

SUB-SURFACE GEOLOGY OF HYDROTHERMAL ALTERATION AND 3D GEOLOGICAL MODEL OF THE WELLS, GLC-1, ASAL 3, 4 and 5 IN ASAL-RIFT GEOTHERMAL FIELD, DJIBOUTI.

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ABSTRACT

The Asal-rift geothermal field is the most active structure which is the westward prolongation of the Gulf of Aden. Almost all the region is covered by volcanic rocks and thermal manifestations with same sediment deposit. All the fault system is oriented NW-SE. Six deep wells were drilled between 1975-88 and one shallow well (Glc1) was drilled in 2016. The maximum depth for all the wells is 2105m with a maximum temperature of 359°C. This study is mainly focused on sub-surface description of hydrothermal alteration of wells Asal 3, 4, 5 and Glc 1. The wells were drilled directionally on the top of Asal-rift. The lithology unit encountered succeed from youngest to oldest; 1) Asal series less 1Ma consisting of porphyritic basalt and hyaloclastite; 2) Pleistocene sediment 3) Afar stratoid, mainly consisting of rhyolite in the upper part ranging between 4 to 1Ma; 4) Pliocene clays 5) Dalha basalt series, this unit consists of a sequence of lava flows, with intercalation of trachytes and detritic deposits are estimated to be formed between 8.9-3.8Ma. The hydrothermal alteration identified in the well Asal-5: unaltered zone, a smectite zone in the lower zone, mixed layer clay, Chlorite zone, Chlorite-Epidote zone and deeper zone referred to as chlorite-Actinolite zone to the bottom. This study integrated 3D geological modelling to understand the regional geology and its structural evolution. The production zones in well Asal 3 are located within Dalha serie at 1075m, Glc 1 well have intermediate reservoir is occurring between 511 and 680m within Stratoid serie. Asal 4 and 5 were unproductive wells. The two wells produce a level of clay from the same zone located immediately below in which the permeability is mainly related to stratigraphic Dalha basalt and stratoid series.

1. INTRODUCTION

The republic of Djibouti is located in the Afar depression, at the junction of the three tectonic plates. The Afar depression is of great scientific interest as it is one of the keys to understand the relationships between of the rift, Red sea and Gulf of Aden in connection with the East African rift (Fig.1). Several papers have described the tectonic of the Afar depression (Mc Kenzie et al., 1970; Acton et al., 1991; Barbarie et al., 1972; Manighetti et al., 1998; Magnighetti et al.; 2001). Asal-Ghoubet rift was to provide an efficient heat source with additional supply from a shallow magma chamber beneath the central part of the Asal shield volcano, seawater circulation from to Asal Lake (155m below sea level) would provide fluids for the fractured. In Asal-Ghoubet rift forms the first of those areas and the transition between submarine and subaerial segments of the ridge. It's characterized by recent or present volcanism, active tectonic and by permanent seismic activity; it has been considered as an active spreading center (Stieltjes, 1973; Harrison et al., 1974; Needham et al., 1976).

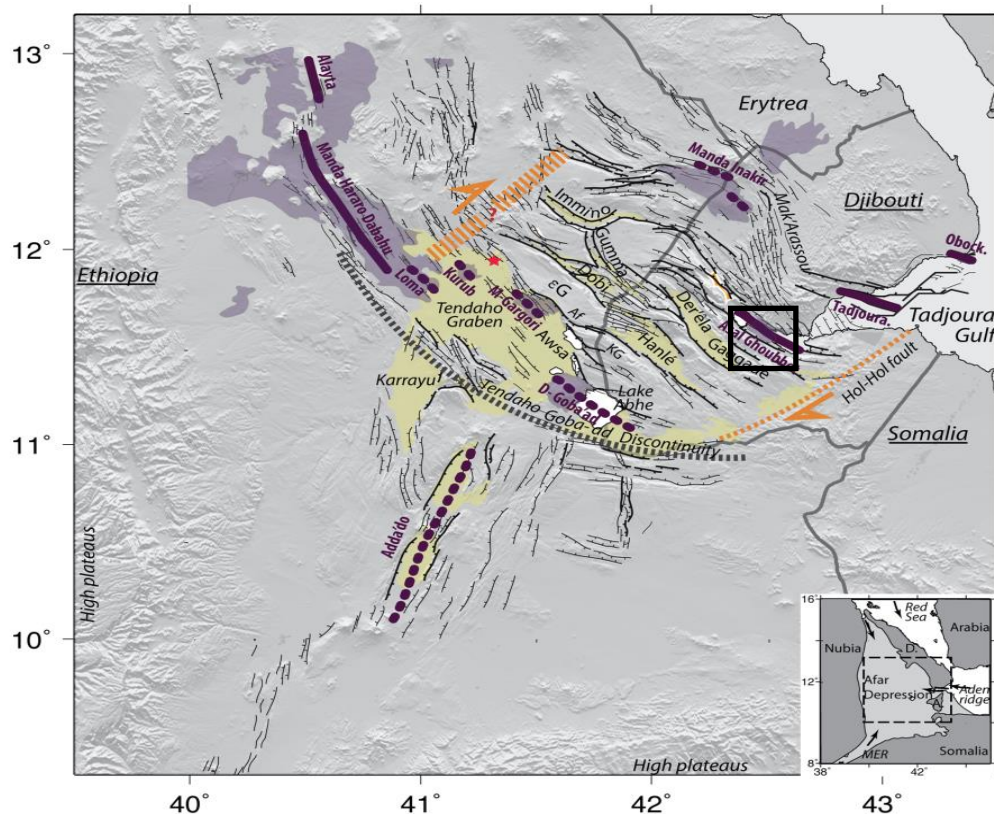
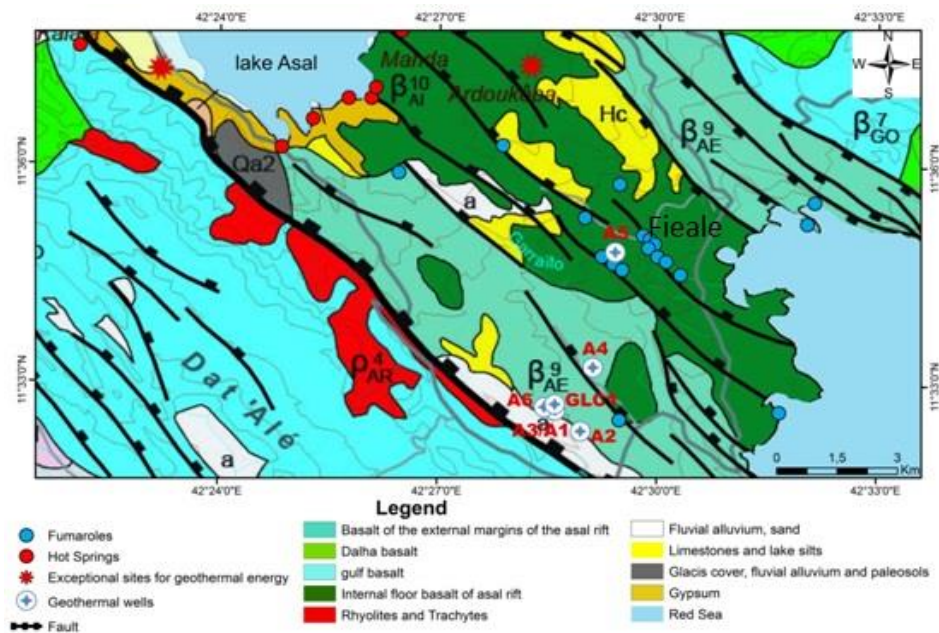


Figure.1: Structural map of the Afar Depression. The mapping of small and large faults indicated in thin and bold lines respectively has been made using the SRTM DEM and modified from Tapponnier *et al.* (1990), Hayward & Ebinger (1996), Manighetti *et al.* (1998) and Jacques *et al.* (2011). The axes and names of the active rift segments are indicated by dark purple lines and recent lava flows in light purple areas (modified from Barberi & Varet 1972). The sedimentary basins are in yellow. KG: Kadda Gamarri plateau; εG: εounda Gamarri plateau, Af: Afambo fault system, Kar: Karrayu Basin. The dashed purple lines represent rift segments not recently affected by known dyking events. The red star corresponds to the location of the 1969 Serdo earthquake (Kebede *et al.* 1989). Inset: Regional map. Continental regions are in dark grey. D: Danakil block, A: Ali Sabieh block; MER: Mid-Ethiopian Rift. The squares indicate the study area Asal-rift geothermal.

The main goal of this paper is to demonstrate the relationship of the geochronology succession, stratigraphic units and hydrothermal alteration. Understanding the lithostratigraphic variations that appear in the subsurface in order to allow a more precise correlation with the surface geology. These correlations are the basis for updating the geologic model of the field, which make possible a better assessment of the geothermal potential of a particular field.

1.1 GEOLOGICAL SETTING OF ASAL-RIFT.

Asal-Ghoubet rift is one of the youngest rifts with an age of 0.9Ma (Varet, 1978; courtillot et al., 1980; Manighetti et al., 1998). As any other rift in Afar, Asal-Ghoubet is a narrow zone (15km) of localized active faulting and magmatism. It currently opens at 16mm/year in a N40 to 5°E direction (Reugg and kasser, 1987, Vigny et al., 2007). The only clear finding is that magmatic and tectonic activities have been combining over the whole rift evolution; phases of dominant magmatic activity have alternated with phases of major faulting (stein et al., 1991; Manighetti et al., 1998). Between 300 and 100ka, tick volcanic series were emplaced in the rift inner floor (bounded at that time by faults) most from the central fieale shield volcano supposedly fed by a long-lived, deep magmatic chamber (van Ngoc et al., 1981). These lava flows progresssesively buried most previous faults. Magmatic activity then almost completely ceased at 100ka. Faulting thus resumed and progressively dismantled the lava pile, only interrupted from time to time by short phases of fissural volcanism (such as those responsible for the recent lava field the extend on either sides of the fieale edifice (Fig.2). The normal fault scarps that are presently observed to shape the Asal-Ghoubet rift were formed during that “amagmatic” 100ka long period.



the graben and horst. Mainly the deposition is basalt and porphyritic basalt with same lacustre sediment however the basalt external is oldest than the basalt internal floor within central of Asal that show the last eruption Ardoukoba 1978 is current magmatic activity.

1.2 GEOTHERMAL OF ASAL-GHOUBET FIELD.

Geothermal exploration in the Asal Rift (Figure 1) has proceeded in three phases drilling. The first phase, in the 1970s, consisted of geological, geochemical, and geophysical surveys conducted in association with the French Geological Survey (BRGM). The first deep well, Asal-1 (A-1), was productive while Asal-2 (A-2) was not. They were both drilled in the southwestern part of the rift (Figure 1). A-1 produced from a feed zone at a depth of 1137 m. A-2 showed no permeability, but both wells showed temperatures above 260°C. The second exploration phase occurred in the 1980s, following the 1977 rifting episode associated with the Ardoukoba eruption (Fig.3). The Italian consultancy Aquater conducted four deep wells were drilled (Asal or A3, -4, -5, and -6, shown in Figure 1), two of which were productive: A-3 and A-6. The last phase ODDEG Company with associated Turkish company (PARS) drill one shallow wells GLC 1 in 2016. So that altogether six deep wells were drilled with one shallow well, GLC1, Asal 1, 2, 3 and 6 are in the same area (Fig.3), located on the SW faulted block inside the rift but away from the active volcanic. Asal 4 and 5 located toward the central part of the rift.

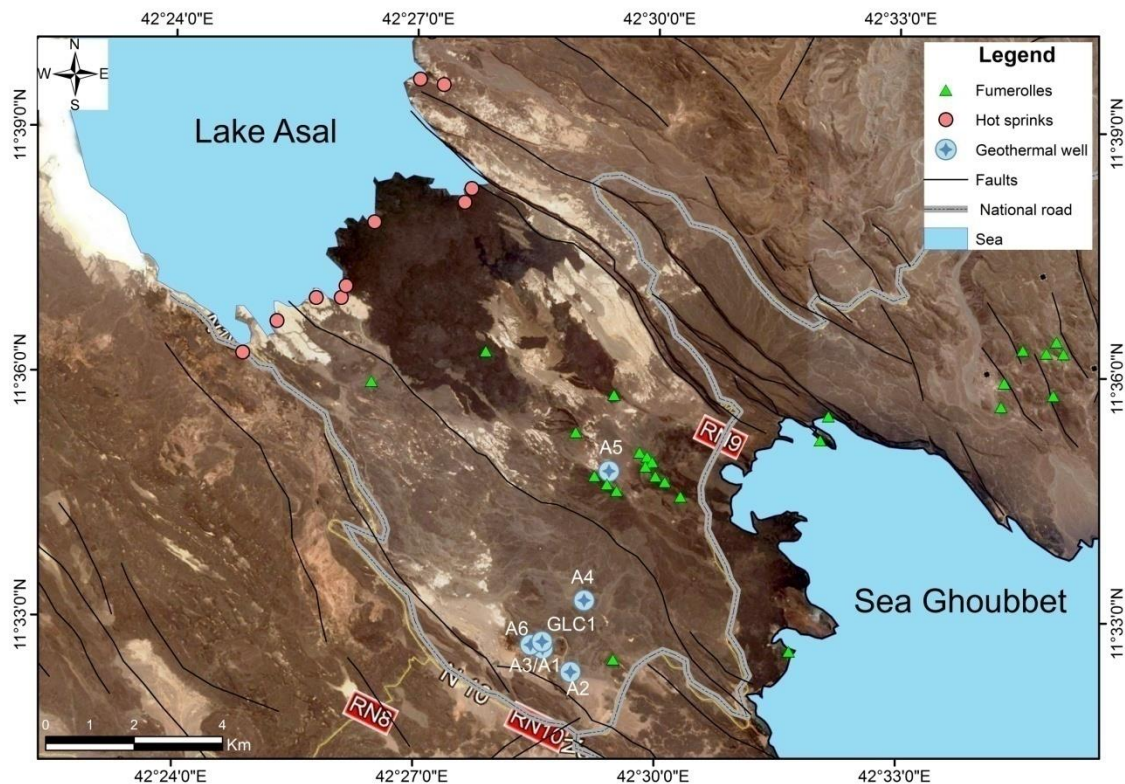


Figure.3: Structural map show the manifestation (hot spring located near the lake Asal and the fumaroles appear in the central part of Asal) and location of the geothermal wells (ODDEG 2017, unpublished report).

Asal 2, 3 and 6 were productive and they intersect same reservoir unfortunately the produced fluid from wells were hypersaline. So that why in 2016 ODDEG targets the intermediate reservoir range between 240m to 600m, this reservoir ranges the temperature 140 to 190°C. Asal 4 and 5 encountered the superficial underground sea water flow towards Asal between 250m and 280m followed by a rapid temperature increase in the hydrothermalized caprock but no deep reservoir was encountered by Asal 4 and 5, and low permeability with bottom-hole temperature reaching 345°C and 359°C.

2. SAMPLING AND ANALYTICAL METHODS

The study of subsurface study of wells involves sampling and measuring at discrete depths, and in situ or laboratory testing. The basic method is to analyze the drill cuttings and prepare lithological and alteration logs. The geological data is mostly based on analysis of drill cutting sample taken every 5m in Asal 3, 4 and 5 but 4m in Glc1 during drilling but after 300m it was taken every 2m to show hydrothermal evolution. The interpretation of cutting analysis is far more difficult as there a lot of problems associated with the collection of cuttings however sometimes it becomes challenging to recognize the rock type when the grain size of the lithology is larger than the cuttings chips. Also, it is difficult to distinguish the rock texture and structure of the rock if the veins and vesicles are damaged.

The binocular microscope is one of the primary rock cuttings analyzing techniques used to identify rock lithology, hydrothermal alteration minerals, primary minerals, rock texture and grain size, intensity of rock alteration and oxidation, rock porosity, fractures and vein fillings. Dilute hydrochloric acid (HCl) was used to identify the presence of calcite.

Analysis of cutting samples by petrographic microscope is one of the most important laboratory Thin sections were prepared every 10m by Aquater company (Asal 3, 4 and 5) for the different representative samples taken from each rock type in the wells but we did not make the thin section in Glc 1. Studies of these samples provided data including: rock type and mineralogy, relative amount of overall alteration (alteration intensity), relative amounts and mineralogy of the veining and the presence of open-space fillings as a function of depth.

XRD analysis is used to examine crystallized materials based upon the scattering of X-rays, which depends on the crystal structure of the material (Koestono, 2010). The X-ray diffractometer analyses (Appendix IV) were carried out to identify different clay minerals, such as smectite, mixed layer clay, illite and chlorite, with depth and infer the temperature regime in the system. XRD analysis also helps to determine alteration zones together with other index minerals found in binocular. In this study, 15 samples were chosen from Glc1 according to the rock type with depth and degree of alteration.

3. RESULT AND DISCUSSION.

3.1 STRATIGRAPHY

The main rock types that comprises the subsurface geology of the studied wells (Glc1, Asal-3- 4 and 5) is mainly volcanic, porphyritic basalt, hyaloclastite, scoriaceous basalt, trachyte basalt, trachyte and rhyolite.

Porphyritic basalt: Dark coloured, consisting of large plagioclase phenocrysts in a fine – grained, intergranular or more rarely with plagioclase, more or less altered granular olivine and abundant in the basalt of the upper Asal unit.

Hyaloclastite: Yellow-brownish rock, formed by a chaotic matrix made up of glassy fragment, partly or wholly altered by palagonite. The rock is strongly vesiculated and encloses calcic plagioclase phenocrysts, flattened pumiceous fragments, scoriaceous fragments and minor clinopyroxene phenocrysts. The correlations are easy in the Glc-1 and Asal -3 zones, the total thickness of this rock is 94 to 105m in Gale le Coma area (Fig.4) because the hyaloclastite is relatively homogeneous, with some intercalations of finely crystallized basalts at their base.

Scoriaceous basalt: with minor hyaloclastite and tuff in Glc1. Medium grained partially hyaloclastite and tuffs altered by clay minerals. Olivine is also a significant constituent in basalt. Large and small olivine crystals can easily be observed in basalt of the wells Asal-3.

Pleistocene clays: upper levels start with red colored clays. Claystone loses its plasticity due to diagenesis and has a very nature. When they are in contact with mud during drilling, they swelled and collapse inside the wellbore. After 325 in the well Glc 1 the color of the clays turned to grey, however Asal-4 and 5 is not observed this clay.

Rhyolites: recrystallized, silicified green the upper level of the unit is gray. In Glc-1 primary texture has completely disappeared. They usually contain tuff interlayer's and clay interlayers at same levels in Asal-3. Rhyolite consisting of Alkali feldspar phenocrysts in a hypocrySTALLINE groundmass, with felsic.

Trachybasalt: These rocks are fine-grained, characterized by aphyric to subaphyric, intersertal, pilotaxitic, hyalopilitic or, more rarely, trachytic textures. This term is used for rocks with petrographic features transitional between trachytes and basalts.

Trachyte: Fine grained dark coloured aphyric, sparsely subaphyric rock, normally consisting of K-feldspar microliths, along with some sodic scarce amounts of granular clinopyroxene may occur, and opaques are abundant.

Volcanoclastic rocks: fragmental textured rock, consisting of an altered glassy matrix which encloses abundant plagioclase crystals, lithic fragments (basalt, trachybasalt, trachytes), glass fragments, scoria and pumices. The pumiceous fragments are sometimes flattened, showing exhaustic textures.

The Stratigraphy model for the subsurface geology of the Asal-rift geothermal field is proposed based on the integration of lithological and geochronological criteria. The 8 lithology rocks were grouped into five unit successions, from youngest to oldest according to the age of the deposit: 1) Asal serie, 2) Pleistocene clays, 3) Stratoid serie, 4) Pliocene clays and 5) Dalha basalt. The general correlation of the groups is represented (Fig.4) as representative profile of the Asal-rift geothermal field with SE-NW orientation. This profile (Fig.4) also shows the correlations for some units from the wells and sub-units. The hyaloclastite and Pleistocene clays are mainly deposit in south-eastern part than northern part. The lithology are identified and confirmed by radiometric k/Ar dating (Aquater, unpublished report, 1989). Their occurrence and distribution is different as described below:

-Asal serie, consisting in upper part porphyritic basalt, than preceding hyaloclastite and in the bottom scoriaceous basalt less than 1 Ma. It appears that volcanic activity was located on the southern area covered by a small slice of water. Hyaloclastite deposits systematically show emersion trends. Asal-3 and Glc-1 are considering have same thickness comparing to the Asal-4 and 5.

-Pleistocene sediment mainly clays were identified in the wells Glc-1, Asal-3 compound more or less compact clays. So this deposit sediment develops above the rhyolite (stratoid serie) and it's represented for the wells Asal-3 and Glc-1 with thickness around 75m but Asal-4 it is 3m and Asal-5 well it is absent. This unit represent the cap-rock for the intermediates reservoir, Gale le Coma area. We distinguish two groups; the upper part is composed of brown clay with red browns, the lower set of gray clays with a plastic. This two groups exist only in Gale le Coma area (Asal-3 and Glc-1) we can consider this sedimentary, has been the seat of many volcanic episodes.

-Stratoid serie range (4-1Ma), constituted by acidic rocks (mainly rhyolites) in the upper part and by trachytes, trachybasalt and basalt in the lower section. We can distinguish four large groups; in the upper part rhyolite silicified and chloritized the thickness is 130 to 160m, in the middle part a trachytic medium dominated by the materials presenting massive sometimes of intercalations often altered ash, below this set pyroclastic with tuff altered and last rhyolite which as before is relatively homogeneous on Asal-3 and Glc-1 wells. Asal-4 well, the acidic rocks is located between the sides 576m and 767m and represents a part of the sequence described previously. The last rhyolite is located only in the south margin of Asal (Asal-3 and Glc-1) and probably deposit after emission of the trachytes.

-Pliocene clays occur the transition between stratoid serie and Dalha serie and also indicate the cap rock for the reservoir below this clay. It is plastic clays with some base of the well Asal-3. From 1075m we found in Asal-4 alternation of clay and trachybasalt, but in Asal-5 this clay will be decreasing to the north the thickness we found between 1080-1095.

Dalha serie range (8.1-3.6Ma) consisting of the basalt and trachybasalt, this unit represent the geothermal fluid reservoir.

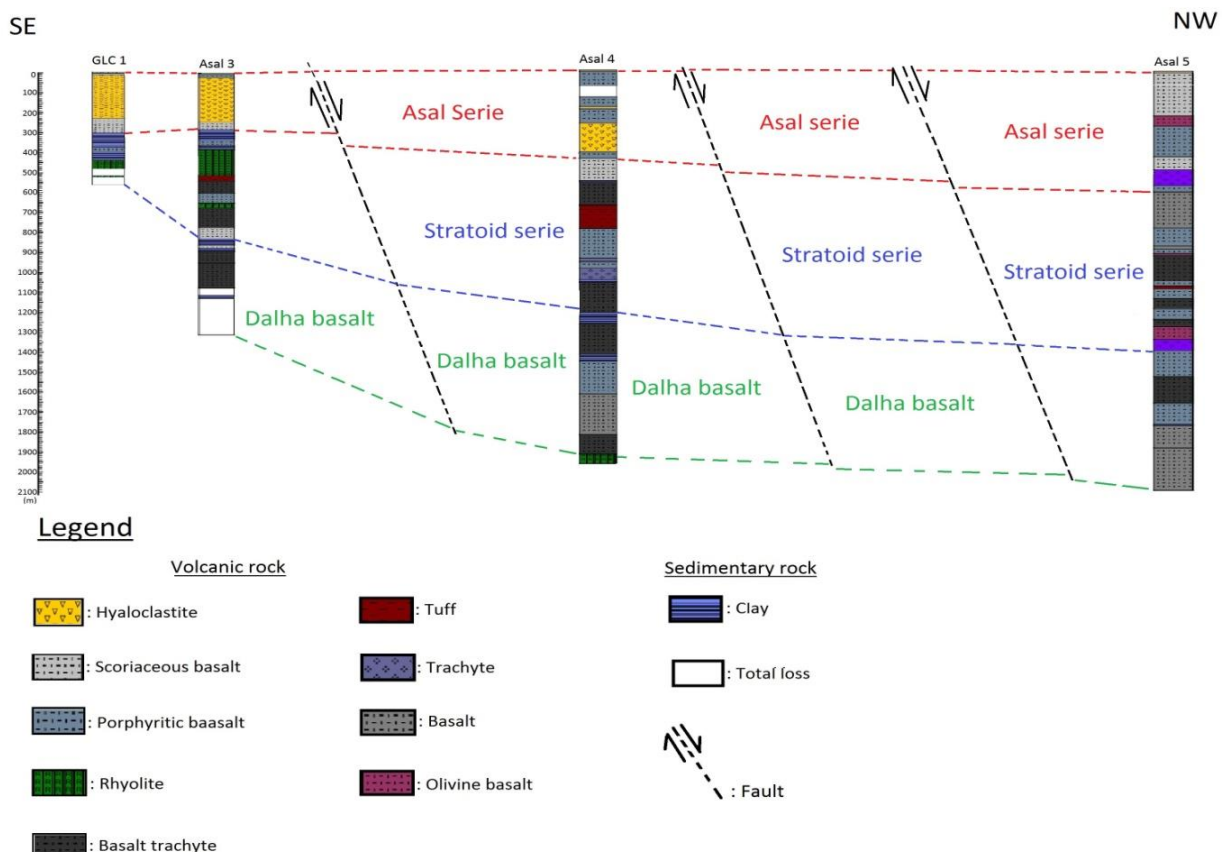


Fig.4. Correlation of lithostratigraphic units and main unit along section E-W: Wells Glc-1, Asal-3, 4 and 5. Location of this correlation line is shown in figure 3.

3.2 HYDROTHERMAL ALTERATION AND TEMPERATURE FORMATION.

3.2.1 HYDROTHERMAL ALTERATION

Hydrothermal Alteration is seen as change in mineralogy, texture and chemistry of rocks due to thermal and environmental changes facilitated by geothermal fluids and gases. The intensity of the changes also depends on texture and time. The factors that control alteration in geothermal systems are temperature, rock type, permeability, fluid composition and the duration of fluid-rock interactions (Reyes, 2000).

Primary minerals, crystallized from magma, governed by the physico-chemical condition under which the magma solidifies, become unstable in a geothermal environment where high permeability, elevated temperature and intense fluid activity are.

Olivine: it is one of the primary minerals that form basaltic rocks (Olivine tholeiites) and is very susceptible to alteration. It is distinguished in thin section by its high birefringence, distinctive. It occurs in the medium to coarse grained intrusive which experienced in well Asal-5.

Plagioclase: it is the most abundant mineral occurring in most igneous rocks and a major mineral in basalts. In crystalline rocks it is readily identified by its low relief and is conspicuous. It also occurs as fine groundmass in rocks exhibiting porphyritic textures like shown in (Fig.6) wells Glc-1.

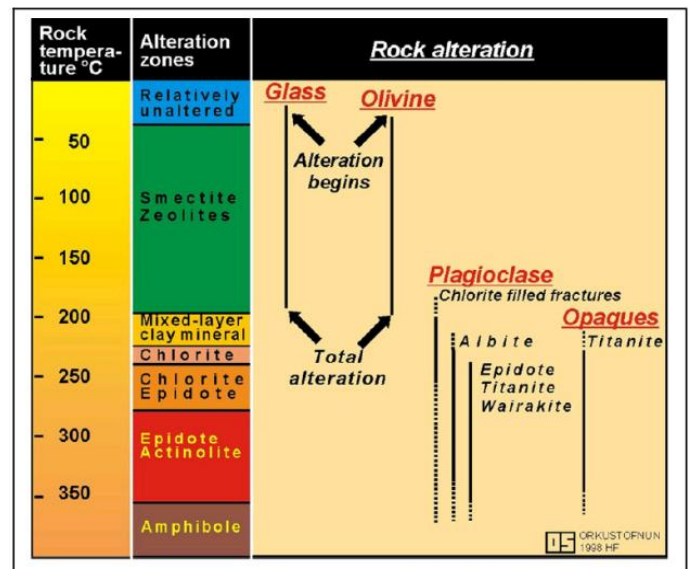


Figure.5: The alteration zones recognized in High temperatures systems (Franzson, 2008)

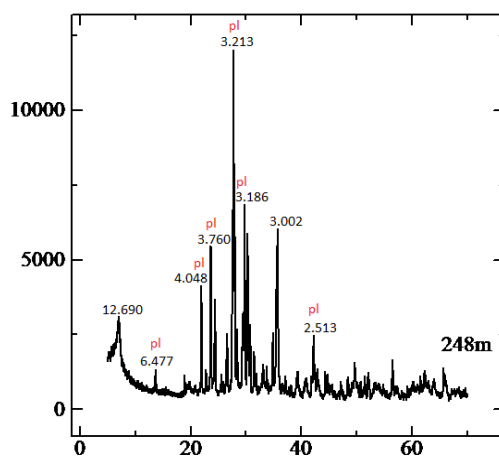


Figure.7: XRD pattern with sample Glc 1, dept 248m represent the most abundant mineral is plagioclase. Pl: Plagioclase.

Alterations mineral zone studied in Asal-rift geothermal wells reveals five zone of hydrothermal alteration beneath a zone of unaltered rock. Each alteration zone is characterized by the dominance of particular mineral(s) (Fig.8) below: zone 1: Unaltered rock 2: Smectite; zone 2: mixed layer clay; zone 3: Chlorite; zone 4: Chlorite-epidote; Zone 5: Epidote actinolite.

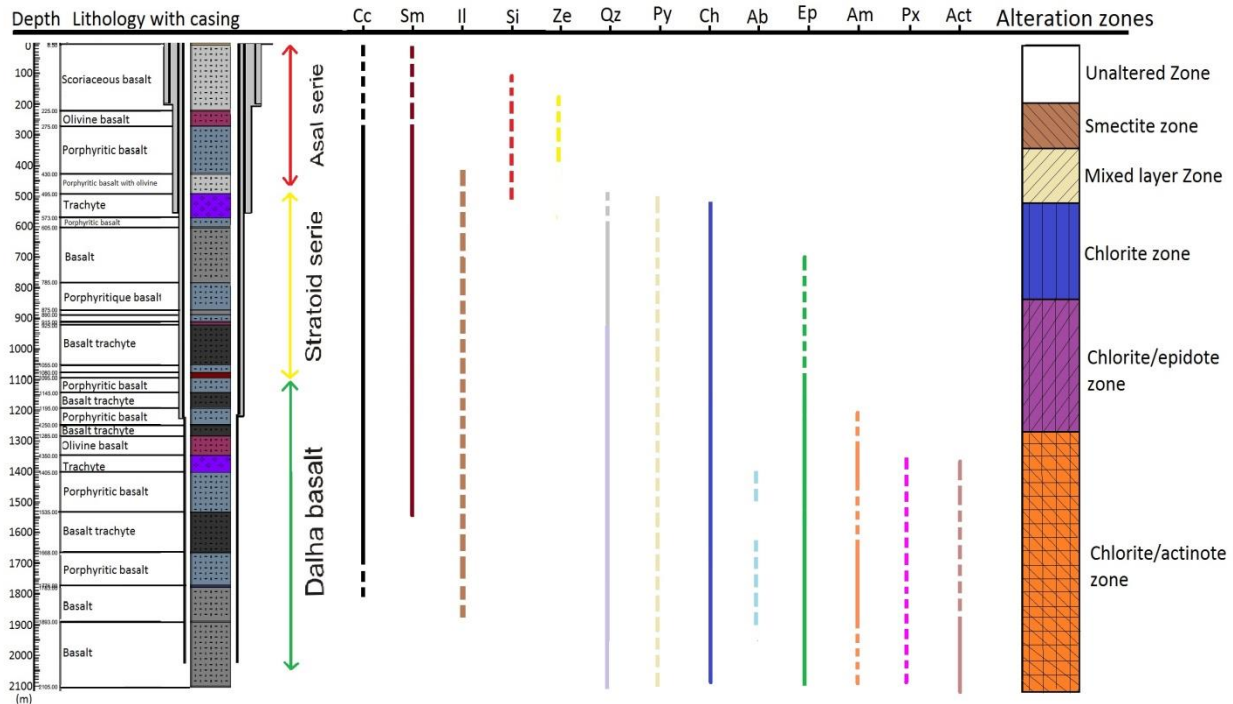


Figure.8: Stratigraphy, alteration minerals and alteration zones of wells Asal-5.

Cc: calcite, Sm: Smectite, Il : Illite, Si : Chalcedony, Ze: Zeolite, Qz : Quartz, Py: Pyrite, Ch: Chlorite, Ab: Albite, Ep: Epidote; Am: Amphibole; Px: Pyroxene Act: Actinolite.

Unaltered zone: This zone extends from the surface to about 200 m depth. The rocks are hardly affected by any hydrothermal alteration and are considered fresh. This is confirmed both by thin sections and XRD analyses.

Smectite zone: The upper boundary of the zone is defined by the appearance of smectite at about 200 m depth. Smectite is the most dominant clay minerals in this zone. The inferred stability temperature is less than 200°C.

Mixed layer clay zone: occur at 360m in well Asal-5 and 285m in well Asal-3 and mark the top boundary of the mixed layer clay zone. These clays are the intermediate product of reactions involving clay minerals (smectite and chlorite). In addition to these calcite and pyrite continues go became more common in this zone.

Chlorite zone: The upper boundary of this zone is at about 500 m depth, where chlorite becomes common and that boundary probably represents a temperature of about 230°C.

Pyrite and calcite still continues to be common with assemblage chalcedony-quartz.

Chlorite-epidote zone: The upper boundary of the zone is at about 800 m depth, where epidote first appears. Chlorite and epidote assemblage indicate a temperature >240°C.

3.2.2 TEMPERATURES DISTRIBUTION ASAL-RIFT GEOTHERMAL FIELD.

In Asal-rift geothermal field, a high-temperature anomaly is located in the central part of the field, where well Asal-5 is located. The highest recorded temperature is about 355°C at the bottom of Asal-5 and 344°C at the bottom of Asal-4 that is exhibit the intrusion magma is located around 4km. The zone with highest temperature in the wells is located within Dalha series formation.

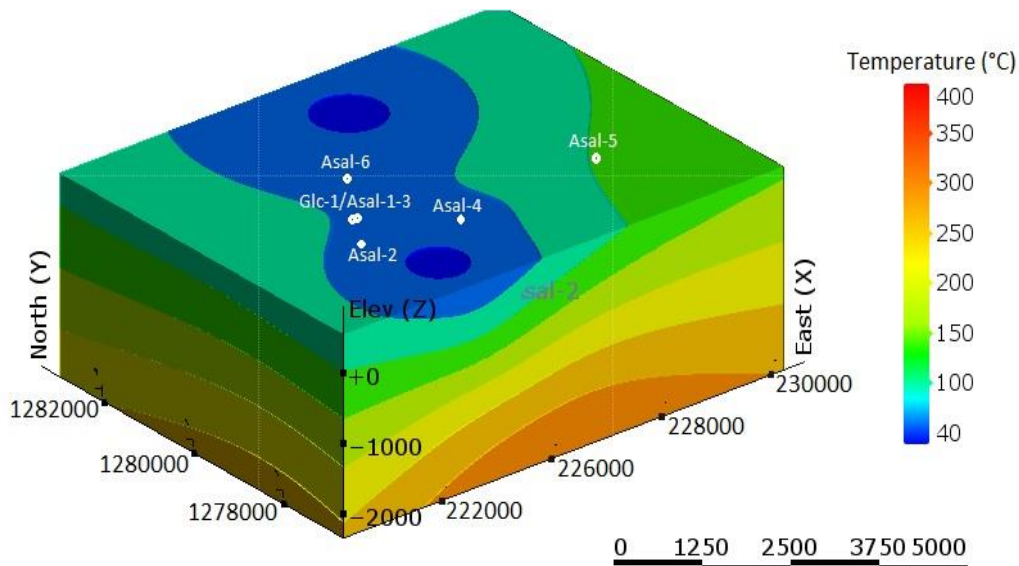


Figure.9: 3D temperature distribution in Asal rift geothermal.

In the upper part of Glc-1, Asal-3 and 4 the temperature is below 150°C. The temperature increase with depth in well Asal-5 at 560-700m dept temperature above 180°C. The highest temperature recorded in well Asal-3 is 264°C at the bottom 1316m. Well Glc-1 the maximum temperature is 127°C at 490°C that is indicate central part fieale the temperature is higher than the Gale le Coma area.

3.3 3D GEOLOGICAL MODEL.

In the present study, 3D geological model of Asal-rift geothermal were not prepared according to available geological data, the main focus was to prepare geological models it's to understand the evolution of the rock. Drilling of the geothermal wells provided new and useful stratigraphic data for a better definition of the geological model which was integrated with all data available to update the conceptual model of the geothermal field. The formations, crossed by the wells drilled are related to the main volcanic units outcropping in the area which are from top to bottom as follows:

- Asal series, consisting of recent porphyritic basalt and hyaloclastite.
 - Afar stratoid series (1-4Ma) mainly consisting of basalts. In the upper part of series a thick layer of Pleistocene clays will be disappeared in wells Asal-4 with rhyolite level.
 - Pliocene clays will be also decreasing in to north (Fig.10).
 - Dalha basalt series, (4-8Ma) consisting of basaltic products, with sedimentary intercalation.
- Well Stratigraphy indicates that below the recent basalt of the Asal series, at the border of the rift, the pre-existing crust is still largely present.

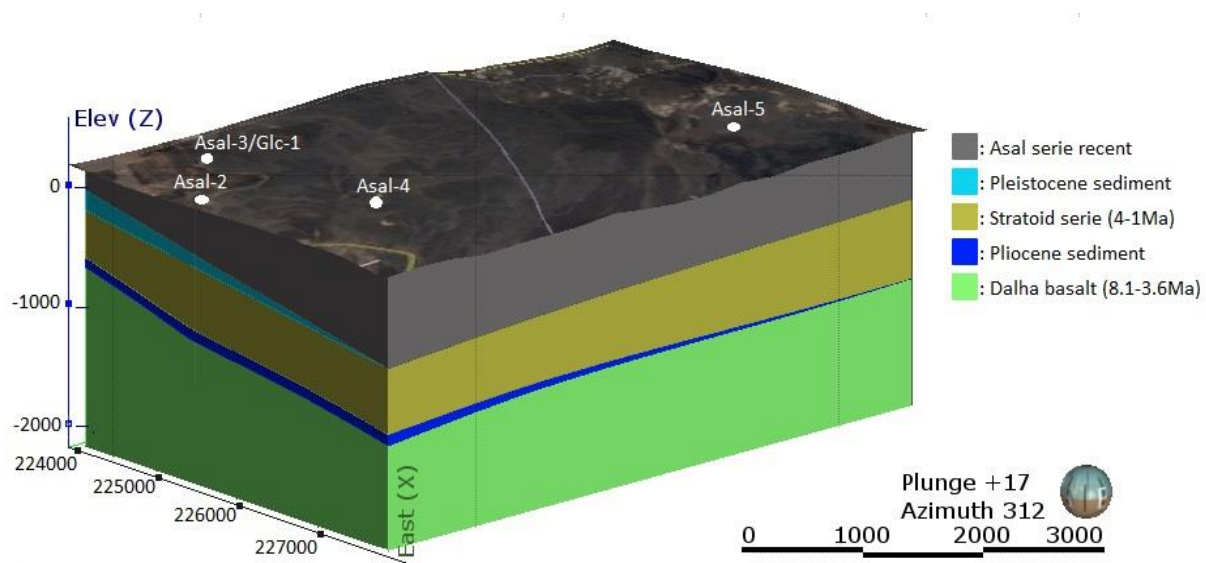


Figure.10: 3D geological model of Asal-rift geothermal with including the geothermal wells.

CONCLUSION

- The major rock units identified in the study wells Glc-1, Asal-3, 4 and 5 is almost volcanic basalt and trachyte with clay sediment.
- The Stratigraphy encountered succeed from oldest to youngest, Dalha basalt serie estimated to be formed between 8.9-3.8Ma, Pliocene clays, Stratoid serie range between 4 to 1Ma, Pleistocene clays and Asal serie younger than 1Ma.
- Low to high temperature hydrothermal alteration minerals are observed in the study wells. The common alteration minerals are calcite, smectite, illite, zeolite, pyrite, chlorite, Epidote and Actinolite.
- Six alteration zone are identified by the abundance and first appearance of alteration minerals, namely an, unaltered zone, smectite zone, mixed layer zone, chlorite zone, chlorite-epidote zone and chlorite-actinolite zone.
- Two reservoirs are identified during drilling; the intermediate reservoir located within stratoid serie and below to the Pleistocene clays range the Temperature 120-170°C, deeper reservoir located within Dalha basalt serie and below to the Pliocene clay range the temperature 250-355°C.
- The Pleistocene clays are very abundant in the South-Est than North that exhibits in the wells Asal-4 and 5 no presence of this sediment.

RECOMMENDATION

Detailed fluid inclusion and rock chemistry need to be carried out, specifically in well Glc-1 and supplement information about alteration and measured formation temperatures, to understand the evolution of the geothermal system and whole rock chemistry.

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