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SIMPLE MODELLING OF GEOTHERMAL RESOURCES IN THE ASAL RIFT AREA, DJIBOUTI

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ABSTRACT

The Asal-rift geothermal field is located in the Ghoubhet Gulf area near Asal Lake in Djibouti. It is the most explored geothermal field in the country. The first geothermal investigation was undertaken in 1975, by the French Geological Survey (BRGM). This investigation lead to the discovery of a high-enthalpy geothermal reservoir. With the financial support of the World Bank and UNEP, six deep boreholes were drilled in the field. The most recent well, GLC-1 in Gale Coma, was drilled by the Government of Djibouti in September 2016. The Asal area has been described as a segment of the world oceanic rift system by earlier investigators. Well A-2 was damaged, wells A-4 and A-5 were impermeable although very hot, but wells A-1, 3 and 6 produced extremely saline fluids from 1000-1300 m depth where the aquifer temperature is about 260°C. Conceptual models are used to describe or illustrate essential features of geological situations and delineate the principal processes in the system, by focusing on data providing information about temperature, pressure and fluid flow. In this study, the conceptual model of the Asal geothermal system has been updated and a Monte Carlo volumetric assessment of the intermediate temperature reservoir in the area performed. Extensive exploration and field-wide production tests need to be performed to accurately estimate the actual size and capacity of the Asal geothermal reservoirs.

1. INTRODUCTION

The Republic of Djibouti is 23,000 km^2 in area and is located in East Africa, where three major extensional structures, the Red Sea, the East African rift and the Gulf of Aden join, forming the Afar Depression (Barberi et al., 1975). The area is characterized by the presence of geothermal resources revealed by numerous hot springs found in different parts of the country (Figure 1). The most active structure is Asal Rift, which is the westward prolongation of the Gulf of Aden - Gulf of Tadjoura Ridge.

Geothermal exploration in the Republic of Djibouti was initiated by the drilling of two wells in the rift of Asal in 1975 (BRGM, 1980) which located a deep reservoir at 1000 m depth, with high salinity and a temperature of 260°C. Additional geothermal exploration in the Republic of Djibouti consisted of drilling of two exploratory wells in the Hanlé plain, followed by four wells in the Asal Rift (Aquater, 1989).

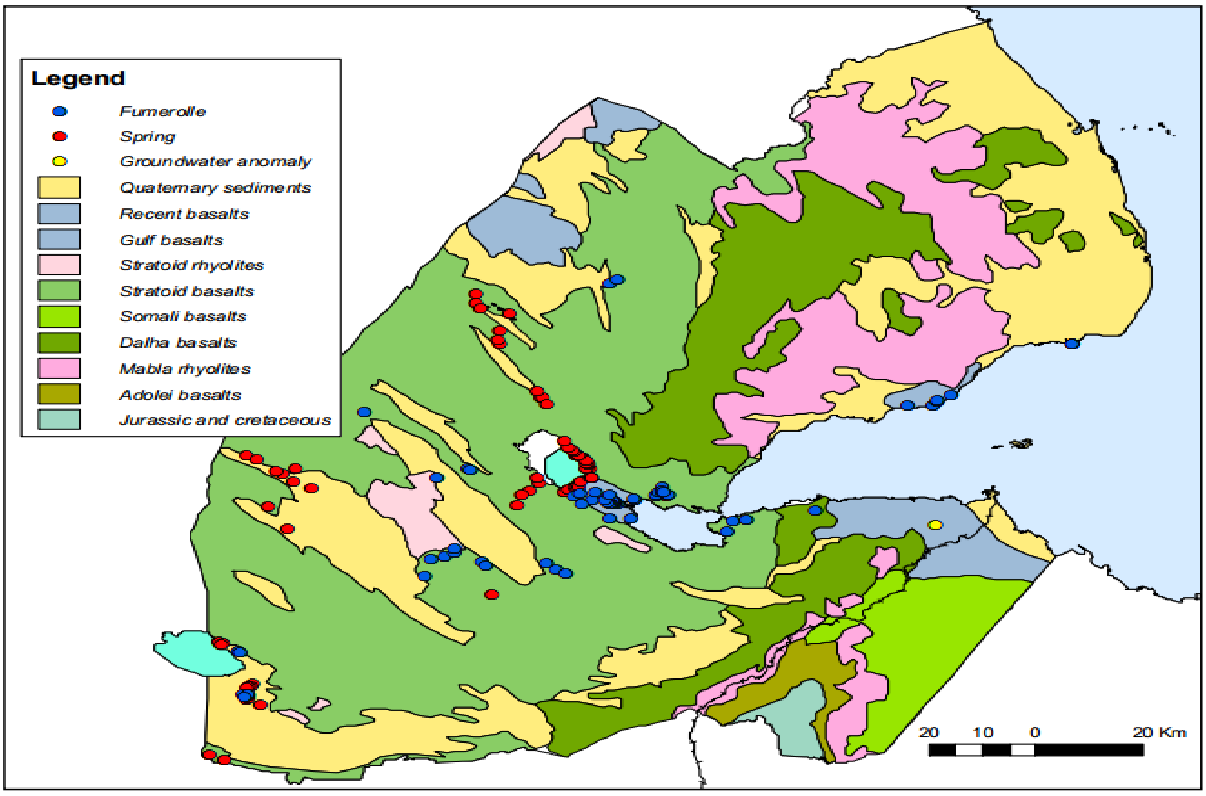

FIGURE 1: Stratigraphy and hydrothermal activity in the Republic of Djibouti (Jalludin, 2002)

The main purpose of this report is to study a simple model of the Asal reservoir, including a volumetric assessment to estimate the production capacity of the Asal geothermal field (see Figure 2). Therefore, the report starts with presentation of the conceptual model of the Asal geothermal field to understand the main characteristics of the reservoir in order to estimate parameters for the volumetric assessment.

2. THE ASAL GEOTHERMAL FIELD

2.1 Geography

The Asal geothermal system is located on the isthmus between Lake Asal and Ghoubhet al Kharab gulf (Figure 2) at a distance of about 120 km from Djibouti City. The altitude ranges from 151 m b.s.l. at Lake Asal to 300 m a.s.l. at the highest point of the Rift valley floor. The area is bound by the high plateaus of Dalha to the north, above 1000 m elevation, and by 400-700 m high plateaus to the south, which separate Asal from the Gaggade and Hanle sedimentary plains. The region is an arid desert with an average rainfall of 79 mm per year. Hydrogeological studies of the region show a general groundwater flow toward Lake Asal, which is the lowest point of the area and is occupied by a salt lake saturated in sodium chloride and calcium sulphates. The area is controlled by tectonic faults that are still active (Figure 3)

2.2 Geology

The geology of the Asal Rift is characterized by an extensional graben, generally in a basaltic environment (Dalha basalts (6-8 Ma) and the basaltic stratoid series (1-4 Ma)) between Ghoubhet and Lake Asal (Figures 2 and 3). Surface rocks are Holocene basalts and the most recent eruption took place in 1978. Geothermal surface manifestations are linked to volcanic activities. The underground activities

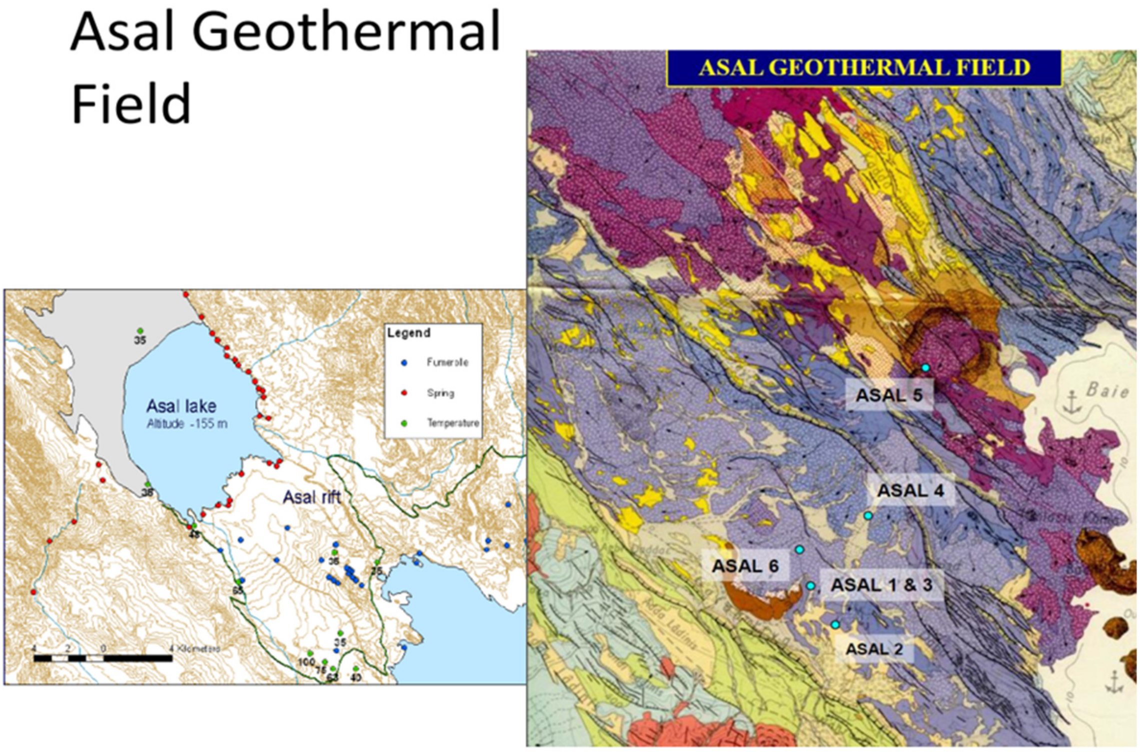

FIGURE 2: Location of geothermal manifestations and boreholes in the Asal Rift (Elmi Houssein, 2005)

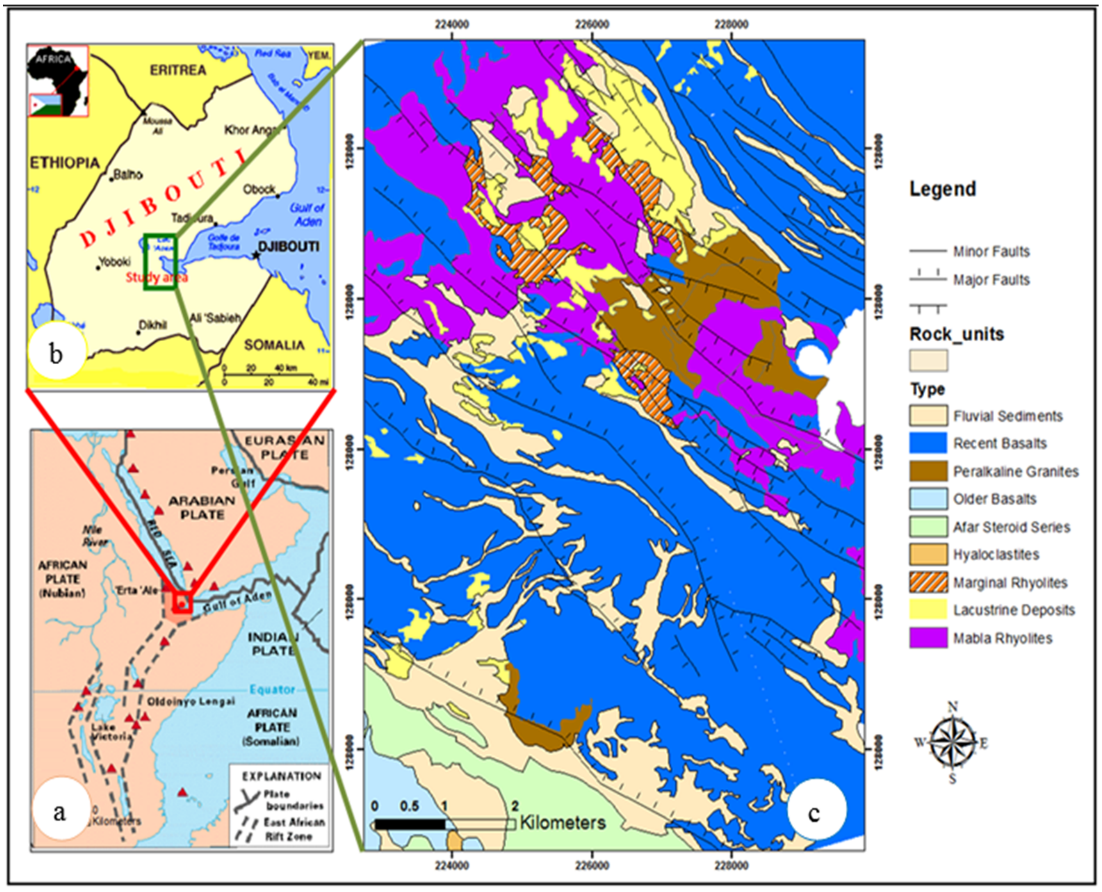

FIGURE 3: Structural map of the Asal geothermal area

are reflected on the surface by the presence of hot springs at Lake Asal, and fumaroles (Figure 3). The Asal Rift is tectonically the most active structure in the zone of crustal divergence in Afar (Figure 2). The Asal area constitutes a typical oceanic type rift valley, with a highly developed graben structure, displaying axial volcanism. The Asal basalt series are relatively complex in structure because of different series of active volcanism in recent Quaternary times, each with different characteristics depending on the sites of appearance (Figure 3). Generally, the Asal series are composed of porphyritic basalt formations and hyaloclastites. The initial basalt series are an ensemble of piles of fine flows with phenocrystals of plagioclases and olivine. The stratoid series are essentially constituted of basalts, where the top series is marked by Pleistocene clay and there are sedimentary layers in between the basalt flows. Three main geological formations are known in the region. The youngest one are the Asal series which are the recent basalts on the geological map in Figure 1, with volcanism dating from the last 800,000 years (volcanism of the external margins of Asal, central volcanism and axial volcanism). Then are the initial basalts series, or the stratoid basalts series, covering the period from 3.4 to 1 My; and then the Dalha basalts series, dating between 9 and 3.4 My (Elmi Houssein, 2005) (Figures 1 and 3).

2.3 Stratigraphy and alteration in Gale Coma 1 well

The Asal volcanic and tectonic range displays a typical rift structure with a shield volcano dissected by faults, having emitted a continuous petrologic series from tholeiitic basalts to ferrobasalts by crystal fractionation of olivine and bytownite at shallow depth (Stieltjes et al., 1976), indicating possible presence of a magmatic heat source at shallow depth.

The last well drilled in the Asal Lake area was the Gale Coma 1 (GLC-1) well, drilled to a depth of only 540 m, and finished in September 2016. The drill rig proved inadequate for drilling deeper. Well cuttings analysis and lithological logs give information on the lithology and the basement stratigraphy of the reservoir (Figure 4). The different types of rock are basalt, hyaloclastites, clay and rhyolite.

2.4 Geochemical origin of the fluid

The chemistry of the fluids from the three wells that have been tested, A-1, A-3 and A-6, is very similar, indicating that they produced from the same aquifer. The fluid is extremely saline, suggesting evaporated seawater. The major constituent composition of the three samples computed to deep water composition collected during the 1989–1990 flow tests, showed total dissolved solids (TDS) in the range of 115,000-121,000 mg/kg, Cl 67,000-71,000 mg/kg, Na 25,000-28,000m mg/kg and Ca 15,000-16,000 mg/kg (Virkir-Orkint, 1990). The main results of geochemical studies of the water from the Asal area were published by Correia et al. (1985) and Aquater **(**1989):

- According to a study performed on samples collected from shallow aquifers from wells A-1, A-2, A-3, A-4 and A-6, and deep-water samples from well A-3, as well as from samples from Lake Asal, it appears that these aquifers are mainly recharged by seawater (Aquater 1989).
- Asal geothermal fluid originates through the mixing of seawater and high TDS continental water of meteoritic origin.
- The geothermal fluid is not produced by the evaporation of seawater as in the case of the Asal Lake Na-Cl brine.
- The equilibrium temperature calculated from all reactive gaseous species (H_2O, CO_2, H_2, CH_4, CO, N_2, NH_3), apart from H_2S, is about 260°C which is compatible with the temperature measured in the wells.
- The water in Lake Asal is composed of very concentrated seawater due to evaporation and its $CaSO_4$ content is modified mainly due to precipitation. Deep geothermal waters seem to have no contact with Lake Asal waters and the Ca/Mg ratio is very different.
- Contrary to what was expected, the fluids collected in well A-5 showed that the water in the centre of the rift has a much higher salinity than water at the borders.

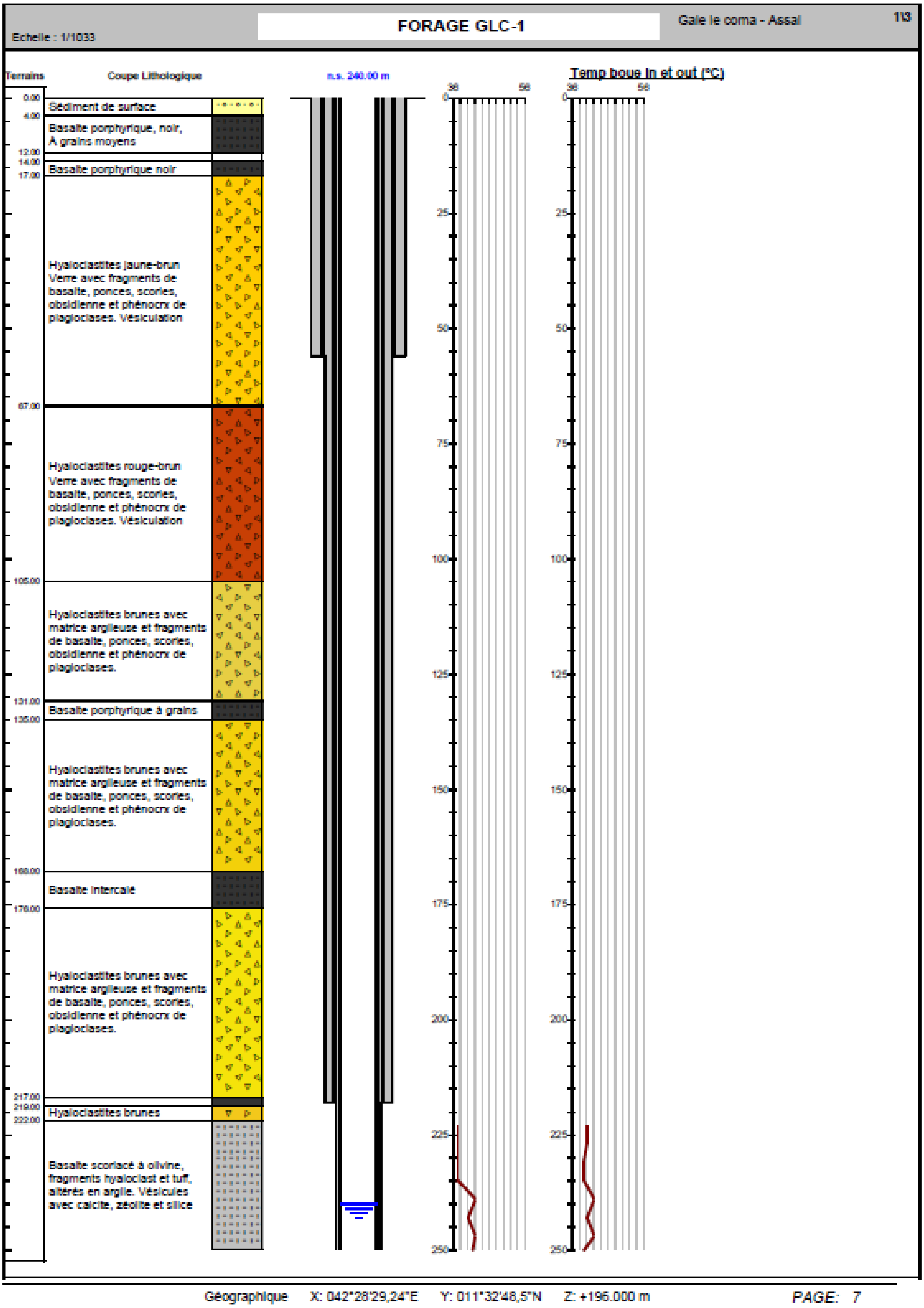

FIGURE 4: Stratigraphic logs and interpretation of the Gale Coma 1 well (GLC-1) (ODDEG, 2016)

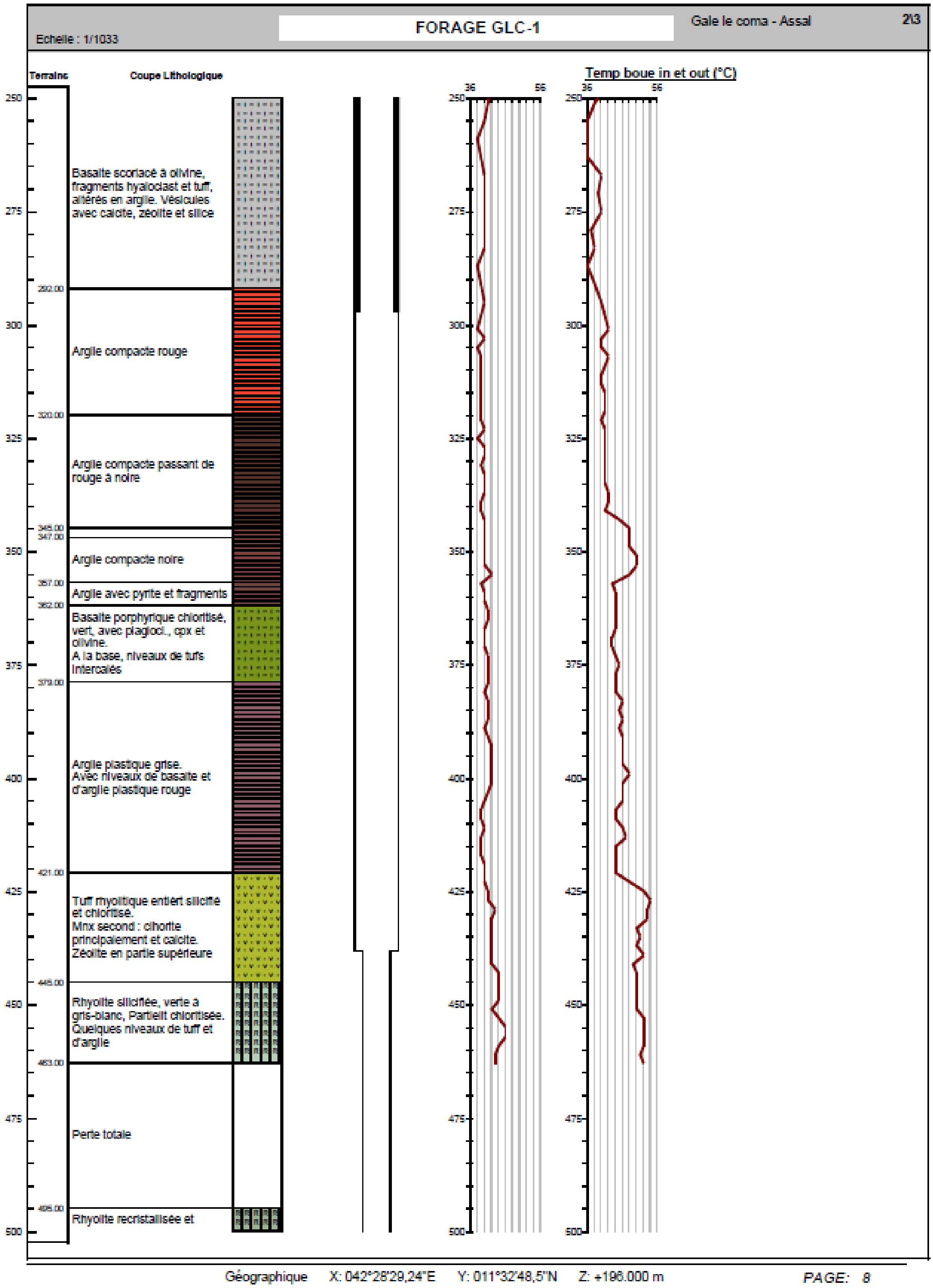

FIGURE 4 cont.: Stratigraphic logs and interpretation of the Gale Coma 1 well (GLC-1) (ODDEG, 2016)

The chemical composition of the Asal reservoir is composed of two parts: deep water and deep steam, shown in Figure 5. The deep water contains a significant amount of Cl, 83058 ppm, and Na, 30975 ppm, and this shows that the reservoir contains seawater. The deep steam has significant amounts of CO_2 gas at 21425 ppm, and H_2 gas at 3099 ppm.

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ORKUSTOFNUN                           DEEP WATER BOILED AT 200.0 DEGREES C.
SAMPLE = 9001110002
==================================================================================================

LOG DISTRIBUTION COEFFICIENTS     CO2 =-2.69     H2S =-2.19     GAS SOLUBILITY MULTIPLYING FACTOR  1.00

DEEP WATER (PPM)                                    DEEP STEAM (PPM)         GAS PRESSURES (BARS ABS.)

SIO2          538.29    CO2          104.10        CO2        21425.28      CO2          .136E+00
NA          30975.26    H2S             .04        H2S            5.50      H2S          .452E-04
K            5208.74    H2              .00        H2             3.91      H2           .543E-03
CA          17588.79    O2              .00        O2            12.91      O2           .113E-03
MG            25.191    CH4             .00        CH4           10.37      CH4          .181E-03
SO4            14.45    N2              .79        N2          3099.65      N2           .310E-01
CL          83058.28    NH3            5.35        NH3            7.37      NH3          .121E-03
F               5.68                                                        H2O          .155E+02
DISS.S.    136142.50                                                        TOTAL        .157E+02
AL            1.7551
B            10.6339                               H2O (%)            14.54
FE           37.7918                               BOILING PORTION      .15
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FIGURE 5: Reservoir water composition (Virkir-Orkint, 1990)

2.5 Geophysical surveys

2.5.1 Gravimetric surveys

Gravimetric survey points out several heavy body anomalies having different dimensions (CFG, 1993). Those located in the central part of the rift are correlated with the injection of a magmatic chamber and the collapse of the ground. Locally, small anomalies could be the result of an intensively fractured zone. The comparison of aeromagnetic data and gravimetric modelling, with the help of geothermal data, demonstrates the existence of a basement represented by the old Dalha basalt series, split into several compartments delimited by intensively fractured zones. The results of another gravimetric survey exhibits three main characteristics. The anomalies' principal direction appears to be in good accordance with the principal tectonic trend of the rift, NW-SE, and high horizontal gradients are aligned with the main axis of recent fractures, thus confirming the existence of these geological structures at depth. Secondly, numerous anomalies demonstrated by the survey reflect the local heterogeneity and their superficial origin in conformity with geological observations, showing numerous structural units and a particularly dense fracture network. Finally, in the central part of the rift a clear anomaly is seen, corresponding to the principal inflow of magma where recent volcanic activities were observed.

The transversal, magneto-telluric profile in the Asal rift generally shows conducting layers underlying resistive layers in some areas in relation to the presence of hyaloclastites overlain partially by recent basaltic formations. The study mainly points out the heterogeneity of the structures. The correlation between the different measuring stations is relatively difficult due to variations in thickness. Another profile in the vicinity of the recent Ardoukoba volcano suggests the presence of saline water in hyaloclastites, basalts, scorias and fissures. Spontaneous polarisation (SP) profiles measured across the rift clearly describe an SP anomaly near the recent volcano of Ardoukoba. The interpretation of the profiles indicates that the general anomaly in the central part of the rift results from a thermal source. This signifies that the heat flow is generally high in this region (BRGM, 1980).

2.5.2 Seismic activity

The Asal Rift is very seismically active and its seismicity has been studied thoroughly. The seismicity is monitored by an eight-station, permanent telemetric seismic network, sending the data to the seismological observatory in Arta. The network was temporarily made denser by adding eight portable stations (from Oct. 2000 to late March 2001) (Doubre, 2004). CERD in Djibouti made seismic data from the database in the seismic observatory in Arta available for this study. The data set contains the time of events, hypocentres (x, y coordinates and depth) and magnitudes. The data spans the period from 1979 to 2003 (both inclusive). Figure 6 shows the epicentres (x and y coordinates) of earthquakes within the Asal Rift area (about 8760 events). It shows that the earthquake activity is most intense in the Inner rift, in the northeast part of the main rift. Some activity is seen northeast of the main north-easterly bordering faults, but the vast majority of the quakes are under Lava Lake (Fiale) and to the northwest in the northeast part of the Inner Rift. It is worth noting that over the 25-year period that the data spans, no clear signs are seen of the main faults of the rift being active. It seems as if there have been very little fault movements since the rifting episode and eruption in 1978.

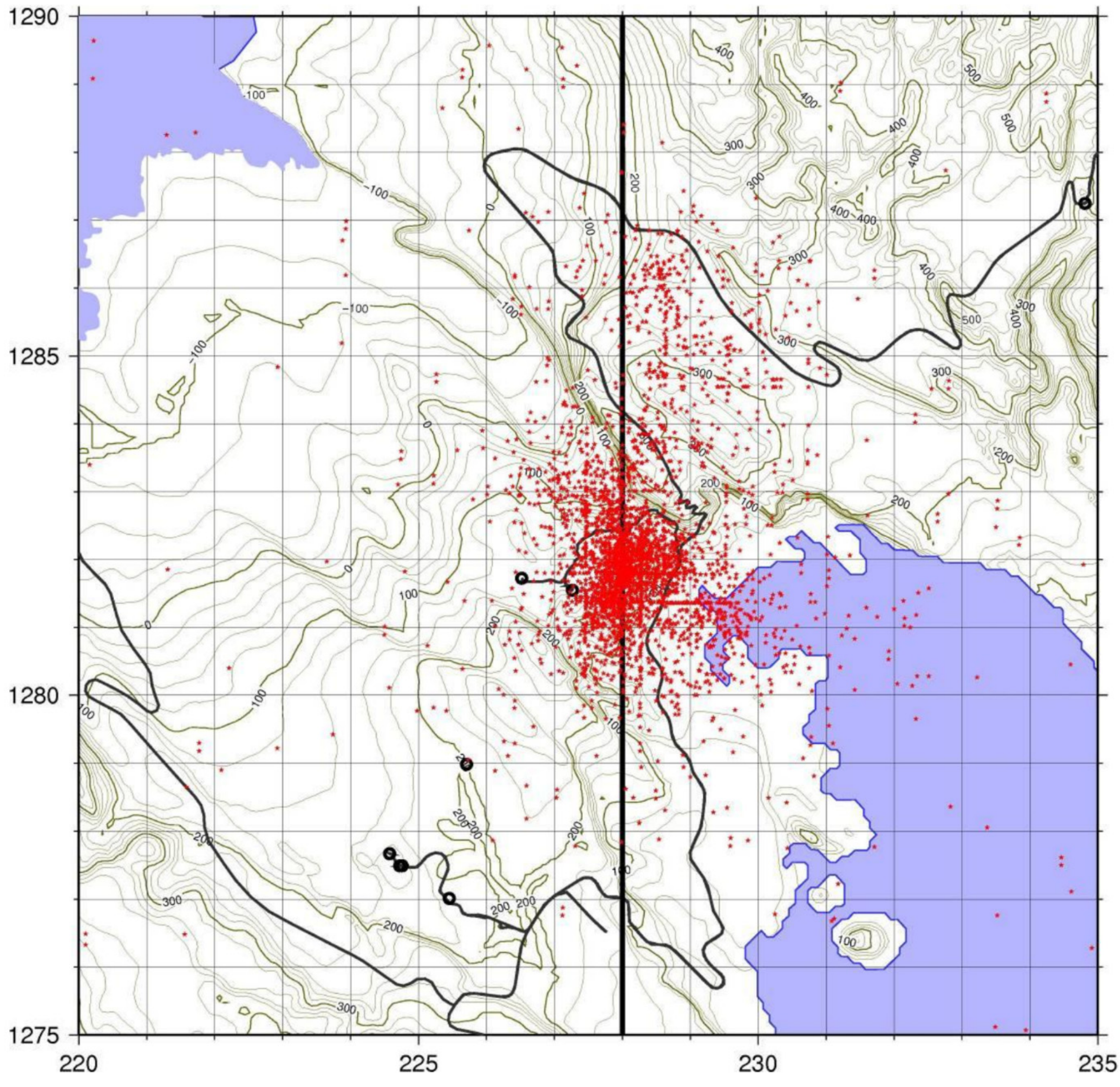


FIGURE 6: Epicentres of earthquakes in the Asal Rift from 1979 to 2003 (Árnason, et al., 2008)

2.5.3 Resistivity

The resistivity of subsurface rocks is usually the most diagnostic parameter of high-temperature geothermal activity that can be measured from the surface. Rocks containing geothermal fluids have different resistivity than cold rocks. Most commonly, geothermal water lowers the resistivity, but in some cases the resistivity increases again at very high temperatures. There exist several methods for measuring the resistivity of subsurface rocks. They can be divided into galvanic or direct-current (DC) methods and electromagnetic (EM) methods. Some decades ago, the DC methods (mainly Schlumberger soundings) were widely used. In recent times, the EM methods have gained more popularity, mainly the Transient Electro-Magnetic (TEM) method and the Magneto-Telluric (MT) method. ÍSOR – Iceland GeoSurvey did electromagnetic measurements in Djibouti – first in 1988, but in 20007-2008, a total of 78 MT soundings were carried out and 27 TEM soundings, three of which were at the same location as soundings from 1988 (Árnason et al., 2008). The 1D models from the interpretation of the TEM/MT sounding pairs were used to compile a 3D subsurface resistivity structure of the Asal Rift. The resistivity structure is presented in iso-resistivity maps at different elevations above and under sea level and also as vertical resistivity cross-sections. Figure 7 shows the resistivity at 100 m below sea level. The resistivity structure changes very little, except that the resistivity decreases to southeast from a line from Lava Lake to the northwest the well field towards Lake Asal (Árnason et al., 2008).

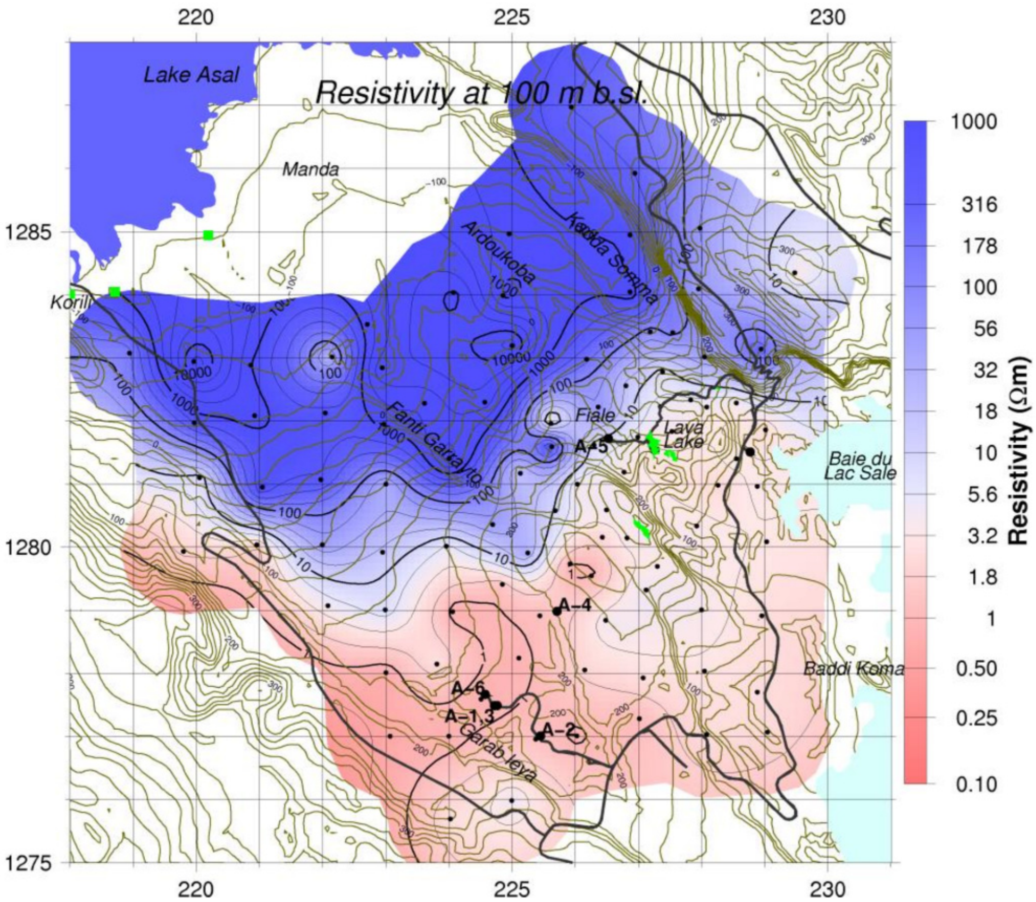


FIGURE 7: Resistivity map at 100 m below sea level with geothermal surface manifestations shown as green spots (Árnason et al., 2008)

2.8 Reservoir conditions and well data

Temperature profiles measured in the Asal wells A-3, A-4, A-5 and A-6 are presented in Figures 8-11 together with the lithology and alteration mineralogy. In particular, the inversion of temperature

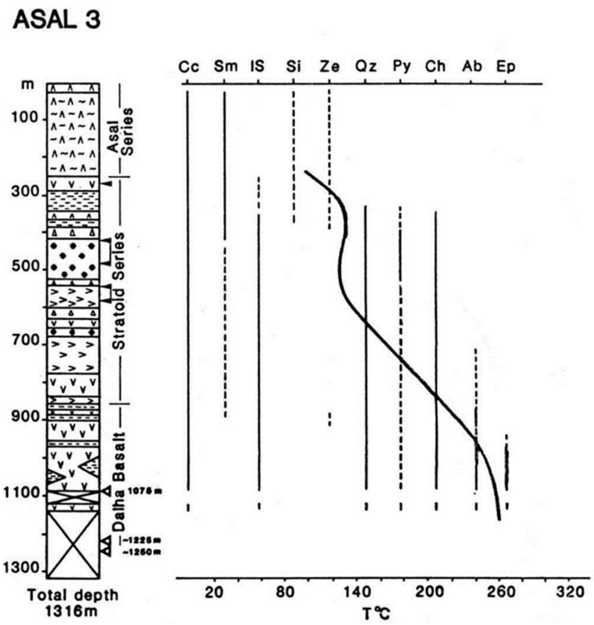


FIGURE 8: Lithology, alteration mineralogy, temperature profile and feed zones in well A-3 (Aquater, 1989)

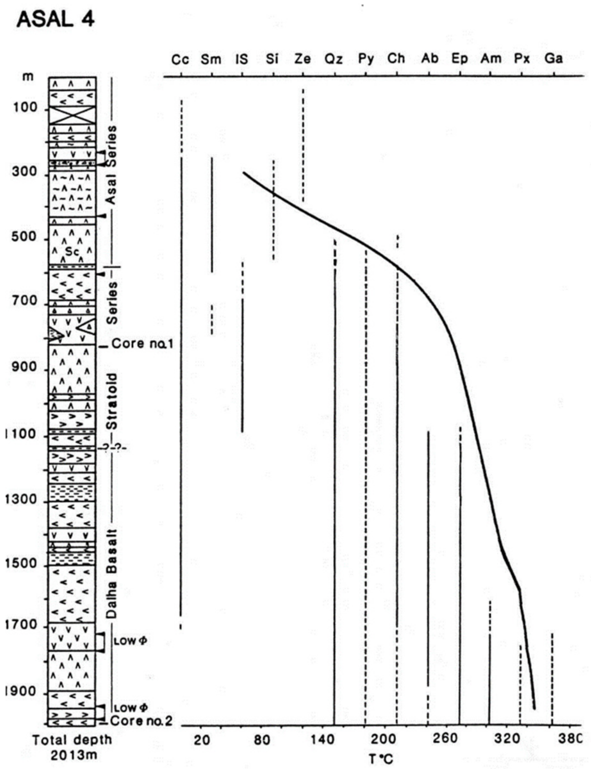


FIGURE 9: Lithology, alteration mineralogy, temperature profile and feed zones in well A-4 (Aquater, 1989)

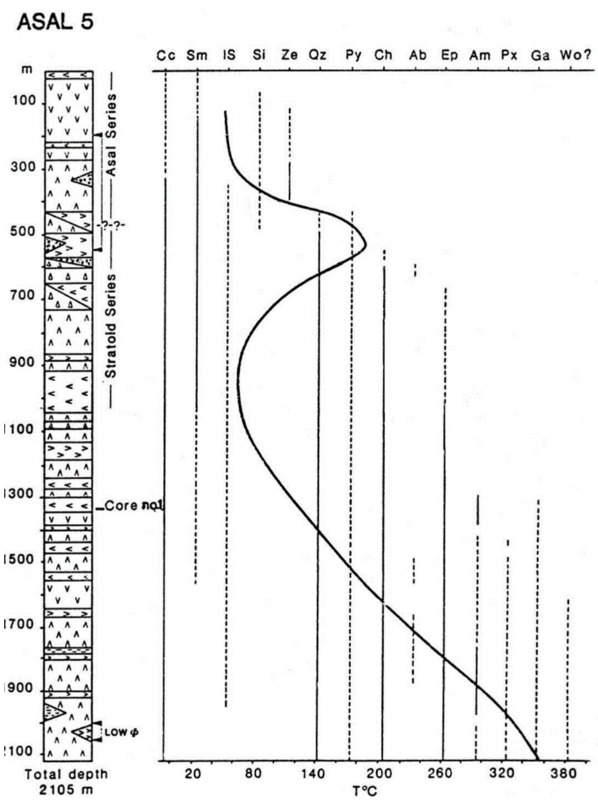


FIGURE 10: Lithology, alteration mineralogy, temperature profile and feed zones in well A-5 (Aquater, 1989)

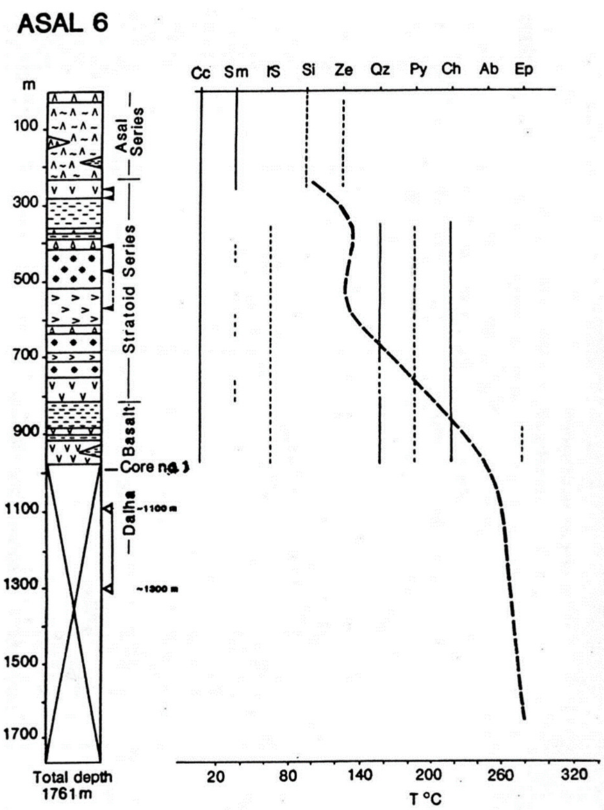


FIGURE 11: Lithology, alteration mineralogy, temperature profile and feed zones in well A-6 (Aquater, 1989)

observed in the A-5 well drilled in 1988 immediately northwest of the Fialé caldera should be noted (Jalludin, 2002). In Figures 8-11, it can be seen that wells A-3 and A-4 show high temperature but A-5 is cold down to 1000 m depth. An intermediate reservoir can be observed at a depth between 250 and 750 m and a temperature between 120 and 190°C. A-6 is also fairly cold down to 1000 m depth.

3. CONCEPTUAL MODELS

3.1 General

A conceptual model is a descriptive or qualitative model of a geothermal system that incorporates the essential physical features of the system and is capable of matching the salient behaviour or characteristics of interest to the model (Grant et al., 1982). In general, this model estimates the heat content of the reservoir system, the upward flow of geothermal fluids and the total flow in the system. A conceptual model is a model made of the composition of concepts, which are used to help people know, understand, or simulate the subject the model represents. In order to make a conceptual model of a geothermal system, it is necessary to screen all available data, and data interpretation, and view them in their context. The key data available for Asal Rift are:

- Surface geology, including the geological units, geothermal manifestations and structures;
- Geophysical measurements, in particular resistivity surveying by TEM and MT methods, and magnetic and gravity measurements;
- Chemical composition of liquid water and steam from natural manifestations;
- Locations of micro-earthquakes;
- Borehole geology;
- Temperature and pressure measurements from wells and information on the main feed zones in each well;
- Well tests, e.g. injection and discharge test data;
- Changes of pressure and temperature in the geothermal system during utilization;
- Chemical compositions of well fluids and their changes over time in response to utilization; and
- Effects on energy reserves and utilization life time.

The main features of a conceptual model of a geothermal system are intended to show the following:

- Geology of individual stratigraphic layers in the region, possible fractures, faults and other structures that may affect the flow of fluids in the geothermal system;
- Initial temperature and pressure conditions;
- Variations within the system, based on the chemical content of liquid and steam, and other factors;
- Location of inflow into the geothermal system, as well as upflow and outflow zones;
- Area size and thickness; and
- Assessment of reservoir permeability, porosity and other related factors.

3.2 The Asal conceptual model

The Asal area has been defined as a part of the world oceanic rift systems by earlier investigators. The exploration was in the beginning focused on the Hanlé area about 60 km southwest of the Asal Rift. After the drilling of the first two deep wells in Hanlé, focus turned to the Asal Rift where the six deep wells were drilled, as has been discussed above. Table 1 summarizes the temperature data from these deep wells.

TABLE 1: Temperature in wells in the Asal Rift (Jalludin, 2002)

Wells	Depth (m)	Max. temperature (°C)	Temperature gradient (°C/100 m)
A-1	1145	261	18
A-2	1554	235	14.3
A-3	1316	280	15.51
A-4	2013	345	15.2
A-5	2105	360	15.2
A-6	1761	280	12.75

3.2.1 Heat source

Geothermal exploration is a science that studies the internal thermal phenomena of the terrestrial globe, and the technology that seeks to exploit it. By extension, geothermal exploration also sometimes focuses on geothermal energy resulting from the energy of the Earth, which is converted into heat.

The Asal Rift is characterized by a diverging plate boundary that has accumulated a substantial volume of basaltic magma. Microseismicity is persistent while large earthquakes are few. The last volcanic eruption took place in 1978 at Ardoukoba, southeast of Lake Asal. The Asal lake region is located in the volcanic zone. The Asal Rift is seismically very active, with a dense distribution of recent epicentres of earthquakes as seen in Figure 6. The heat source of the geothermal system is believed to be located beneath the area of the densest seismic activity, shown in Figure 6.

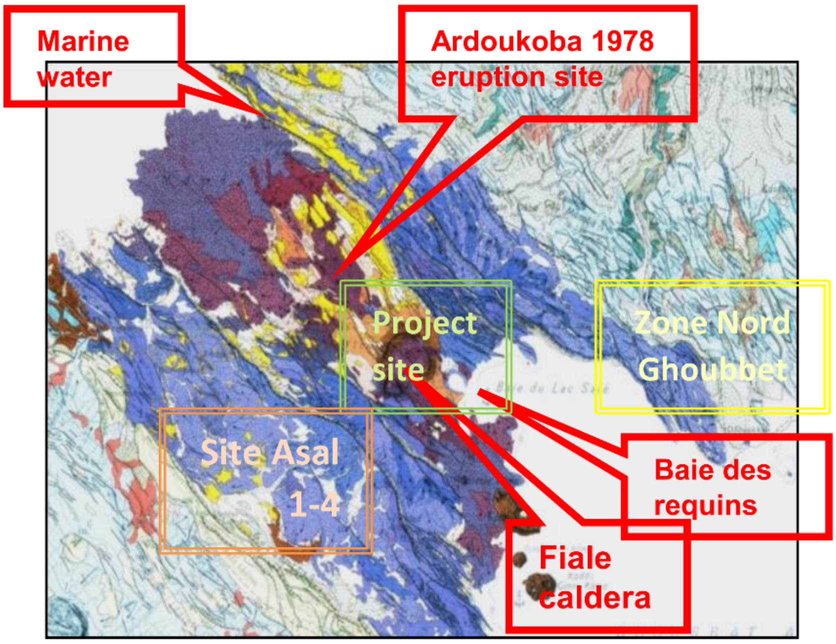


FIGURE 12: Geological map of the Asal Rift (Stieltjes, 1976)

3.2.2 Rock type

The geology of the Asal Rift has been studied intensively. In the 1970s, geologists from the French Geological Survey (BRGM) thoroughly mapped the area and published a detailed geological map. The map shows geological units on the surface and tectonic features (faults and fissures). A more thorough tectonic mapping has since been carried out by BRGM but not yet published. On the geological map of the Asal Rift (Figure 12), hyaloclastites are in orange, recent basalts in deep blue and violet whereas early rift basalts are in pale blue and the stratoid series is in very pale blue colour. Lacustrine deposits (diatomite) are yellow.

The stratigraphy encountered in the Asal wells, confirms what was expected from surface studies, except in well A-5 where it was difficult to distinguish between the Asal series and Dalha series. Information on all the feed zones encountered during drilling of the six wells is summarised in Table 2, while Figure 1 in Appendix I shows a geological cross-section through the Asal field with feed zones and their relation to geological units (Jalludin, 2013).

TABLE 2**:** Stratigraphy and feed zones of the Asal wells (Elmi Houssein, 2005)

Wells	Coordinates			Depth (m)	Feed zones (m)	Aquifer formations
	x (m)	y (m)	Z (m a.s.l.)			
A-1	224781.47	1277342.33	191.026	1146	See A-3	
A-2	225429.28	1276814.12	187.63	1554	250-500	Stratoid basalt series
A-3	224800.36	1277342.35	192.665	1316	240-250 400-460 540-550 1050-1075 1225-1250 1275-1316	Contact hyaloclastite/scoria A.S. Rhyolite of stratoid series Trachyte of stratoid series Dalha basalts series
A-4	225740.92	1278432.56	201.607	2013	250-420	Basalts, and contact basalt-hyaloclastite of Asal series
A-5	226303	1281353	125	2105	200-500	Basalts, trachytes and alluvium of Asal series
A-6	224525.25	1277427.46	183.223	1761	220-270 400-600 1000-1300	Scoria of stratoid series Rhyolite/trachyte stratoid series Dalha basalts series

3.2.3 Temperature

The temperature profiles measured in the Asal wells A-3, A-4 and A-5 show that at a depth of 500 m, the average intermediate temperature observed is between 130 and 180°C (Figure 13). Well A-5 shows a relatively cold flow with temperatures of 130-180°C. Wells A-4 and A-5, located towards the central part of the rift, encountered a superficial flow of underground seawater to Asal at 250-280 m, followed by a rapid increase in the temperature in the hydrothermalized caprock, but did not reach a productive geothermal reservoir. In wells A-3 and A-6 the temperature profiles are almost similar (Figures 8 and 11), with an intermediate mean temperature and a high temperatures at depth. Figure 2 in Appendix I shows a deep temperature cross-section through the Asal field from Zan et al. (1990).

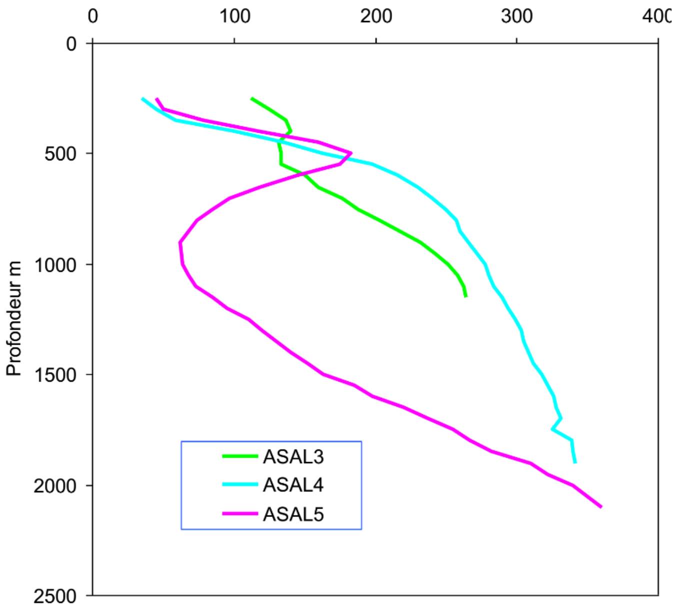


FIGURE 13: Temperature profiles measured in the Asal wells A-3, A-4 and A-5; note the inversion of temperature observed in the A-5 well located along the rift axis (Jalludin, 2002)

3.2.4 Size of the geothermal area based on resistivity surveys

Asal Lake is located in the eastern Afar depression, at an altitude of 153 m b.s.l., making it the lowest point on the African continent. It is part of a graben framed by two horsts, formed by the opening of the valley of the great rift. It is separated from the Ghoubhet-el-Kharab, which is the extension of the Gulf of Aden via the Gulf of Tadjoura, by the Ardoukoba volcano, which had its last eruption in 1978. The Asal-rift geothermal field is located in the Gulf of Ghoubhet, near Lake Asal. This is the most explored geothermal area in the country. The first geothermal study was undertaken in 1975 by the French geological survey (BRGM). According to geophysical studies carried out in 2008 by ÍSOR, the area of geothermal activity is between 15 and 30 km^2 (Árnason et al., 2008). The 1D interpretation models of all TEM / MT sounding pairs were used to compile a 3D subsurface resistivity model of the Asal Rift. Figure 7 showing the resistivity at 100 m b.s.l. was a part of that work.

3.2.5 Structures associated with Asal wells

Three of the Asal wells, A-1, A-3 and A-6, are located in the southern zone of the Asal rift, inside the half circle of hyaloclastites known as Gale le Koma, with wells A-1 and A-3 only 30 m apart. The distance between A-3 and A-6 is approximately 300 m, along a line striking NW-SE. The two sites, A-1 / A-3 and A-6 are located near a NW-SE fracture. Well A-2 is located 800 m southeast of the A-3 site. A-4 is located about 2 km north-northeast of the site of A-3 and A-6, close to a NW-SE fracture, the same tectonic segment as sites A-3 and A-6. A major tectonic step-out is located 3 km further to the northeast; and well A-5 is located further away in the same direction at the axis of the rift. One should also note that A-5 is located nearly 500 m from a major active fault. Figure 3 in Appendix I shows the location of the drilled sites and the main fumaroles in the Asal rift with a recent interpretation of deep fluid flow (Varet, 2014).

A conceptual model of the geothermal upflow in the Asal Rift was made using all the information, which has been reviewed in this Section 3. The result shown in Figure 14.

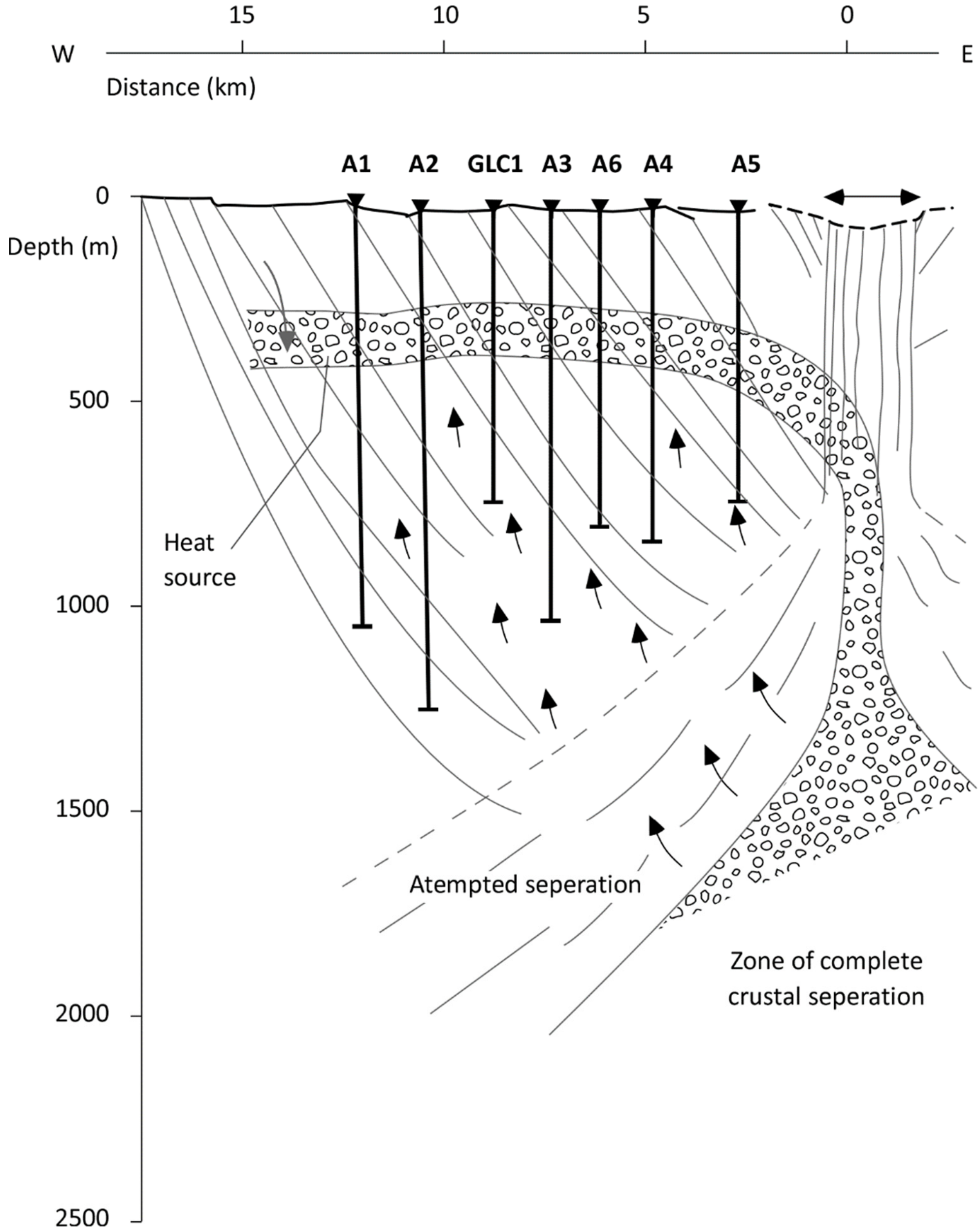


FIGURE 14: Conceptual model of the Asal geothermal area.

4. MONTE CARLO VOLUMETRIC RESOURCE ASSESSMENT

4.1 General

The volumetric method refers to the calculation of thermal energy in the rock and the fluid of a reservoir, and an estimate of how much of that can be extracted, based on specified reservoir volume, reservoir temperature, reference or final temperature, and utilization period. It is an approximate method suitable for resource assessment, when limited data is available for more detailed modelling, e.g. numerical modelling.

There is usually great uncertainty in many of the parameters used in volumetric calculations. Therefore, the Monte Carlo method is usually applied in the calculations. It enables the incorporation of overall uncertainty in the results by assigning probability distributions to the different parameters of the equations above and estimating the system potential with probability. The outcome of the volumetric assessment is then presented through a probability distribution and associated P values, i.e. P90 (90% probability of a given outcome), P50 (50% probability) and P10 (10%).

The equations used in calculating the thermal energy stored in a liquid-dominated reservoir are as follows (Tulinius, 2017):

$$E_{res} = E_{rock} + E_{fluid} \tag{1}$$

$$E_{rock} = V(1-\emptyset)\, \rho_{rock} * C_{rock} * (T_{res} - T_{reference}) \tag{2}$$

$$E_{fluid} = V * \phi * \rho_{fluid} * C_{fluid} * (T_{res} - T_{reference}) \tag{3}$$

or

$$E_{fluid} = V * \emptyset * \rho_{fluid} * (h_{res} - h_{reference}) \tag{4}$$

where T = Temperature (°C);
V = Reservoir volume studied (m^3);
ϕ = Porosity (-);
C = Heat capacity (J/kg°C);
ρ = Density (kg/m^3);
h = Enthalpy (J/kg); and
res = Reservoir.

The total recoverable thermal energy is then given by:

$$E_{recoverable} = A * R * E_{res} \tag{5}$$

where R = Recovery factor; and
A = Accessibility.

Consequently, the electrical energy generation capacity (E_e) and power capacity (P_e) are estimated by:

$$E_e = \eta_e * E_{recovrable} * (above\ ref.\ temp.) \tag{6}$$

$$P_e = \frac{E_e}{\Delta t} \tag{7}$$

where Δt = Production time of the electric power (s); and
η_e = Efficiency of the power plant (see below).

The main input parameters for the assessment are the surface area, thickness and temperature conditions, clearly derived from a corresponding conceptual model. The recovery factor is also a key factor, it depends on the nature of the system; permeability, porosity, significance of fractures and recharge, all of which depends on a conceptual model. It is a crucial parameter, but ill-defined before any production experience has been gathered. These parameters are described, as determined for the Asal Rift geothermal system.

4.2 Different parameters for the calculation of the resource capacity

4.2.1 Surface area of the Asal geothermal system

The most important factor in the volumetric assessment is an estimation of the volume of the geothermal system, which is a product of the surface area and estimated reservoir thickness. Resistivity data is used to estimate the possible maximum surface area of the system and how the temperature is distributed within the estimated volume of the geothermal system. Geological mapping also helps with estimating the surface area, with mapping of surface manifestations often helping to estimate the minimum area. Finally, information from wells drilled, including temperature conditions, is used to estimate the surface area, when available. Here, the production capacity of the intermediate temperature, shallow geothermal resources in the Asal area is estimated with the volumetric method. Based on available information on geology and resistivity the surface area was estimated to be in the range of 2-9 km^2.

4.2.2 Thickness of the system

The typical depth of the Asal geothermal wells is in the range of 1000-2000 m, with well A-5 reaching a depth of more than 2100 m. The present volumetric assessment only considers the intermediate temperature shallow reservoir. Therefore, the thickness of the system was assumed to be in the range of 150-300 m, based on well and resistivity data.

4.2.3 Temperature conditions

The temperature conditions of the reservoir, as determined by temperature logging of available wells, have been discussed previously. Based on that, the temperature range of 150-180°C was selected.

4.2.4 Porosity, density and heat capacity

The porosity of a rock is an important consideration when attempting to evaluate the potential volume of water it may contain. Porosity is a complicated function of many factors, including, but not limited to: type of rock, alteration, rate of burial and depth of burial.

The main geological characteristics of the subsurface rocks have been identified from well cuttings, and have been determined to be basalt, and the porosity is estimated to be in the range of 2-10%. Other rock parameters used are common average values for heat capacity and density for basalt. The density and heat capacity of the water in the reservoir are evaluated from the temperature assumed in the calculations.

4.2.5 Recovery factor

Recovery factor is defined as the ratio between the heat that can be extracted from the geothermal system and the total heat in the geothermal system. The recovery factor is mostly affected by the porosity and the permeability of the reservoir rocks, as well as fluid recharge to the reservoir, both natural recharge and reinjection. It is dependent on the fraction of the reservoir that is considered permeable and on the efficiency by which heat can be extracted from the rock surrounding the permeable channels. The permeability thickness of the deep geothermal reservoir has been estimated to be about 4-8 mDarcy (Elmi Houssein, 2005).

Here the recovery factor, R, is set as 10-25%.

4.2.6 Conversion efficiency

The conversion efficiency describes the conversion of the recoverable thermal energy into electricity. More accurately the conversion can be estimated in two stages, first the conversion of the thermal energy into mechanical energy and later the conversion of the mechanical energy into electrical energy. This is not considered necessary, in view of all the uncertainties involved in the volumetric assessment method, so applying a single thermal-mechanical-electrical efficiency is considered sufficiently accurate to estimate the electrical generation efficiency.

Here a range of 10-14% is assumed, based on Figure 15, after a correction for different cut-off temperatures.

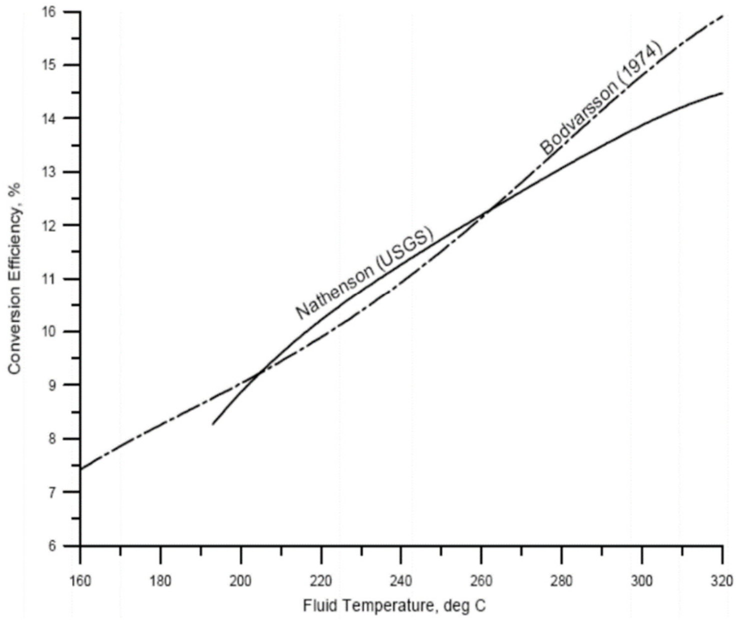


FIGURE 15: Conversion factor versus temperature (Sarmiento et al., 2013).

4.2.7 Economic life and plant factor

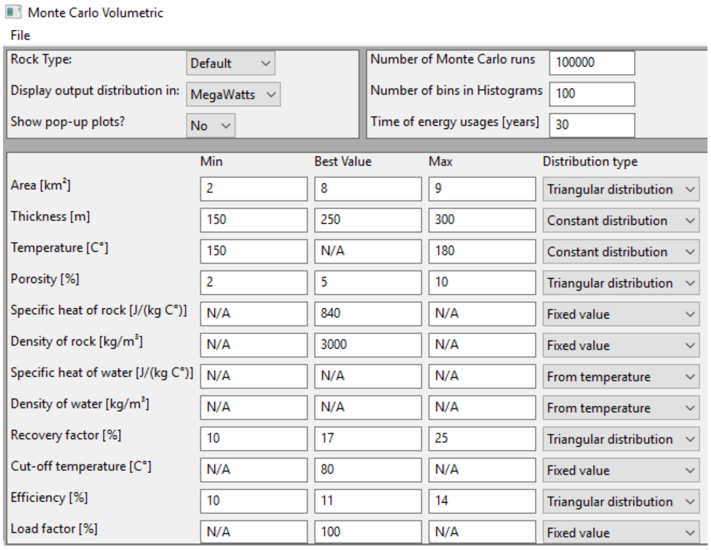
The economic life of the project is the period it takes the whole investment to be recovered within its target internal rate of return. This is usually 25 years, but here 30 years are used.

The plant factor refers to the plant availability throughout the year taking into consideration the period when the plant is scheduled for maintenance, or whether the plant is operated as a base-load or peaking plant. The good performance of many geothermal plants around the world places the availability factor close to 100%, which is used here. It may also be considered that even though a power plant shuts down, the well flow may remain 100%.

4.3 Volumetric calculations for the shallow medium-temperature reservoir

A volumetric resource assessment for the shallow medium-temperature geothermal reservoir in the Asal Rift was carried out using the *Volumetric* software developed at ÍSOR – Iceland GeoSurvey. The software efficiently incorporates Monte Carlo calculations on the basis of probability distributions for the main parameters. Figure 16 shows an input table for the software and lists the parameters, their range (according to the information above) and probability distribution types.

The results of the Monte Carlo volumetric calculations, based on the parameters in the input table, are presented in Figures 17 and 18. Figure 17 shows the probability distribution for the assessment while Figure 18 shows the cumulative distribution. In addition. Table 3 summarizes the results. Finally, Figure 19 presents the sensitivity of the calculated results to the main parameters, showing that the results depend mostly on the recovery factor, thickness and surface area.



Monte Carlo Volumetric

File

Rock Type:	Default	Number of Monte Carlo runs	100000
Display output distribution in:	MegaWatts	Number of bins in Histograms	100
Show pop-up plots?	No	Time of energy usages [years]	30

	Min	Best Value	Max	Distribution type
Area [km²]	2	8	9	Triangular distribution
Thickness [m]	150	250	300	Constant distribution
Temperature [C°]	150	N/A	180	Constant distribution
Porosity [%]	2	5	10	Triangular distribution
Specific heat of rock [J/(kg C°)]	N/A	840	N/A	Fixed value
Density of rock [kg/m³]	N/A	3000	N/A	Fixed value
Specific heat of water [J/(kg C°)]	N/A	N/A	N/A	From temperature
Density of water [kg/m³]	N/A	N/A	N/A	From temperature
Recovery factor [%]	10	17	25	Triangular distribution
Cut-off temperature [C°]	N/A	80	N/A	Fixed value
Efficiency [%]	10	11	14	Triangular distribution
Load factor [%]	N/A	100	N/A	Fixed value

FIGURE 16: Parameters for Monte Carlo volumetric assessment of the shallow intermediate-temperature geothermal reservoir in Asal (input table for software used).

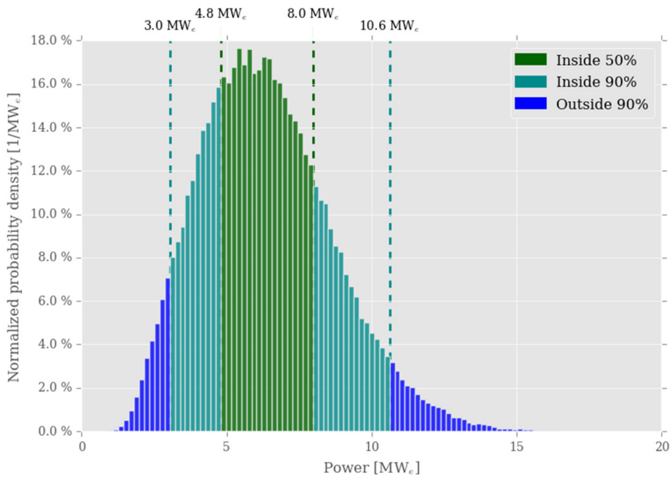


FIGURE 17: Probability distribution (Monte Carlo) of the outcome of the volumetric assessment for the shallow intermediate-temperature Asal geothermal system

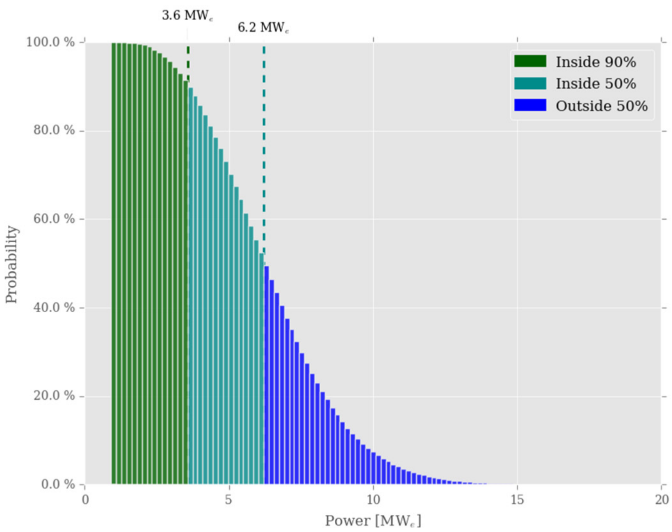


FIGURE 18: Cumulative distribution (Monte Carlo) of the outcome of the volumetric assessment for the shallow intermediate-temperature Asal geothermal system

TABLE 3: Summarized results of the Monte Carlo volumetric assessment presented as cumulative probability thresholds, and other statical parameters

P90%	3.6	MWe
P50%	6.3	MWe
P10%	9.5	MWe
Mean	6.4	MWe
Median	6.2	MWe
Standard deviation	2.3	MWe

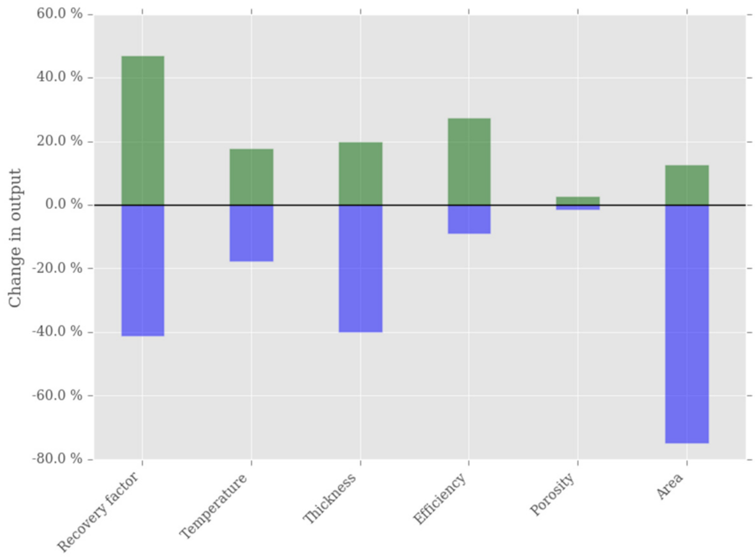


FIGURE 19: Sensitivity of the volumetric assessment results to variations in the main assessment parameters

The results of the volumetric assessment indicate that the electrical generation capacity of the shallow intermediate-geothermal reservoir in Asal is in the range of 3.6–9.5 MWe, based on the P90/P10 range resulting from the Monte Carlo calculations. Therefore, a conservative estimate is of the order of 3-4 MWe. However, it should be kept in mind that this estimate only refers to a small part of the possible geothermal resources in the Asal region. Assessing the possible capacity of deeper, higher-temperature resources would be highly inaccurate, considering the uncertainty in most parameters. Once more, deeper wells have to be drilled so that these deeper resources can be assessed in a similar manner as the shallow resources have been assessed here.

5. CONCLUSIONS

Geothermal exploration and development in the Republic of Djibouti is presently at different stages. The main field studied is the Asal area with six wells drilled in the past, as well as the recently drilled Gale Coma well. The Asal rift zone is the most advanced in terms of exploration, where the existence of deep and intermediate geothermal reservoirs has been demonstrated. The geophysical methods applied can be compared in some way to drilling data, but they reveal that the Asal rift is a very complex structural system and correlations are not systematically evident. More generally, some geophysical methods applied in the past show their limits in investigating geothermal reservoirs at medium and great depths and their interpretation remains sometimes questionable. Here, the high salinity of the fluids is important as it makes the interpretation of the resistivity soundings difficult. Estimated deep reservoir temperatures based on geothermometers range between 220 and 260°C.

In this study, the conceptual model of the Asal geothermal system has been updated. It demonstrates the important potential of the geothermal resources in the Asal region. A Monte Carlo volumetric assessment of the possible electrical power production capacity of the intermediate-temperature reservoir in the area was also performed. The results indicate that the electrical generation capacity of the shallow intermediate geothermal reservoir is in the range of 3.6–9.5 MWe, based on the P90/P10 range. Therefore, a conservative estimate is of the order of 3–4 MWe. However, it should be kept in mind, that this estimate only refers to a small part of the possible geothermal resources in the Asal region. Assessing the possible capacity of the deeper, higher-temperature resources would be quite inaccurate, considering the uncertainty in most parameters. Deeper wells have to be drilled so that these deeper resources can be assessed in a similar manner as the shallow resources have been assessed here. Consequently, extensive exploration and field-wide production tests need to be carried out to accurately estimate the actual size and capacity of the Asal geothermal reservoirs.

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REFERENCES

Aquater, 1989: *Djibouti geothermal exploration project Republic of Djibouti, final report*. Aquater, report, 159 pp.

Árnason, K., Eysteinsson, H., and Vilhjálmsson, A.M. 2008: *The Asal geothermal field, Djibouti. Geophysical surface exploration 2007-2008.* ÍSOR - Iceland GeoSurvey, Reykjavík, report ÍSOR-2008/019, prepared for Reykjavík Energy Invest, 74 pp.

Barberi, F., Ferrara, G., Santacroce, R., and Varet, J., 1975: Structural evolution of the Afar triple junction. *Proceedings of the Conference "Afar Depression of Ethiopia", Bad Bergzarben, F.R. Germany, 1974, 1,* 38-54.

BRGM 1980: *Asal geothermal field, Republic of Djibouti: analysis of available data* (in French). BRGM, report 80SGN525GTH, 42 pp.

CFG, 1993: *The Asal geothermal field, Djibouti. Synthesis of data*. CFG, report 93CFG06 (in French), 87 pp.

Correia, H., Fouillac, C., Gerard, A., and Varet, J., 1985: The Asal geothermal field, Republic of Djibouti. *Geothermal Resource Council, Transactions, 9,* 513-519.

Doubre, C., 2004: *Structure et mecanismes des segments de rift volcano-tectoniques. Etudes de rift anciens (Ecosse, Islande) et d'un rift active (Asal-Ghoubbet).* University of Maine, PhD thesis (in French), 438 pp.

Elmi Houssein, D., 2005: Analysis of geothermal well test data from the Asal Rift area, Republic of Djibouti. Report 6 in: *Geothermal training in Iceland.* UNU-GTP, Iceland, 39-59.

Grant, M.A., Donaldson, I.G., and Bixley, P.F., 1982: *Geothermal reservoir engineering*. Academic Press, New York, 369 pp.

Jalludin, M., 2002: An overview of the geothermal prospections in the Republic of Djibouti. Results and perspectives. *Proceedings of the 2nd KenGen Geothermal Conference, Kenya,* 20 pp.

Jalludin, M., 2013: State of knowledge of the geothermal provinces of the Republic of Djibouti. *Proceedings of the Short Course VIII on Exploration for Geothermal Resources, organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, 17 pp.*

ODDEG, 2016: *Stratigraphy of well GLC-1, Asal.* ODDEG, drilling deptm., Djibouti, unpubl. report.

Sarmiento, Z.F., Steingrímsson, B., and Axelsson, G., 2013: Volumetric resource assessment. *Proceedings of "Short Course V on Conceptual Modelling of Geothermal Systems", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador,* UNU-GTP SC-16, 15 pp.

Stieltjes, L., 1976: Research for a geothermal field in a zone of oceanic spreading: example of the Asal Rift. *Proceedings of the 2nd UN Symposium on the Development and Use of Geothermal Resources, San Francisco, 1,* 613-623.

Stieltjes, L., Joron, J.L., Treuil, M., Varet, J., 1976: Asal rift, dorsal segment emerged, petrological and geochemical discussion (in French). *Bull. Soc. Géol. France* 18-4, 851-862.

Tulinius, H., 2017: *Conceptual models of geothermal systems*. UNU-GTP, unpublished lecture notes.

Varet, J., 2014: Asal-Fialé geothermal field (Djibouti republic): A new interpretation for a geothermal reservoir in an actively spreading rift segment. *Proceedings of the 5th African Rift Geothermal Conference, Arusha, Tanzania*, ?? pp.

Virkir-Orkint 1990: *Djibouti, geothermal scaling and corrosion study***.** Virkir-Orkint, Reykjavík, report, 109 pp.

Zan, L., Gianelli, G., Passerini, P., Troisi, C., and Omar Haga, A., 1990: Geothermal exploration in the Republic of Djibouti: thermal and geological data of the Hanlé and Asal areas. *Geothermics, 19-6,* 561-582.

APPENDIX I: Additional geothermal information on the Asal geothermal area

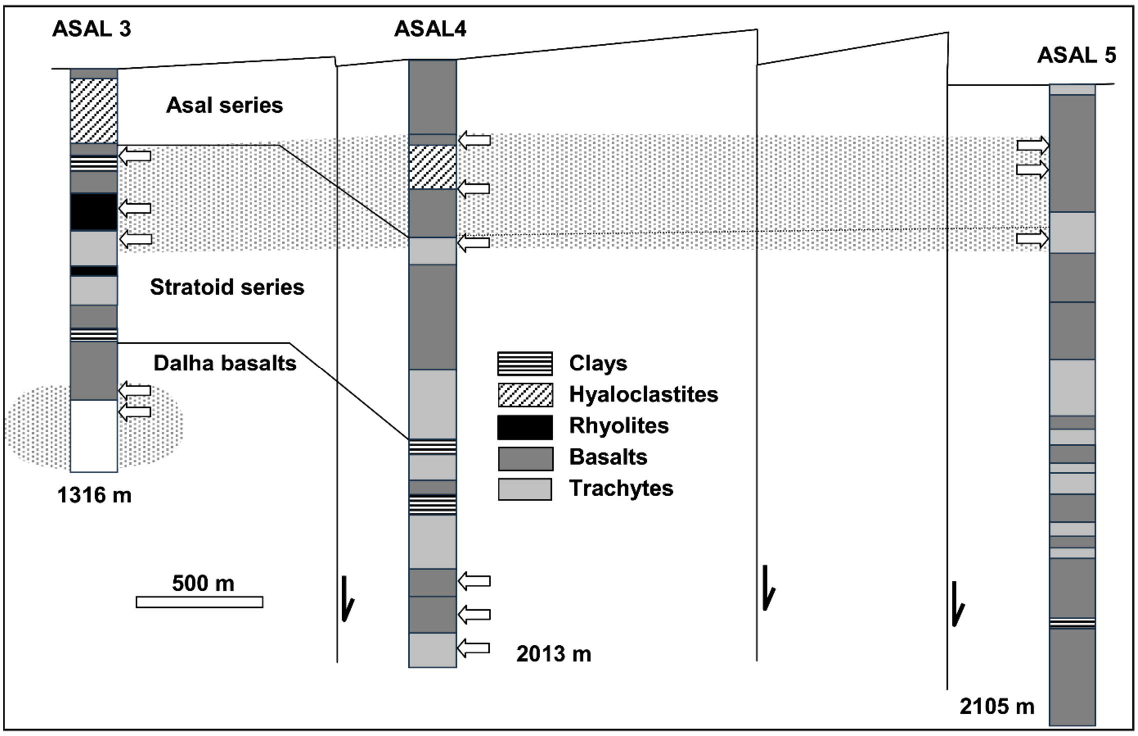

FIGURE 1: Interpreted geological cross-section in the Asal rift zone (Jalludin, 2013)

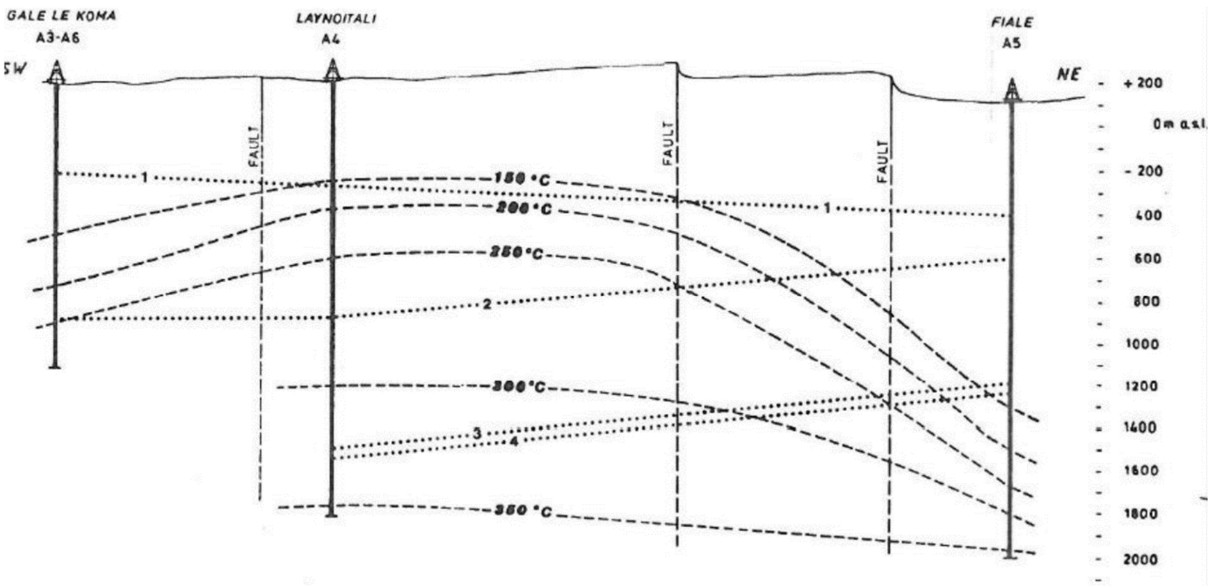

FIGURE 2: Deep exploration – temperature cross-section through the Asal field (Zan et al., 1990)

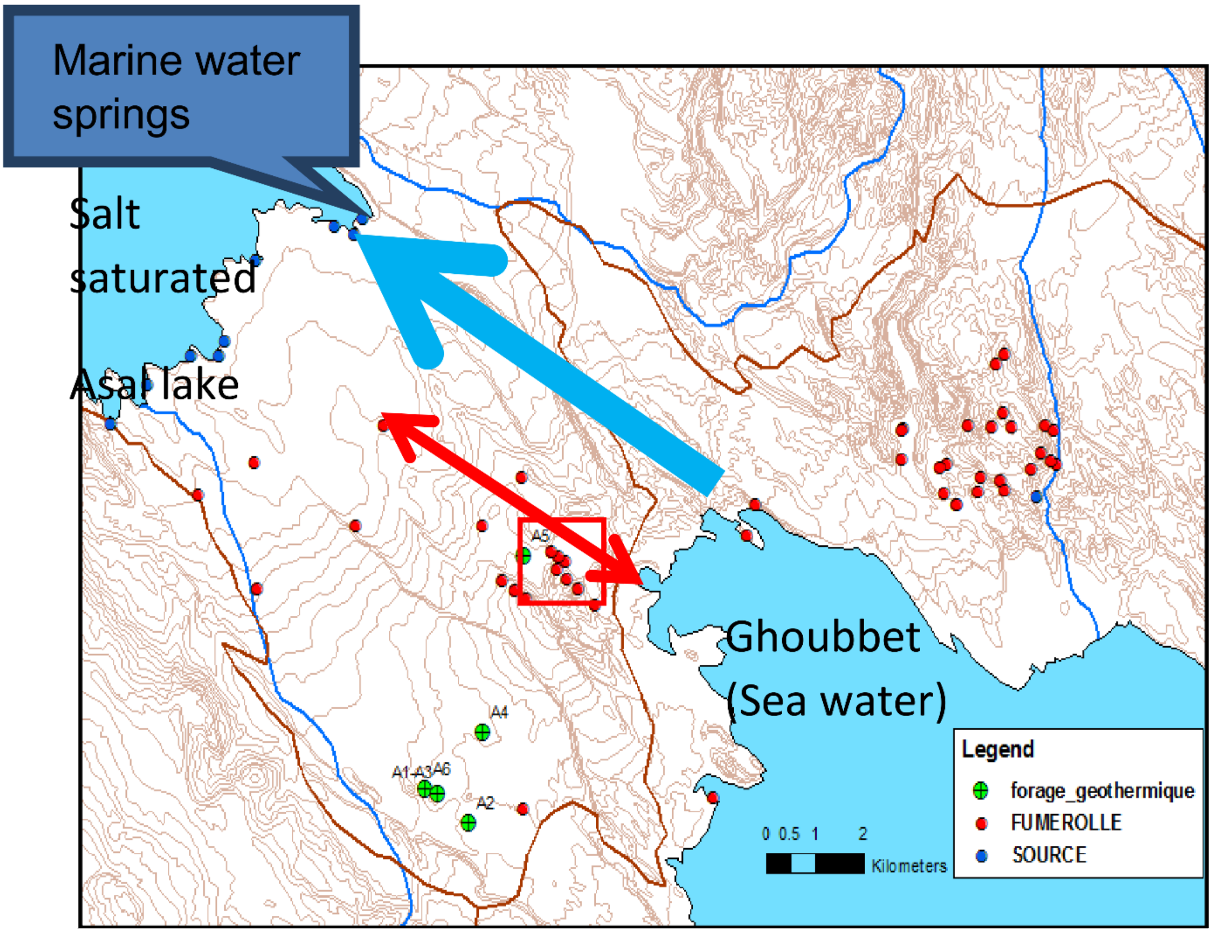

FIGURE 3: Location of the drilled sites (in green, numbered), and main fumaroles in the Asal rift (red dots) on a topographic map, with a recent interpretation of deep fluid flow (Varet, 2014)