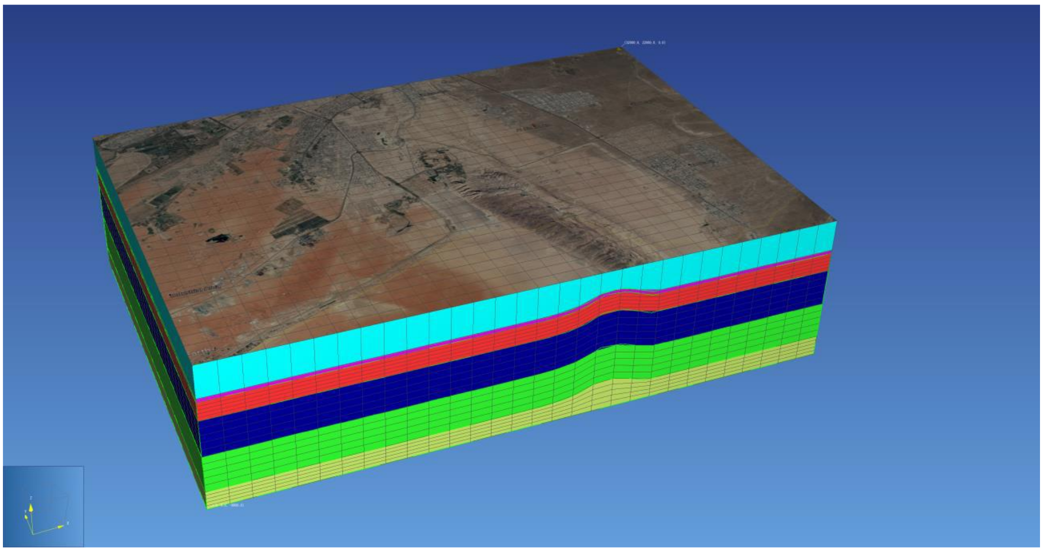

Figure 11: 3D geological model of Mubazzarah – Ain Faidha geothermal systems in Al-Ain.

4. GEOTHERMAL ENERGY POTENTIALITIES

4.1 Overview

The geothermal resource assessment is an estimation of the amount of thermal energy that can be transformed from a geothermal reservoir for economic use in a variety of applications. However, such data are often limited or missing during initial geothermal exploration and a basic assessment method is needed. In the 1970s, researchers at the United States Geological Survey (USGS) developed a method to quantify geothermal resource estimate uncertainties associated with a given hydrothermal area. This simple technique, called the USGS volumetric "heat in place" method, (Cataldi et al., 1978; DiPippo, 2015; Garg & Combs, 2015; Muffler & Cataldi, 1978), is employed in the present study. The primary purpose of this study is to use the volumetric method to estimate electrical energy production ability from a geothermal liquid-dominated reservoir in UAE (MB, AF, and AK). The calculation of geothermal energy stored in a given volume is based on a range of reservoir parameters, carried out using a stochastic Monte Carlo simulation, and applies a probabilistic method for evaluating reserves or resources and the associated estimation uncertainties. Given the geological complexity and heterogeneity of most geothermal reservoirs, this method is more appropriate than the usual deterministic approach that assumes a single value for each parameter to represent the entire reservoir. Instead of assigning a fixed value to a reservoir parameter, numbers within a range of the distribution model are randomly selected and drawn for each calculation cycle over a thousand iterations (Sarmiento & Steingrímsson, 2011; Wakeyama & Ehara, 2009).

The equation used in thermal energy calculations for a liquid-dominated reservoir is as follows:

$$P = A \cdot h \cdot (T_r - T_a) \cdot [\rho_r C_r (1 - \phi) + \rho_w C_w \phi] \cdot \frac{RF \cdot C_e}{PF \cdot t} \quad (1)$$

with parameters defined in Table 1.

Table 1: Thermodynamic parameters of the reservoir and Power plant sizing parameters.

Symbol	Description	Units
Q_T	Total thermal energy	kJ
Q_r	Heat in rock	kJ
Q_w	Heat in fluid	kJ
A	Area of the reservoir	km^2
h	The average thickness of the reservoir	m
ρ_r	Rock density	kg/m^3
ρ_w	Fluid density	kg/m^3
C_r	Rock specific heat at reservoir conditions	kJ/kg-°C
C_w	Fluid specific heat at reservoir conditions	kJ/kg-°C
ϕ	Porosity	%
T_r	The average temperature of the reservoir	°C
T_a	Final or abandon temperature	°C
P	Geothermal power potential	We
Q_T	Total thermal energy	kJ
RF	Recovery factor	%
C_e	Conversion efficiency	%
PF	Plant net capacity factor or plant factor	%
t	Lifespan (economic life)	years

4.2 Energy assessment in UAE (MB, AF, and AK)

The geothermal power potential assessment is presented below using the Python implementation called GPPeval (Pocasangre & Fujimitsu, 2018).

Table 2 considers the following assumptions (Garg & Combs, 2015; Kang, 2012):

1. Assuming an ORC Binary Geothermal Power Plant that has a pinch point of 5 ºC, working fluid of R245fa, and temperature of 78 ºC (7.5 bara) for Mubazzarah-Ain Faidh; and also assuming an ORC Binary Geothermal Power Plant that can use fluid between 56-63 ºC for Ain Khatt.
2. The conversion efficiency of less than 25 % according to USGS.
3. Recovery factor for sedimentary rocks of 0.1-0.25.
4. Limestone porosity of 5% to 10%.

Table 2: Energy assessment data.

Reservoir Properties	Mubazzarah-Ain Faidha (Al-Ain)			Ain Khatt (RAK)		
	Min	Most Likely	Max	Min	Most Likely	Max
Reservoir Area, A[km^2]	9	10	11	0.9	1	1.1
Rock type		Carbonate			Carbonate	
Thickness, h[m]	270	300	330	90	100	110
Reservoir Temp., Tr[°C]	82		87	56		63
Abandon Temp., Ta[°C]		82			56	
Porosity, ϕ	0.05		0.1	0.05		0.1
Rock SH C_r[kJ/kg °C]		0.91			0.91	
Water SH, C_f[kJ/kg °C]		4.2			4.2	
Rock Density ρ_r[kg/m^3]	2300	2500	2700	2300	2500	2700
Water Density, ρ_f[kg/m^3]	967.34		970.57	981.64		985.22
Recovery Factor, RF	0.1		0.25	0.1		0.25
Conversion Efficiency, η_e	0.1		0.25	0.1		0.25
Plant Net Capacity Factor, PF	0.9	0.95	1	0.9	0.95	1
Lifespan, t[years]		Scenario 1: 25 Scenario 2: 50			Scenario 1: 25 Scenario 2: 50	

4.3 Interpretation of Monte Carlo simulation results:

Table 3 shows the Monte Carlo simulations results for MB, AF, and AK reservoirs.

- In MB, AF the possible inference when the output is greater than or equal to 306.6 kWe is 90%, and when the capacity is greater than or equal to 779.5 kWe is 43%. Additionally, the probability that the output is greater than or equal to 1.45 MWe is only 5% for 25 years. These results imply that the field could initially support a 306.6 kWe geothermal power plant for 25 years maximum with a possible expansion to 779.5 kWe. Similarly, the possible inference when the output greater than or equal to 155.6 kWe is 90%, and when the capacity is greater than or equal to 389.7 kWe it is 43%. Additionally, the probability that the output is greater than or equal to 732.9 kWe is only 5% for 50 years. These results imply that the field could initially support a 155.6 kWe geothermal power plant for 50 years maximum with a possible expansion to 389.7 kWe. These preliminary results are subject to further delineation drilling and availability of field performance data and assumed that the geothermal power plant has either a single or multiple ORC systems. The risk that the field could not sustain 306.6 kWe and 155.6 kWe for 25 and 50 years respectively is equal to or less than 10 % can be affirmed.

- In AK the possible inference when the output is greater than or equal to 14.2 kWe is 90%, and when the capacity is greater than or equal to 34.53 kWe is 45%. Additionally, the probability that the output is greater than or equal to 65.77 kWe is only 5% for 25 years. These results imply that the field could initially support a 14.02 kWe geothermal power plant for 25 years maximum with a possible expansion to 34.53 kWe. Similarly, the possible inference with the output greater than or equal to 6.94 kWe is 90%, and when the capacity is greater than or equal to 17.26 kWe it is 45%. Additionally, the probability that the output is greater than or equal to 32.92 kWe is only 5% for 50 years. These results imply that the field could initially support a 6.94 kWe geothermal power plant for 50 years maximum with a possible expansion to 17.26 kWe. These preliminary results are subject to further delineation drilling and availability of field performance data and assumed that the geothermal power plant has single ORC system due to the very low temperature. The risk that the field could not sustain 14.2 kWe and 6.9 kWe for 25 and 50 years respectively is equal to or less than 10 % can be affirmed.

Table 3: Power Potential assessment results

Scenarios	Mubazzarah-Ain Faidha (Al-Ain) [kWe]			Ain Khatt (RAK) [kWe]		
	P10 %	Most Likely	P95 %	P10 %	Most Likely	P95 %
For 25 years	306.6	779.5	1458	14.02	34.53	65.77
For 50 years	155.6	389.7	732.9	6.937	17.26	32.92

5. CONCLUSIONS

Two main low-enthalpy geothermal systems exist in UAE: 1) Mubazzarah – Ain Faidha in Al-Ain city (Abu Dhabi Emirate) and 2) Ain Khatt in RAK Emirate. These hot springs are mainly used for bathing and the waters are extracted from wells.

Potential field geophysical surveys were carried out at and around these hot springs to understand the subsurface structure. The 2D and 3D results showed that the hot springs are emerging at contact boundaries (geological structures) thus explaining the role of such contacts/faults in bringing hot waters from deeper parts to the surface. The ANN method applied to both gravity and magnetic data highlighted a "U" shape geological structure at the studied geothermal fields.

The surface temperature of discharged hot waters ranges from 32.5 °C to 49 °C. The hot waters were sampled to study their chemical and geothermal characteristics. The chemistry results show that they belong to the Na-Cl water group. The applied cation geothermometers showed a reservoir temperature with values from 56 °C and 87 °C. If we assume a normal geothermal gradient of 3 °C / 100 m, then the geothermal reservoir could have a depth of around 1 km. The heating of such geothermal systems is mainly by conduction (Figure 12).

Monte Carlo simulation was used to estimate the geothermal-energetic potential production after 25 and 50 years of production at these low-enthalpy geothermal fields. The results showed that a power potential of 162 kWe to 320 kWe for 25 and 50 years, respectively.

The calculated geothermal electricity production is based on results obtained from scientific research. A comprehensive feasibility study using actual field data needs to be undertaken from the view point of economic feasibility.

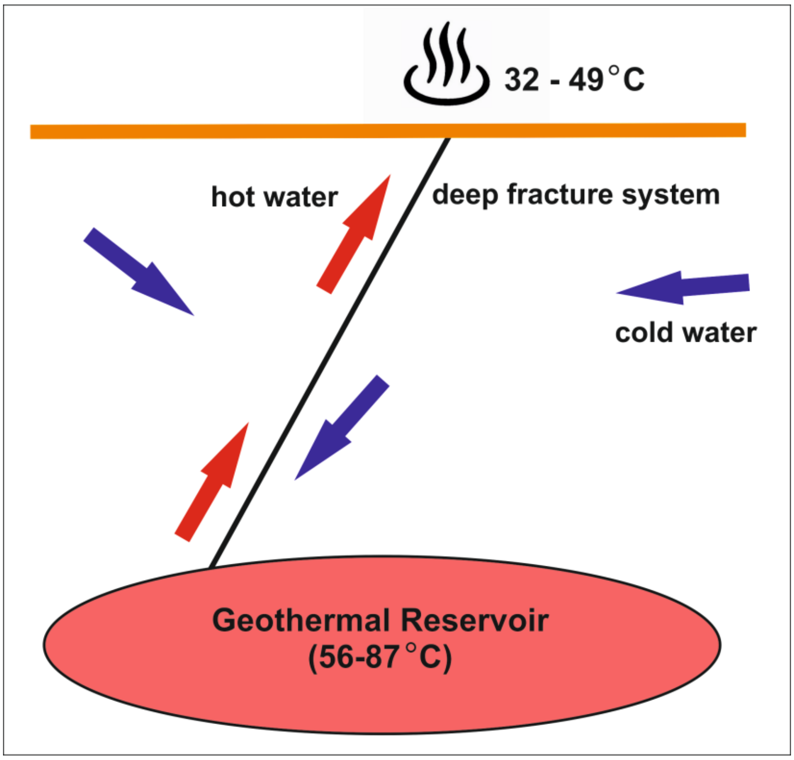

Figure 12: Simplified geothermal-geological model of the low-enthalpy geothermal systems in UAE.

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