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Geological Study in Hanle Geothermal Prospect, Djibouti

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ABSTRACT

The aim of this paper is to give an approach for the geothermal system in Hanle prospect by previous data of 1980s' and recent survey by JICA. Hanle geothermal prospect is located at approximately 110 km west of Djibouti city, away from the urban area. Hanle prospect is a plateau located between the Hanle Plain and the Gaggade Plain, extending NW-SE direction with an altitude of between 300 m and 500 m. This topographic structure is delineated by faults oriented in the NW-SE direction, which is concordant with the direction of spreading axis of the Red Sea - plate boundary between Africa and Arabia. The geodynamic model proposed for the previous study in the area, specified by more recent geophysical considerations, shows that the whole area is dextral rotated. Hot springs and fumaroles are observed in some locations along the major faults limiting the grabens, both in Hanlé and Gaggadé. In early 1980s', three gradient wells at an average of 450m depth (Teweo-1, Garabayyis-1 and Garabayyis-2) were drilled in Hanlé prospect to confirm the geothermal model and the precise temperature at depth before undertaking deep drillings. Measurements gave up to 121,7°C at Garabayyis-1 at 445m and a maximum temperature of 87°C on Garabayyis-2 at 75m. In late 1980s', two deep wells were drilled, named Hanlé-1 (1623m) and Hanlé-2 (2038m) respectively. Hanle-1 recorded a maximum of 72°C at 1420m while only 124°C at 2020m in Hanle-2. 3D visualization of these wells was done in Rockworks 17 to evaluate the permeable zone, correlate the formation and alteration distribution and have an approach of the evolution of the reservoir. In Hanle plateau, basaltic lava of Afar Stratoid Series is distributed as lava flow which can be divided into 3 layers, namely lower, middle and top basalt layer. Aqueous sedimentary tuff is often intercalated in basalt layers. In the northern part, underlying the basalt layer a thick rhyolite lava layer is distributed (Baba Alou Rhyolite). Besides, around the boundary of Hanle plateau and Hanle plain, widespread travertines of unknown age have been confirmed. Among the volcanic rocks in the survey area, altered minerals of zeolite, calcite and quartz are identified by XRD analysis (JICA survey 2014/2015). Geo-thermometer indicates that reservoir temperature may range from 180°C to 260°C (Daher and al WGC 2020). Considering the fact that permeable reservoir could exist along NW-SE fault/fracture system that is located around the fumaroles according to the geophysical investigation. Based on those data, the conceptual geothermal model was created, temperature and volume of the geothermal reservoir were estimated, and drilling target for test well was determined.

1. INTRODUCTION

The geology of the Republic of Djibouti is marked by the meeting between three different plates that created the Afar depression. The convergence of these plates generated a deep chink in the earth's crust called rift, giving escarpments and normal faults along the axes. During this activity, three rifts are created the geodynamic plates in different directions: Red Sea, the Gulf of Aden and the East African Rift. The Gulf of Aden is the divergent to south-east boundary of the Arabian Plate and was formed by oceanic accretion. The direction of the Red Sea aligned NNW-SSE which corresponds to the separation between the plate Arabia and Africa (Figure 1). Finally, the Gulf of Aden have the direction of East-West extends towards the west in the Gulf of Tadjourah. The Aden ridge is torn apart and changes in south-west direction to Asal and across Makarassou to Manda Inakir. Almost all of the Afar depression (Barberi and Varet, 1977) is covered by the stratoid basalts.

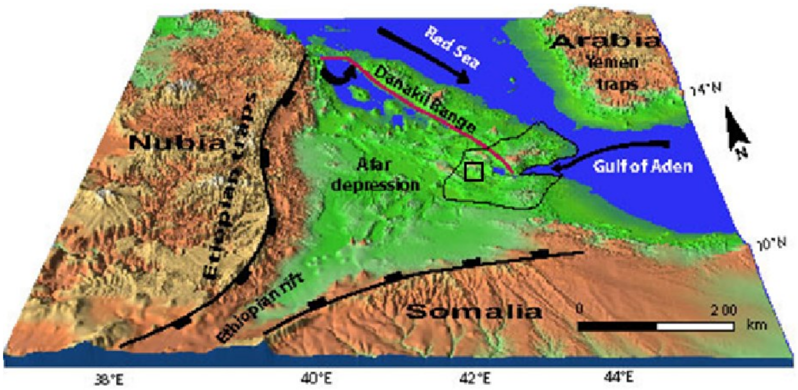


Figure 1: MNT GTOPO 30 of Afar depression.

The Republic of Djibouti is located in the Afar depression (Figure 1), at the junction of the three tectonic plates mentioned above. Djibouti's bedrock is mostly characterized by volcanic rocks from Miocene, Pliocene and Pleistocene. It is in the Ali-Sabieh region (Figure 2) that the oldest geological formations of the Afar Depression appears, These are sedimentary rocks composed of Jurassic limestones and Cretaceous sandstones abut and the same for volcanic rock, the unit of the Ali Sabieh rock are the oldest dated back to Miocene, is a marker of the first movement of Arabo-Nubian block. The Mabla rhyolite, located in the north of the country and the Ali-Sabieh basalt in the south, shaped the Oligocene-Miocene bedrock, the initial stage of Afar rifting is also marked by the emplacement of the Mabla rhyolite (25-9 Ma). Just before the opening of the latter, large trap type basaltic effusions were erupted. These are the basalts of Dalha (8-4 Ma) and Somali (7-3 Ma). Basalt Gulf (3-1 Ma) meanwhile, are associated with the opening of the Gulf of Tadjoura. Lacustrine sedimentary formations, both detrital and evaporitic have developed the sedimentary formations in the graben (Pleistocene to present).

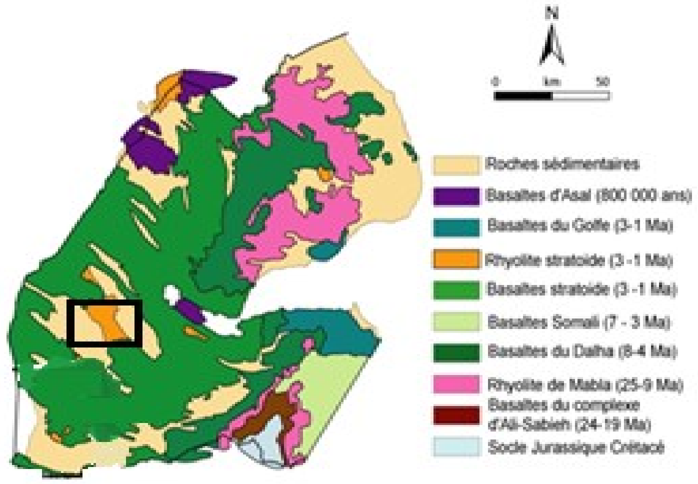


Figure 2: Simplified geological map of the Republic of Djibouti. The square shows the study area.

The Hanle-Garabbayis site is located west of the city of Djibouti about 110 km from the urban area in the Afar Stratoide series distribution zone which is mainly composed of Quaternary Pliocene basaltic rocks. The alluvial and / or marine lake deposits cover the Hanle Plain and the Afar stratatoid series are distributed underground. Several thermal manifestations (fumaroles, hydrothermal alterations, hot soils, etc.) are observed along the NW-SE faults limiting the Baba Alou horst and the Hanle and Gaggade graben, they extend in a transverse direction (NNE-SSW). These are convective hydrothermal features on faults in the absence of a magmatic heat source (age of the most recent volcanic formations: 1Ma).

2. GENERAL DESCRIPTION OF HANLE-GARRABAYYIS GEOTHERMAL FIELD

2.1 Surface Geology

The Hanle-Gaggadé system is located in the southern zone of the Afar Depression which represents the crosspoint of three rift zones: two oceanic (Red Sea and Gulf of Aden) and a continental one (East Africa Rift). According to bibliographie data, the rifting process started during the Lower Miocene with a substantial basaltic activity. The following stage was characterized by the deposition of prevalently acid products (Mabla Rhyolites; 15.3 - 9.6 M.Y.). The third stage consists in the emplacement of mainly basaltic products (Dalha Basalts; 8.5 - 4.5 M.Y.). During the interval 4 - 1 M.Y. the inner part of the Depression was characterized by an intense fissural volcanic activity (Afar Stratoid series). This data confirms that in the Afar Depression the crust is very young. In the upper Pliocene began a configuration dominated by the main rift zone of Asal with a series of depression extending up to Lac Abbé zone.

The two main depressions of Hanlè-Gaggadé represent Half-graben disturbed by the uplift movement of the Ryolite massif Baba'Alou of 5.5 M. Y old and tranversal tectonic. This massif is associated to upward sub-vertical movements which displace the previous faults with an eastward inclination, connected to the formation of the Hanle monocline. In Hanle Plateau, basaltic lava Afar Stratoid Series is distributed as stratiform sediment which can be divided into 3 layers, namely lower basalt layer, middle basalt layer and top basalt layer according to lithofacies situation. Aqueous sedimentary tuff can be found between two basalt layers. In north part of survey area, underlying the basalt layer a thick rhyolite lava layer is distributed. Contrast with it, in Hanle Plain and Gagade Plain, there deposited marine sediments, lake sediments, river sediment and aeolian sediments formed in Pliocene ~ Pleistocene. A great deal of well consecutive faults or fractured system in NW-SE direction has been formed within survey area. Most of the faults are normal fault declining towards NE direction. These faults form fault scarp with altitude difference of about 5~20 m and are consecutively distributed in Hanle Plateau. Most of these faults have induced the displacement of the middle basalt layer in plateau.

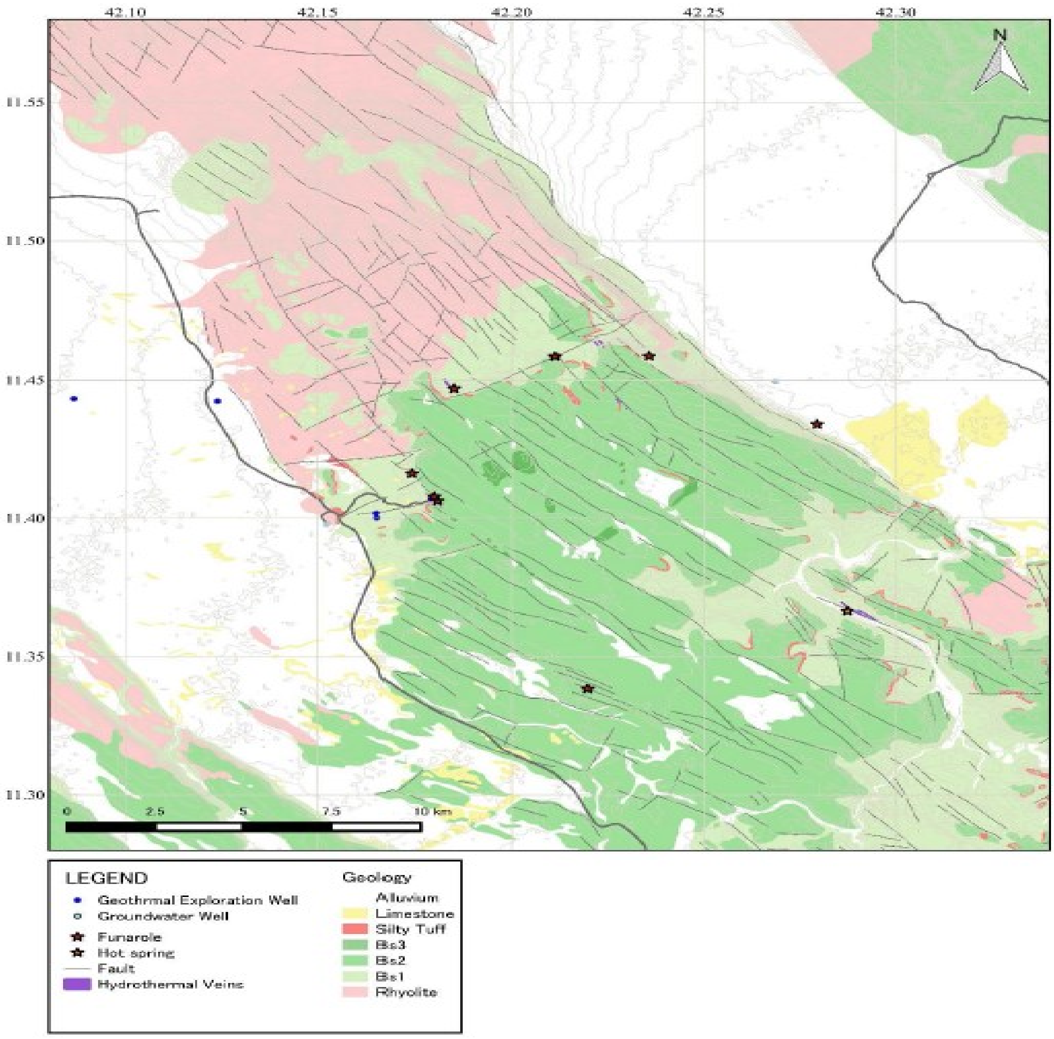


Figure 3: Geological map of Hanle Area (source JICA report 2015).

In survey area, lots of coral limestones with unknown age have also been found located on plateau bevel at altitude of 250 - 280 m, which may indicate the sea level of that time. Besides, around the boundary of Hanle Plateau and Hanle Plain, widespread travertines with unknown age have been confirmed. These travertines can be considered as the fossil remains of hot spring in geological time.

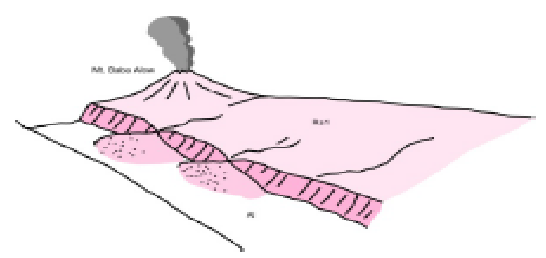
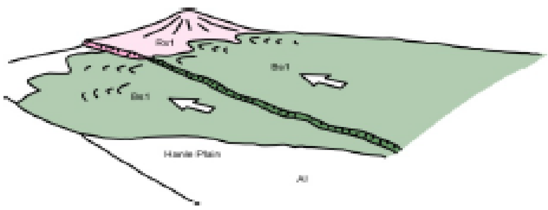
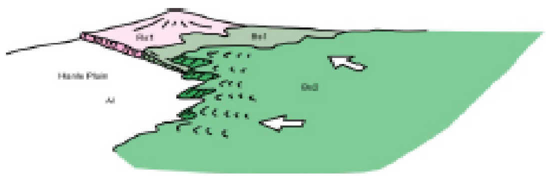
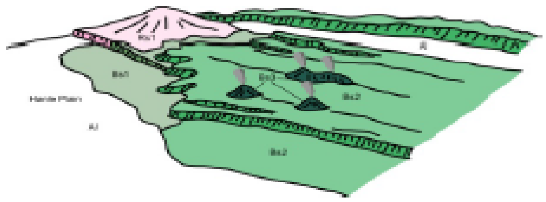
2.2 Tectonic of Hanle

From the tectonic point of view, the region of the hanle represents a graben delimited by two horst. This tectonic style is found in most of the Republic of Djibouti, meeting place of three fracture systems (Gulf of Aden, Rif Valley, and Red Sea). The Hanle region is dominated by the tectonic direction of the Red Sea (NW-SE) and the region is not on the direct extension of the Red Sea ditch but has moved west about 150 meters into the African continent.

North part can be distinctly separated into plateau zone and plain zone by the NW-SE strike and SW declining fault, south part of which is covered by middle basalt layer. This indicates that the middle basalt layer making up of plateau in south side forms terraced landform along NW-SE direction, and is connecting with the lower part of Hanle Plain. Middle basalt layer here inclines with about 5 ° towards SW direction (facing to Hanle Plain). Most of faults in plateau in NW-SE direction incline towards NE direction (facing to Gagade Plain). Through north to south, the area can be separated into Hanle Plateau and Gagade Plain clearly by the fault in NE-SE direction inclining towards NE. Geological formation group of lower and middle basalt layer confirmed in Hanle Plateau has also been found on opposite side of Gagade Plain (ORSTOM, 1988). It thus can be considered that the formation group made up of the lower part of Gagade Plain.

The Hanle depression with two other large depressions parallel to it (those of Lake Abhe about 40 km SW and that of Ghoubbet-Lake Asal about 50 km NE) is precisely on the SE prolongation of the great danakil depression. Hanle Graben is about 50 km long and 20 km wide in NE and in the center and shrinks progressively to the point of losing its characteristic to SE. The graben is filled with alluviums and lacustrine deposits which, moreover, do not have a very large thickness. In the NW part of the Hanle, it seems at first sight, that the plain has been invaded by several lava flows from the formation of recent trappings from the great horst Gamarri that virtually closes the depression of the Hanle NW. The western part of the depression is only slightly affected by recent movements which maintain the fault direction towards the East. The NW-SE tectonic system in this part of the graben is connected to the Dimbir transversal system with transforming features, whose present activity is demonstrated by the alignment of groups of microseisms and fumaroles.

Table 1: Geological structure evolution history in survey area (source: JICA survey team).

Sedimentary period of Baba Alou rhyolite-sandy siltstone layer ・Centering on Baba Alow Mountain, rhyolite was erupted and then deposit. ・In west side of survey area, fracture occurred and graben was formed. ・The fault in northwest side of survey area developed along NW-SE direction accompanying with graben forming	
Active period of lower basalt layer ・Graben in the west side furthermore spread and plain area is formed. ・Accompanying with spreading of graben, the lower basalt layer covered survey area widely.	
Active period of middle basalt layer ・Graben spreading activity stopped, and middle basalt layer began to cover the survey area and faults.	
Active period of top basalt layer ・Fracture occurred in east side of survey area, graben was formed. ・The fault in NW-SE direction in northwest side of survey area spread fast accompanying with graben forming ・Fault of top basalt layer was formed in NW-SE direction. Along the fault, top basalt layer intruded and erupted.	

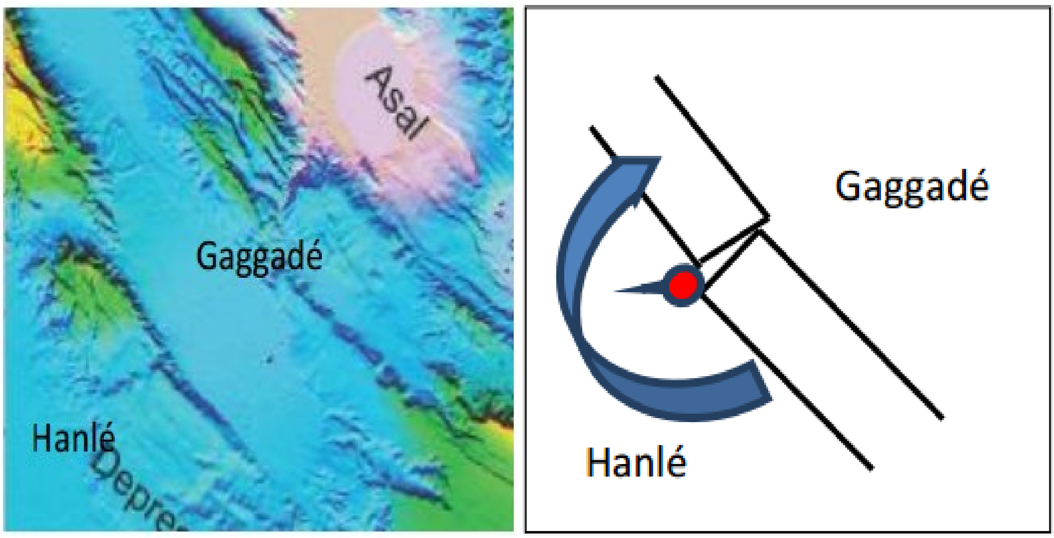


Figure 4: The schematic interpretation we propose for the presently active Garabbayis fumaroles (in red) along transverse faults opening affecting the horst between Hanle and Gaggadé plains. This fracture results from the whole rotation of the area located between the two major spreading segments of Asal-Ghoubbet and Manda-Harraro-Dama'Ale (Magnetti et al, 2017).

The occurrence of such faults was already observed from previous studies. In their small-scale plate tectonics interpretation of the Afar region, Barberi&Varet (1977) inferred the presence of a transform fault system linking the Northern Asal Rift with the Manda-

Hararo/Dama Ale rift. In a more recent approach, Manighetti et al. (2007) confirmed the idea, already developed by these authors 30 years earlier, of the rotation of the block located between the two spreading segment (Figure 5).

3. INTERPRETATION OF EXISTING DATA

3.1 Previous Work

The Hanle Plain was considered as a potential geothermal site, and an intensive exploration program was thus developed from 1981 to 1987, led by Italian experts and enterprises under bilateral assistance with the support of the World Bank. Through these surveys, fluid flow system has been clarified by geological/geochemical survey (Aquater, 1981), and the shallow subsurface structure has also been made clear by electrical exploration (Aquater, 1982). Based that, led to the implementation of 3 geothermal gradient drillings at depths of 450m (Teweo1, Garabayyis 1 and Garabayyis 2) for obtaining geological information and subsurface temperature distribution (Aquater, 1987; Geotermica, 1985). Based on the drilling wells results, two deep wells were drilled for further investigation (Aquater, 1987 and 1989) respectively at 1620 and 2038 meters.

The location of these existing wells is shown in Figure 6 and Temperature distribution inside drilling well is shown in Figure 7.

In the Hanle Plain, the presence of geothermal fluid that can be used for the development of geothermal energy is practically low. for this, some fumaroles located in the plateau northeast of the Hanle Plain and that the results of geochemical studies carried out by JICA (2014) indicate that a geothermal reservoir that can reach a temperature of 250 ° C can exist, it is possible that the geothermal system exist in the region of the lava plateau. Based on this hypothesis, an MT / TEM study was conducted by JICA (2015) to construct a geothermal conceptual model.

3.2 Geological Investigation

The weIls encountered deposits which can be ascribed to the Afar Stratoid Sequence although the older Dalha BasaIt could have been encountered in the lower part of the hole. ln order to clarify this problem, radiometric age determinations on core samples have been scheduled. The main rock type is basaIt; in the upper part some other lithologies are encountered such as trachyts,rhyolites, rhyolitic tuffs and sedimentary levels. Below 300 m, the sequence becomes very monotonous, consisting of basaltic, olivin-basaltic and ferro-basaltic lava flows, intercalated with scoriaceous interflow levels. The hot aquifer (85°C) at 140-160 m can be correlated with the aquifer encountered at 140-160 m in Garabbayis 2 and at 85 m in Garabbayis 1. Other indices of permeability or water circulation in the formation exist down to about 1000 m. The formation is nearly impervious below 1000 m; apart from a possible minor water entry at arcund 1590 m. The water level in the well was quite constante, around 75-76 m while drilling in the upper aquifers. The features that can be deduced from the geological data are as follows:

- ✓ In the exploration well, basalt layer has thick distribution.
- ✓ In Teweo-1 and Hanle-1, the rhyolite layer appeared between the basalt layers. Distribution depth is as follows: Teweo-1: 257-278 m, Hanle-1: 98-220 m, 230-310 m, 610-680 m.
- ✓ Alluvium was confirmed in the surface portion of Teweo-1, Hanle-1, and Hanle-2.
- ✓ Mudstone layer was confirmed on Teweo-1 at the depth of 65 m-257 m. The geological column of each exploration well is attached.

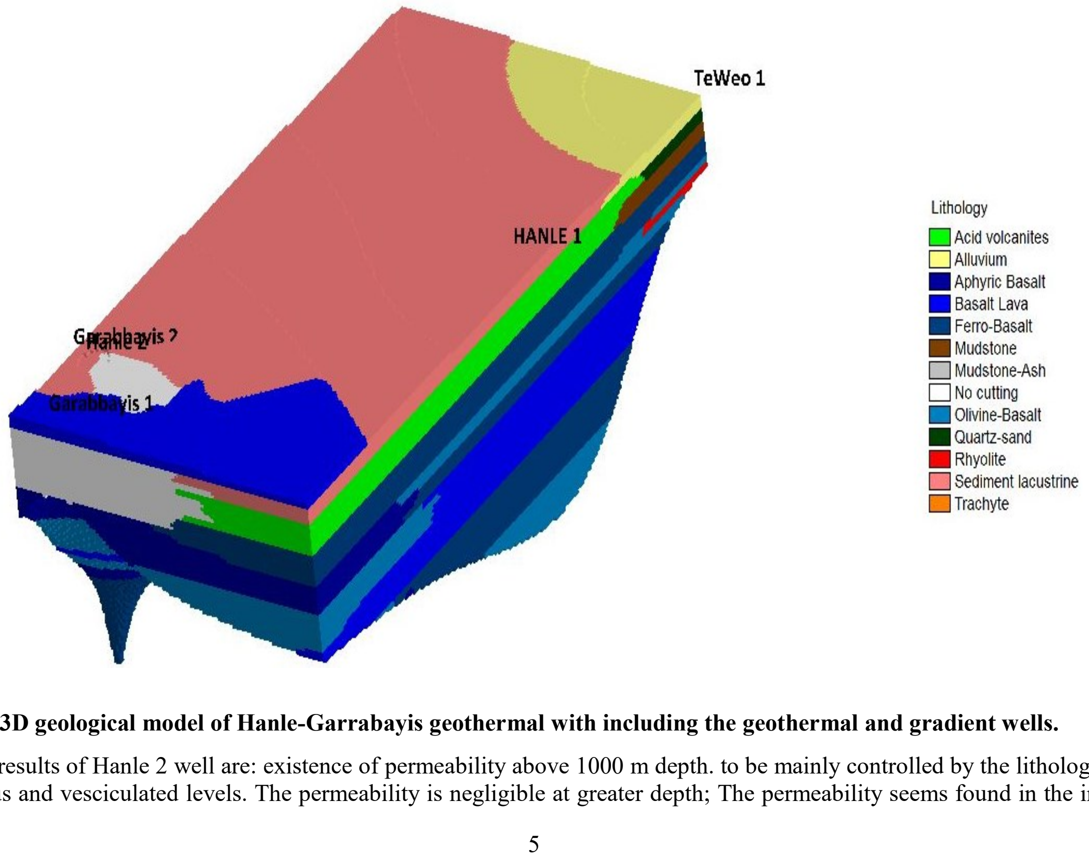


Figure 5: 3D geological model of Hanle-Garrabayis geothermal with including the geothermal and gradient wells.

The main results of Hanle 2 well are: existence of permeability above 1000 m depth. to be mainly controlled by the lithology, being scoriaceous and vesciculated levels. The permeability is negligible at greater depth; The permeability seems found in the interflow

low temperature even at depth (maximum 123°C at 2020 m) and low temperature gradient (25°C/km) in the nearly impermeable section of the hole. The hydrothermal paragenesis study confirms that, even in the past, this area was not interested by circulation of high temperature fluids. Based on these results, the drilling was stopped at 2038 m, according to the program.

3.3 Temperature

The gradient wells drilled in Hanle area (Teweo 1, Garabbayis 1 and Garabbayis 2) at an average of 450m depth were drilled to confirm the geothermal model and the precise temperature at depth before undertaking deep drillings (GEOTHERMICA 1985; GENZL 1985)., Measurements gave up to 121,7°C at Garabayyis 1 and a maximum temperature of 87°C on Garabayyis 2. Two deep wells drilled in the plain reached 1623 and 2038m respectively (Hanlé 1 and Hanlé 2, AQUATER 1989). Hanlé 1 recorded a maximum of 72°C at 1420m (lower than normal gradient in continental environment). Hanlé 1 well showed that the strong effects of convective heat transport decrease or disappear at depths exceeding 700-900 m. However, the temperatures revealed significantly by Hanlé 1 well down to about 1500 m were far below those required for industrial exploitation. The weil Hanlé 2 *was* placed in Garabbayis area, between the two former gradient wells one of which (Garabbayis 1) gave promising results (more than 120°C at 450 m depth). The planned depth of Hanlé 2, about 2000 m was such that possible high temperatures at economically accessible depth below the zone disturbed by water circulation could be revealed. Furthermore, because of the short distance from the longitudinal fault feeding the Garabbayis fumaroles, the well could reveal how wide is the temperature anomaly observed in Garabbayis 1 produced by the hot fluid rising up that fault. A maximum temperature of only 124°C was reached at the very bottom of Hanlé 2, 2020m deep. Highly permeable levels were observed down to 450m (with fluid TDS 2 g/l) and the rest of the well remains impervious with a dominantly basaltic lithological sequence from the stratoid series (AQUATER 1989; Jalludin, 2003).

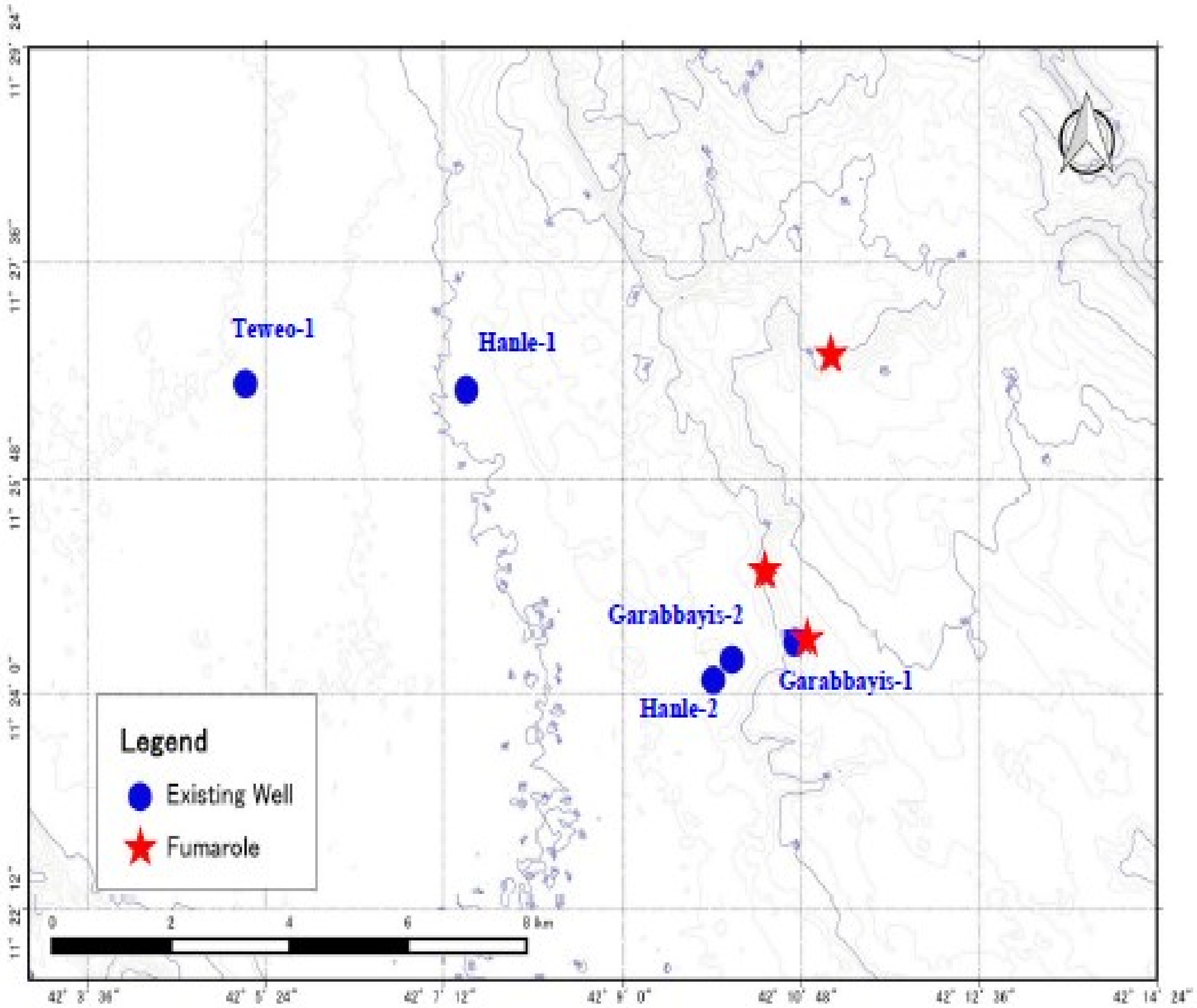


Figure 6: Location Map of previous wells (source JICA 2015).

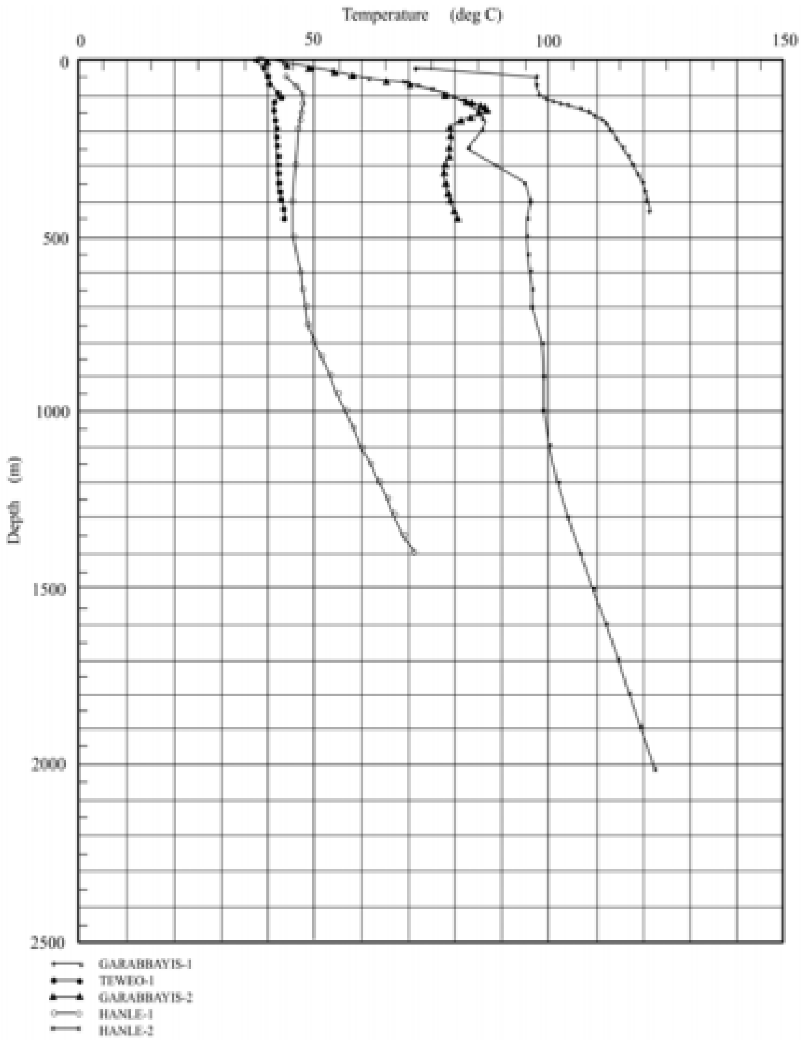


Figure 7: Temperature Distribution of existing wells.

The temperatures recorded in Hanle 2 well are systematically higher than in Hanlé 1 well this fact can be attributed to different causes:

- ✓ The well is closer than Hanle 1 to a hot zone (e.g. the fault along which are located the Garabbayis fumaroles.
- ✓ The reservoir volume around this well is less affected by the cooling resulting from groundwater circulation.
- ✓ The temperature profiles of the well show as all the other wells in the area, local maxima with temperature inversions at shallow depths, which are due to the thermal effects of groundwater circulation. In the low permeability section of the hole the temperature increases linearly with depth. The gradient is 25°C/km and the maximum measured temperature is 124°C at 2020 m. Based on these data, even the zone explored by this well presents scarce prospects of industrial exploitation.

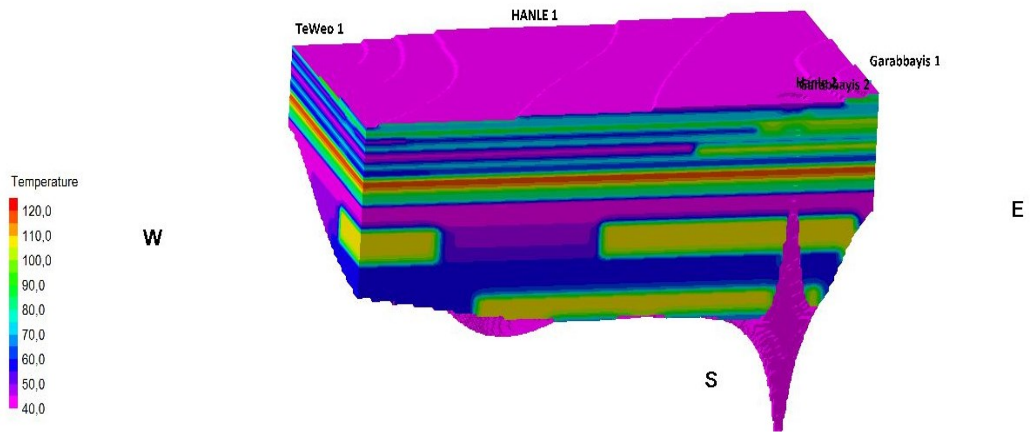


Figure 8: 3D temperature distribution in Hanle geothermal field.

The permeable intervals encountered in the upper part of the well, at 140-160 m at 250-270 m and around 400 m emplaced in interflow levels or in alluvial beds. The hot aquifer (85°C) at 140-160 m can be correlated with the aquifer encountered at 140-160 m in Garabbayis 2 and at 85 m in Garabbayis 1. Other indices of permeability or water circulation in the formation exist down to about 1000 m. The formation is nearly impervious below 1000 m; apart from a possible minor water entry at around 1590 m. The water level in the well was quite constant, around 75-76 m while drilling in the upper aquifers. The intensity of alteration is variable and is in close relationship with permeability. The interflow scoriaceous level, that are more permeable, are always much altered over the sequence, while the lava flow itself tends to be fresher. This is only a general statement, because from about 770 to 1000 m and from about 1400 m to hole bottom also the groundmass the basalts is very (sometimes wholly) altered.

3.4 Alteration Hydrothermal

Among the volcanic rocks in survey area, altered minerals of zeolite, calcite and quartz have been confirmed, which show different combination and occurrence in different stratigraphy. Through the field survey, the presence of widespread calcite hydrothermal dike and accompanying altered minerals have been confirmed.

The alteration minerals occurrence depth in each exploration well is shown in Figure 9. Documentation indicating the alteration mineral occurrence for Garabbayis-1 was not available. As a feature of the whole alteration minerals, low-grade alteration is observed characterized by occurrence of zeolites. The following issues are presumed by the combination of alteration mineral occurrence:

- The transition zone between heulandite (He) – laumontite (Lm) is located at GL-1400m in Hanle-1, GL-1000m at Hanle-2, presumed that the zone was approximately 140 degrees of alteration environment.
- Smectite is disappeared and chlorite is commonly observed at the depth of 1400m in hanle-2, presumed that the alteration environment is 180 to 200 degrees.
- Epidote (EP) and Hematite (Hm) is observed at the limited depth of 200m and 300m. The appearance temperature of those minerals are approximately 200 degrees, therefore those minerals are originated by vein-let hydrothermal alteration.
- Pyrite is intermittently observed at the depth from GL-1000m to 1900m, indicates hydrothermal alteration caused by acidic fluid.
- Occurrence of zeolite and chlorite is described, but the detail is not identified in Garabbayis-2 and Teweo-1, indicates that the data may not be reliable. Combination of alteration minerals deeper than the depth of GL-1500m may indicate more than 200 degrees of alteration environment.

Three hydrothermal zones were defined, on the basis of Secondary mineralogy. Argillitic zone, from the surface to 250 m; Transition argillitic/phyllitic zone from 250 to 1450 m; phyllitic zone from 1450 to 2038 m. The temperature obtained from the literature for a phyllitic zone (about 140-180 °C) is not in agreement with the maximum downhole temperature (about 123°C at b.h.), that the paragenesis does not seem to be in equilibrium.

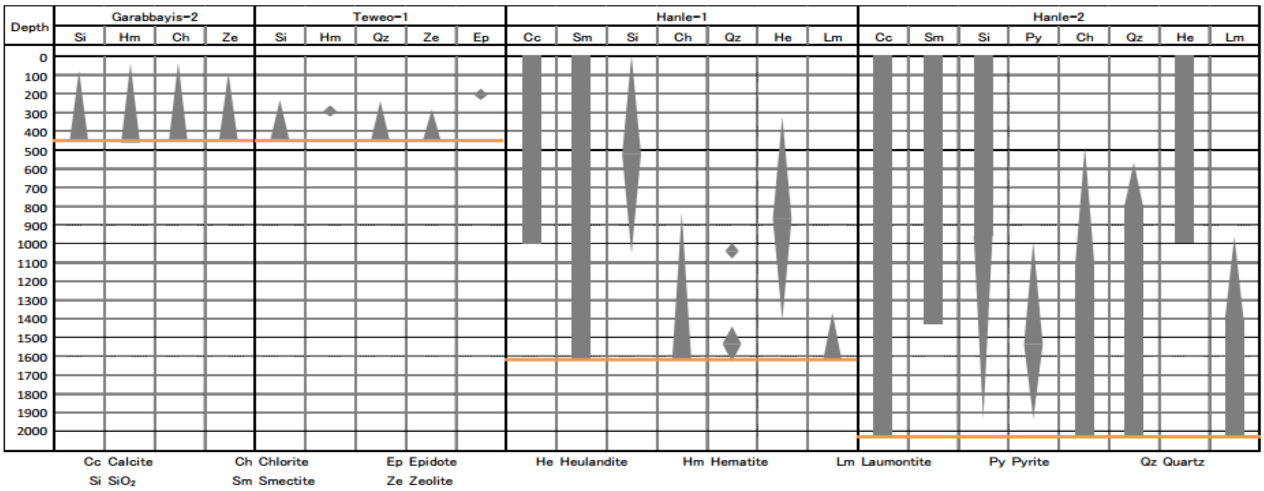


Figure 9: Distribution of hydrothermal minerals (source JICA report 2015," for data collection survey for geothermal development in the republic of Djibouti "geophysical survey")

4. RESULTS AND DISCUSSION OF JICA SURVEY IN HANLE-GARABBAYIS AREA

4.1 Conceptual Model

The geothermal reservoir conceptual model was constructed. Here, three rational models were proposed. The general information of each model is shown in Table 2, and the map of each model along the B-B′ cross section line can be found in Figure 10 and Figure 11.

Table 2: Conceptual Model of Geothermal Reservoirs.

		Model 1
Reservoir Situation		Strong convection of geothermal fluid is induced by heat source, and reservoir is widely spread under the lava plateau.
Reservoir	Distribution	Under the area where the middle basalt layer is distributed.
	Permeability	High
	Temperature	Maximum 260℃
Fluid	Origin	Recharged by groundwater from the Hanle and Gagade plain areas. Source could be derived from Ethiopian side (mountain side)
	Upflow Zone	Upflow is generated above the heat source in the center of the lava plateau, and then fluid flows to the side, and reaches up to the surface along faults.
Heat Source		Intrusive basalt rock distributed at or under a depth of 3 km (a part of the basalt rose up along the faults and formed Bs3 after reaching the surface)
		Model 2
Reservoir Situation		It was not long since heat source intruded, thus reservoir locally formed only along the faults.
Reservoir	Distribution	Around faults (close to fumarole area) in the middle basalt layer area
	Permeability	Significantly low
	Temperature	Maximum 260℃
Fluid	Origin	Recharged by groundwater from the Hanle and Gagade plain areas. Source could be derived from Ethiopian side (mountain side)
	Upflow Zone	Upflowing along the faults above the heat source.
Heat Source		Intrusive basalt rock distributed at or under a depth of 3 km (a part of the basalt rose up along the faults and formed Bs3 after reaching the surface)
		Model 3
Reservoir Situation		It was not long since heat source intruded, thus reservoir locally formed only along the faults.
Reservoir	Distribution	Around all faults in the middle basalt layer area
	Permeability	Low
	Temperature	Maximum 260℃
Fluid	Origin	Recharged by groundwater from the Hanle and Gagade plain areas. Source could be derived from Ethiopian side (mountain side)
	Upflow Zone	Upflowing along the faults above the heat source.

✓ Reservoir Structure

Based on the fact that fumaroles are distributed along the surface boundary between the middle basalt layer and lower basalt layer, the middle basalt layer may play a role in cutting off the pathway of rising fumarolic gas like a cap rock. Hanle-Garabbayis geothermal field is dominated by faults in the NW-SE direction. Since fumaroles are located on the extension line of the fault, these faults are thought to be the pathway of geothermal fluid. Reservoir should be fractured faults themselves or together with permeable layers in the lower basalt, with capping structure made up of upper basalt. The reservoir could be 260 °C according to the geochemical survey that the Survey Team conducted.

✓ Heat Source

Heat source should be a body that shows high resistivity and is considered to be an intrusion body. The heat source could be rather expanded to the south than estimation in JICA 2014 and JICA 2015, according to distribution of high resistivity. The heat source and geothermal reservoir exist underneath the northwest plateau.

✓ Fluid

Geothermal fluid should be recharged from the Hanle Plain where groundwater level is higher than in the plateau. Source of fluid could be derived from Ethiopian side (mountain side).

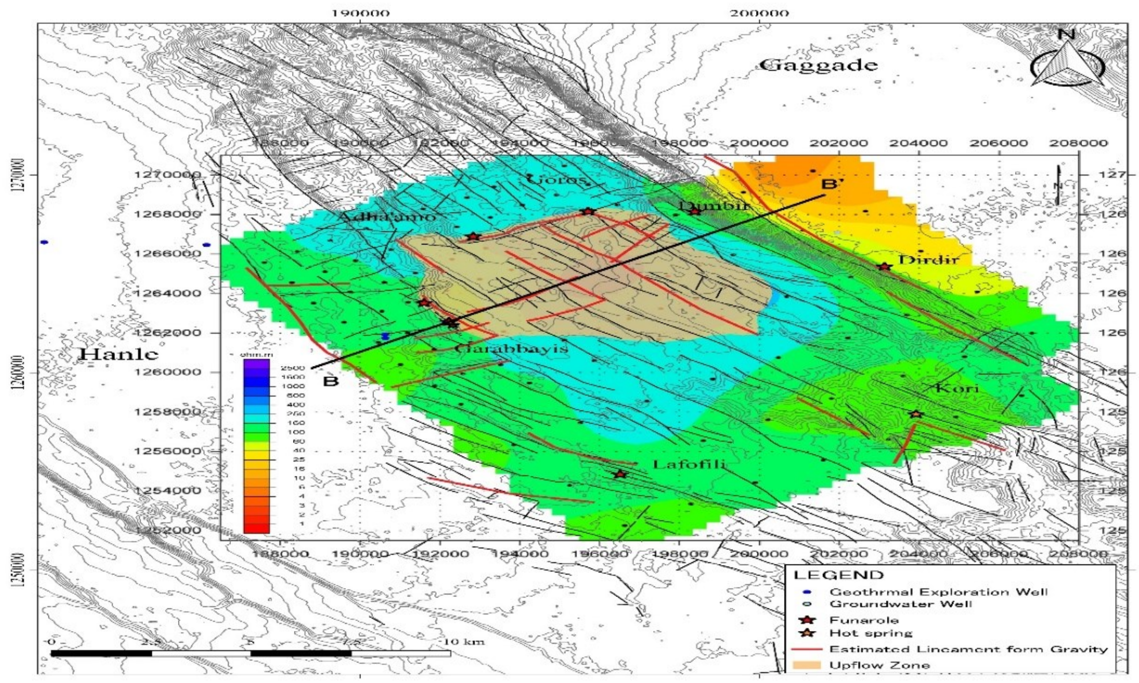


Figure 10: Resistivity Plain Map (-1,500m.a.s.l).

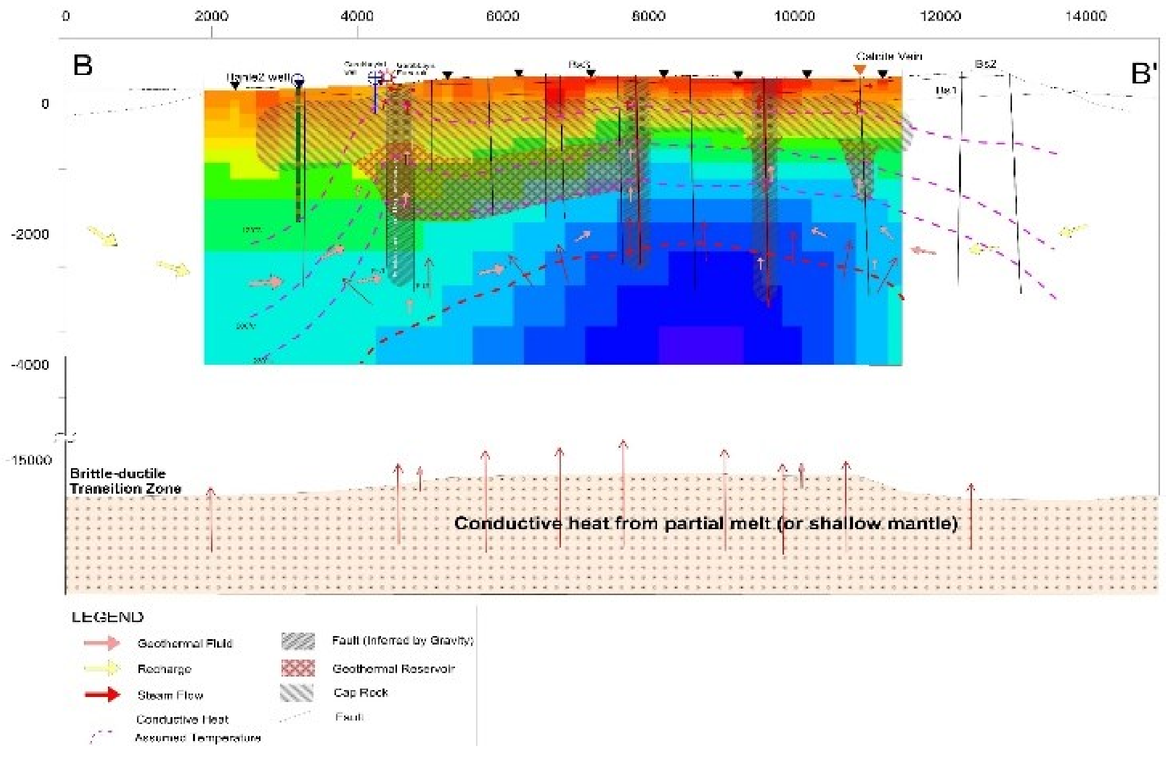


Figure 11: Geothermal Reservoir Models 1.

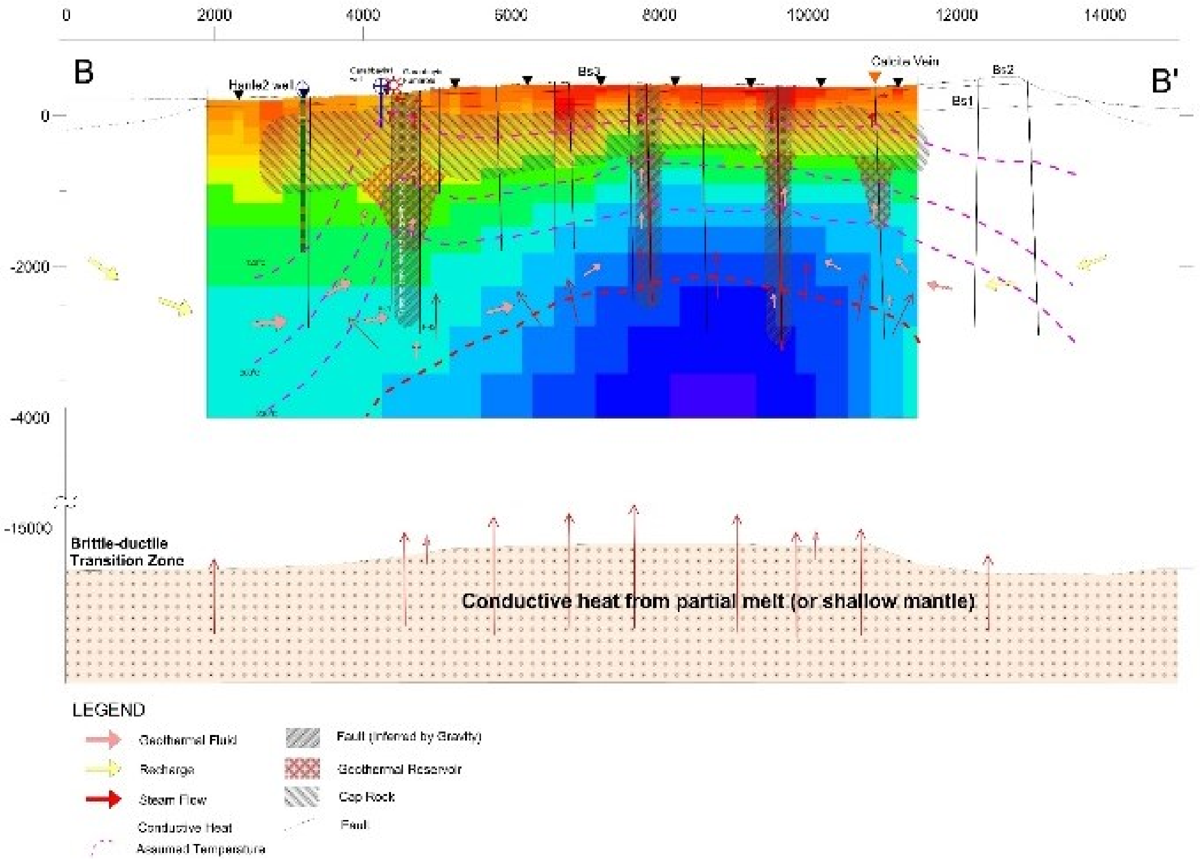


Figure 12: Geothermal Reservoir Models 2.

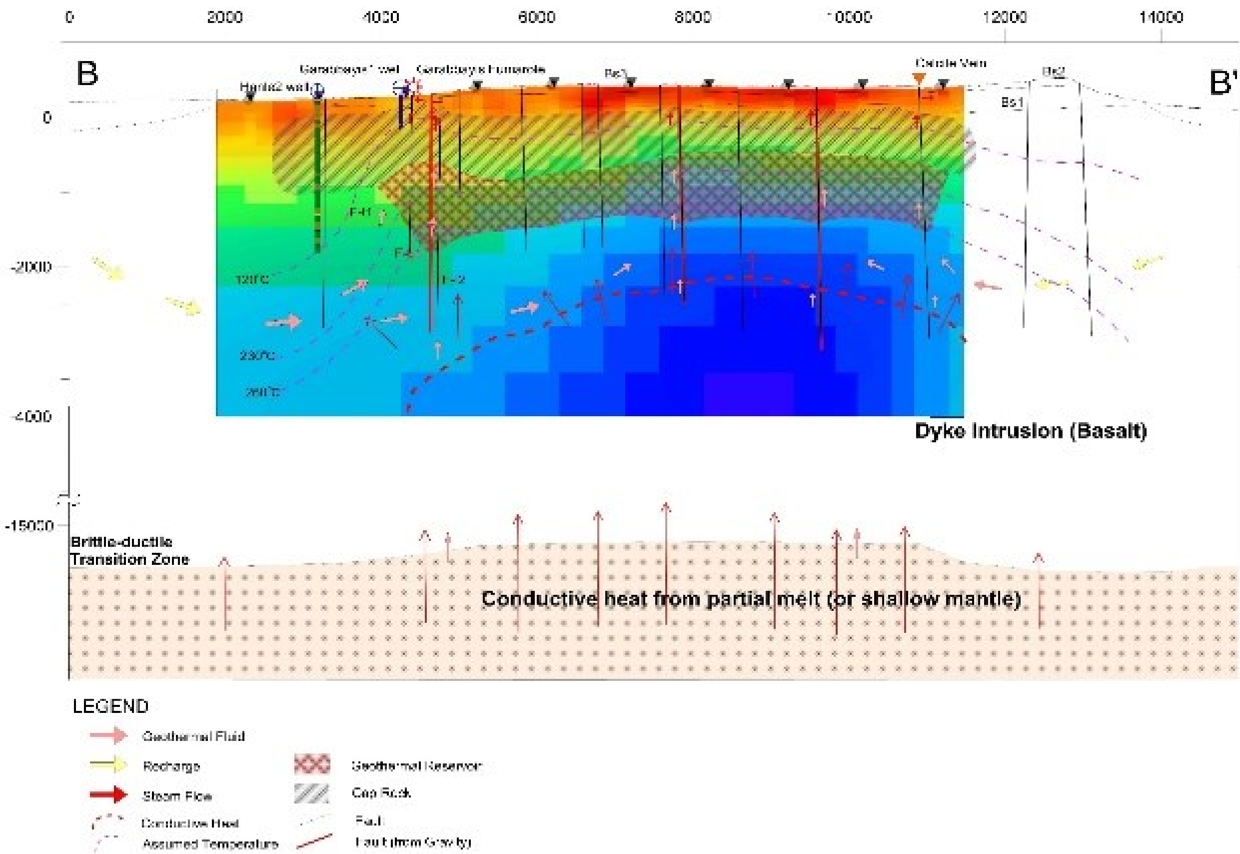


Figure 13: Geothermal Reservoir Models 3.

4.2 Drilling target

Taking into account surface manifestation, geothermal conceptual model and accessibility, five places were selected as candidate drilling target at present. The biggest surface manifestation in Hanle region is in Zone A (Garabbayis fumarole), and the fumarolic gas contains the mantle origin components. The fault systems in NW-SE and NE-SW direction which is clear target for drilling is estimated from topographic survey and gravity survey. About the workability, there are an available access roads and drilling pad for Garabbayis-1 well in Zone A. For these reason, Zone A, Garabbayis area was selected as the first prospective of drilling target in Hanle region. Zone C, Goros area was selected as the second prospective.

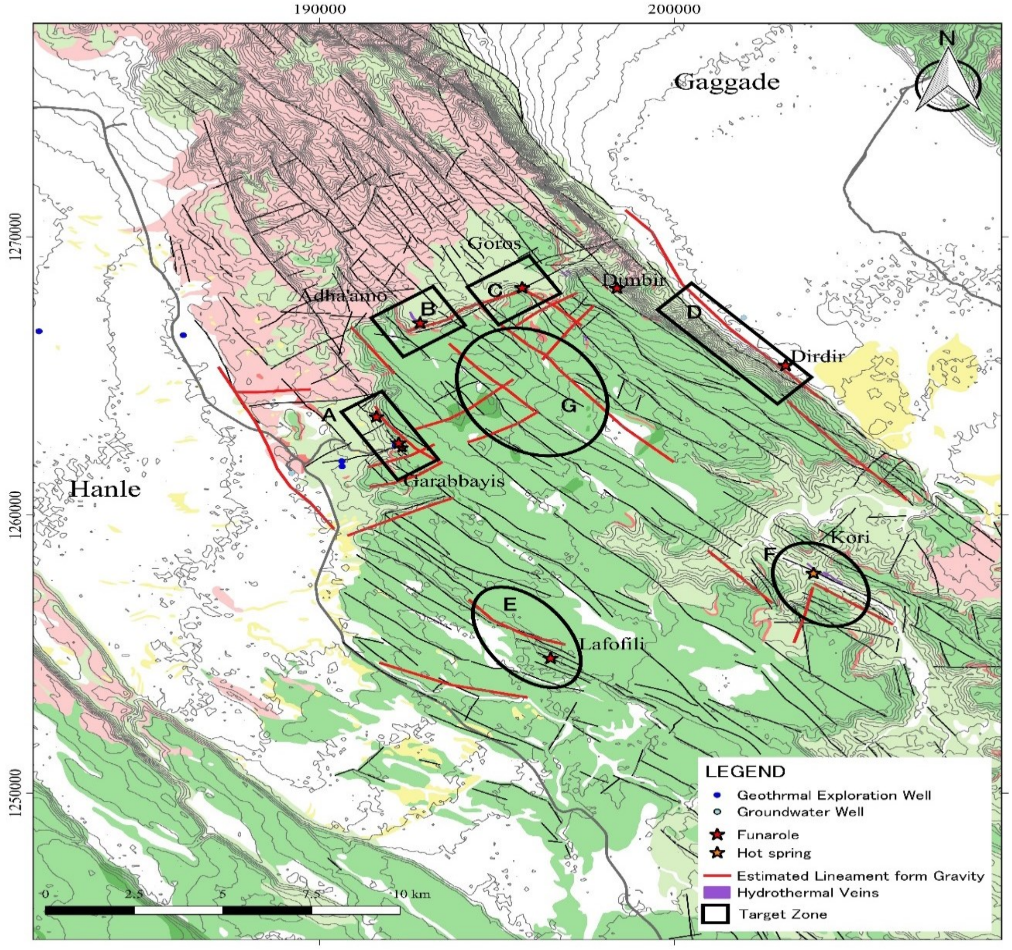


Figure 14: Location of Candidate Drilling Target.

- ✓ Zone A: located at Southwest of Garabbayis fumarole, near the drilling site of existing Garabbayis-1 well. The Fumarolic gas (99.7 °C) volume is large, containing much mantle-originated component and controlled by the faults in NW-SE and NE-SW direction were confirmed by topographic and gravity survey. There is an existing road that can be used as access but needs to be widened.
- ✓ Zone B: Exposed area of the lower basalt layer in the north of Goros fumaroles, the fumerolic gas (102.1 °C) volume is large, containing much mantle-originated component and controlled by the faults in NW-SE and NE-SW direction were confirmed by topographic and gravity survey. The accessibility is detour road along the stream in the north, or new pavement above the lava plateau.
- ✓ Zone C: Exposed area of the lower basalt layer in the north of Adha' amo fumaroles, Fumarolic gas (98.5 °C) volume is less than that in A and B Zone. The faults in NW-SE and NE-SW direction controlled the system and confirmed by topographic and gravity survey, Detour road along the stream in the north, or new pavement above the lava plateau
- ✓ Zone D: Inside Gagade Plain in the northeast of Dirdir fumaroles, Fumarolic gas (113.8 °C) volume is small but mantle-originated component was confirmed. Controlled by the faults in NW-SE direction were confirmed by topographic and gravity survey. There is an existing detour road near Yoboki Town in the north but needs to be widened.
- ✓ Zone E: Located in lafofili fumaroles. Fumarolic gas (108.8 °C) volume in Lafofili is small. The faults in NW-SE direction were confirmed by topographic and gravity survey controlled the system. There is an existing road extending from Garabous Town in the south, but new pavement and widening is needed.
- ✓ Zone F: Kori hot spring, Hot spring (48.0 °C) flow in Kori is small. Hydrothermal alteration vein is elongated in NW-SE direction, the faults in NW-SE and NE-SW direction were confirmed by topographic and gravity survey were controlled the system. There is an existing road extending from Garabous Town in the south, but new pavement and widening is needed.
- ✓ Zone G: Located at the central area of lava plateau, Surface manifestation (fumarole and/or hot spring) were not confirmed, the faults in NW-SE and NE-SW direction were confirmed by topographic and gravity survey, There is an existing road extending from Garabbayis, but new pavement and widening is needed.

5. CONCLUSION

Based on the fact that fumaroles are distributed along the surface boundary between the middle basalt layer and lower basalt layer, the middle basalt layer may play a role in cutting off the pathway of rising fumarolic gas like a cap rock. The survey area is dominated by faults in the NW-SE direction. Since fumaroles are located on the extension line of the fault, these faults are thought to be the pathway of geothermal fluid.

High-resistivity zone was found at the center of the distribution of surface manifestations in deep area of the lava plateau. This zone is perhaps the high-temperature zone generated by intrusive basalt rock body. Temperature contour map of 500 m underground drawn based on five existing wells indicates the tendency of temperature to increase from the plain area to the lava plateau (Figure 4-1-1). All the fumaroles were found in the lava plateau, which indicates that heat source may be located beneath the plateau.

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