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Preliminary Study on Surface Geology and Hydrothermal Alteration of Ambado_PK20 Prospect Zone, Djibouti

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ABSTRACT

Djibouti is among one the few countries that import a bigger percentage of its electrical power. Currently Djibouti is putting efforts on developing indigenous sources of power such as geothermal and solar energy to meet the current demand as well as reduce over-reliance on importation of power. Ambado_PK20 is one of the promising geothermal fields in Djibouti. This study used the ability of remote sensing technology to identify and map the fault and alteration zones in a Ambado_PK20 geothermal prospect area by using ASTER L1T data source. Though the Ambado_PK20 geothermal field lacks active fumaroles and rock alterations are not visible on the surface, some water wells located in this zone have temperatures between 40°C and 73.6°C. Due to the presence of this ground thermal anomaly, the Ambado_PK20 geothermal field was identified as a geothermal exploration prospect. Structurally, the study area is mainly affected by a network of normal faults that are N80°-N110°, i.e. EW, which are parallel and synchronized with the rifting of the Tadjoura gulf. The latter are intersected by a minority of the faults which are N20°-N70° directions, i.e. NS. The movements resulted by these fault networks are believed to have a direct impact on the thermal anomaly occurrences in the area. The first objective of this study was to identify the faulting and to assess whether there is any relationship between faults and the occurrence of thermal anomaly in the area. The second was to map the distribution of the alteration mineral assemblages and verify them by laboratory analysis (Petrography and X-Ray Diffraction analysis). The fault map showed that areas with a high number of faults were also associated with thermal anomaly occurrences. The alteration map identified clay minerals and iron oxyhydroxides (e.g. hematite, goethite) of hydrothermal origin. Results of the alteration map from the aerial image are consistent with mineralogical data obtained from XRD and petrographic studies of the samples taken near the anomaly zone. These alteration minerals can be attributed to hydrothermal fluid flowing upward with a high water-rock ratio, through highly permeable rocks and controlled by geological structures in the study area. The results of this study showed that the Ambado_PK20 geothermal field has intermediate seated reservoir with temperatures in the range of 100 -130°C. This energy can be converted to electricity via binary power plants and the exhausted brine can be used directly for other applications.

1. INTRODUCTION

PK20_Ambado geothermal field located 20 km west of Djibouti city has been selected as the study area because there is the existence of a thermal anomaly; some of the well water drilled in this area indicate high temperatures up to 73.6 °C (Fig.1). The purpose of this study comes from this question: what are the possible reasons for thermal anomaly in groundwater when there is no direct evidence of geothermal activity in the area? For this study, we wanted to answer part of this question. First, we investigated the relationship between the fault network and the thermal anomaly groundwater (the high temperature well water). Then, we determined the alteration minerals and their distribution. Lastly, we made petrographic and XRD rock analysis to distinctively understand the rocks types and the effects of the alteration.

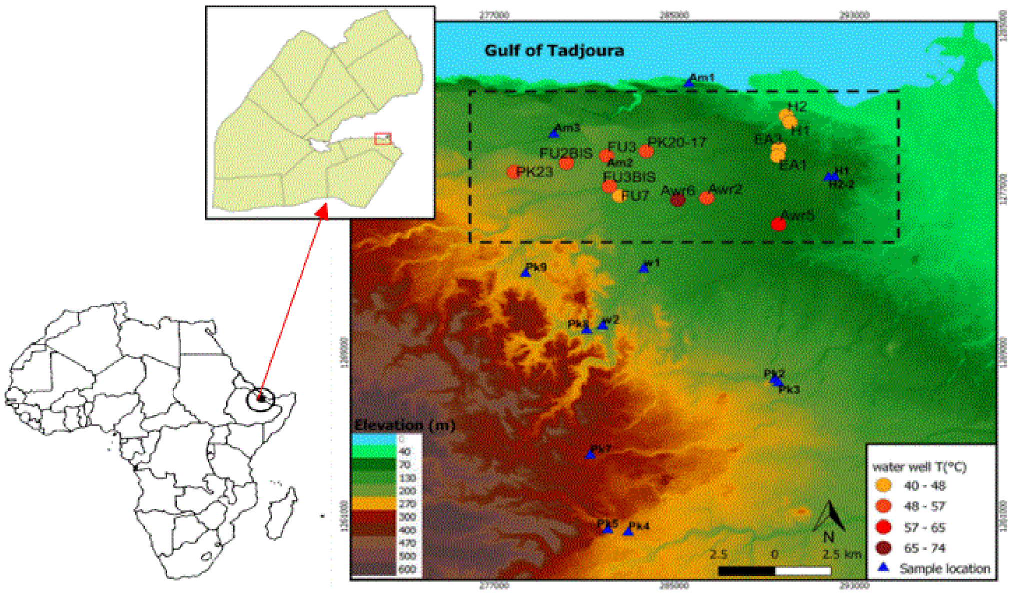


Figure 1: Location map of the study area at the Ambado_PK20 Prospect Zone, Djibouti presented by black rectangle overlaid on DEM SRTM 30 m.

2. METHODOLOGY

2.1 Remote sensing data:

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery was used to extract the fault and to identify alteration mineral.

<u>2.1.1 Structural geology mapping</u>

For this study, PC1 was getting Aster Image by using ENVI, then the fault was extracted automatically PCI by using Geomatica software and saved as AutoCAD vectors in a data interchange file (DXF) format in order to be compatible with Rockworks software where the rose diagrams were plotted. The relationship between faults and the groundwater thermal anomaly in the study area was evaluated by using fault density analysis. The faults are believed to have a relation with the groundwater anomaly occurrences in the study area. As such, it was necessary to establish their relationship. Rose diagrams were used to assess the general orientation of faults, while faults density analysis was used to assess the density of faults in the area.

<u>2.1.2 Hydrothermal Alteration Mapping</u>

The ASTER (VNIR-SWIR, i.e. 9 bands) data was used for mapping hydrothermal alteration zones. The higher spectral resolution of ASTER makes it possible to identify minerals and mineral groups such as clays, carbonates, silica, iron-oxides and other silicates. The image used in this study was downloaded from the United States Geological Survey (USGS) website and was captured on 2006/04/12 (Fig.2). The band ratio is a technique that has been used for many years in remote sensing to display spectral variations effectively (Goetz et al. 1983). In this case, the method used for data processing was band ratio. The band ratio method employs selecting bands, using the best ratios to obtain the desired information and most meaningful order to display these ratios. In this study, the spectral characteristics of the alteration minerals was used to select the pairs of bands for various ratios. It is well recognized that ASTER L1T band ratios of 2/1, 5/3 +1/2, (5*7)/(6*6) are used for ferric oxides, ferrous oxides and clay minerals (Rowan & Mars, 2003).

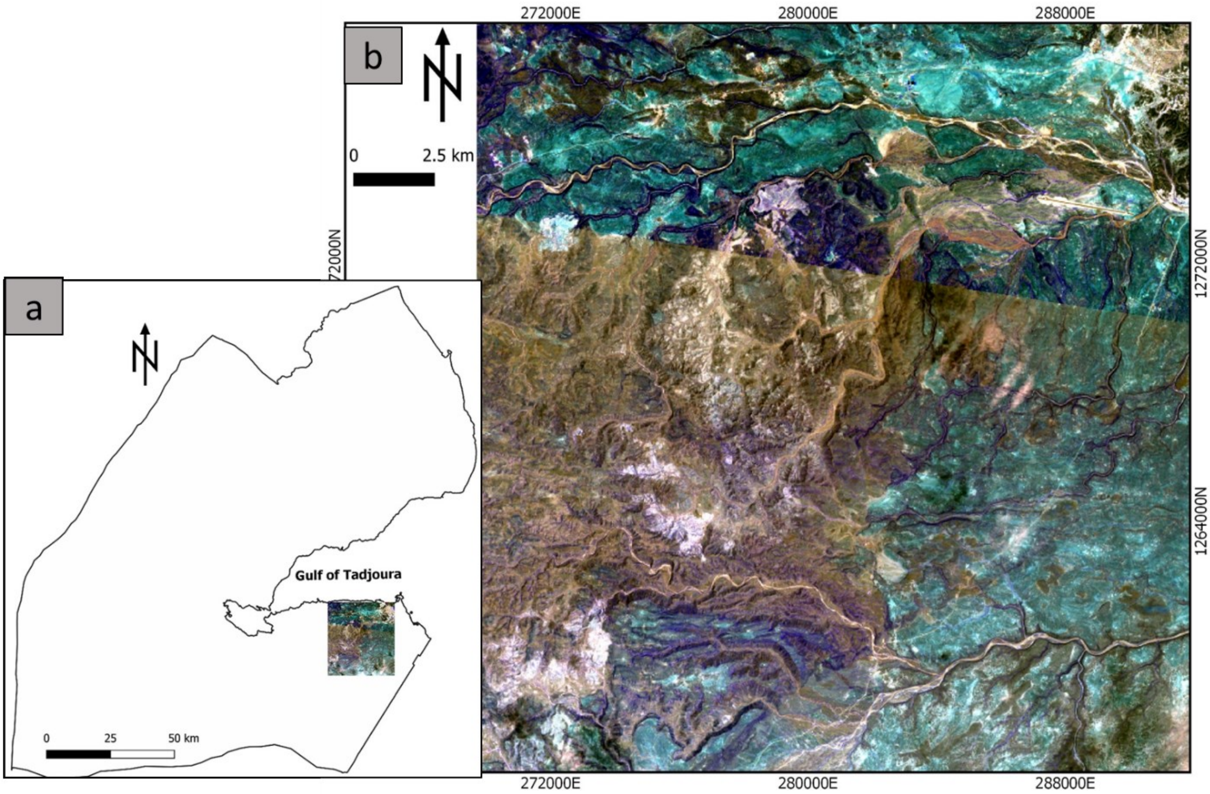


Figure 2: ASTER image coverage: (a) Position map and image reference. (b) Mosaic of two images used for this study. Color composition band 132 (VNIR).

2.2Analytical methods:

<u>2.2.1 X-Ray Diffractometer (XRD):</u>

XRD analysis was used to identify individual minerals for 14 rocks samples from the surface in the PK20-Ambado area (Fig.1b) collected in 2016 by ODDEG geology staff during fieldwork. Oriented sample analysis has been done on 4 samples to identify clay minerals. These rocks were analyzed using an X-ray Diffractometer (Rigaku) at the Department of Earth Resource Engineering at Kyushu University.

<u>2.2.2 Petrography microscope:</u>

Petrography is the study of rocks and minerals using a microscope where each mineral has its own optical characteristics; therefore, microscopic observation is one of the most fundamental methods to identify minerals. For this study the representative samples were selected, and thin sections were prepared and observed using a polarizing microscope (Nikon Eclipse) at the Economic Geology Laboratory of the Department of Earth Resources Engineering, Kyushu University.

3.0 RESULTS

3.1 Surface Geology

The Ambado-PK20 study area presents several types of geological formations (Fig.3): The Gulf basalt linked with the Tadjourah opening, the Dalha basalt to the south in the "Bour Ougoul" massif and the Somali basalt to the south-east and the Mabla rhyolite. The contact between these geological formations and tectonics is related to the opening of the Gulf of Tadjourah.

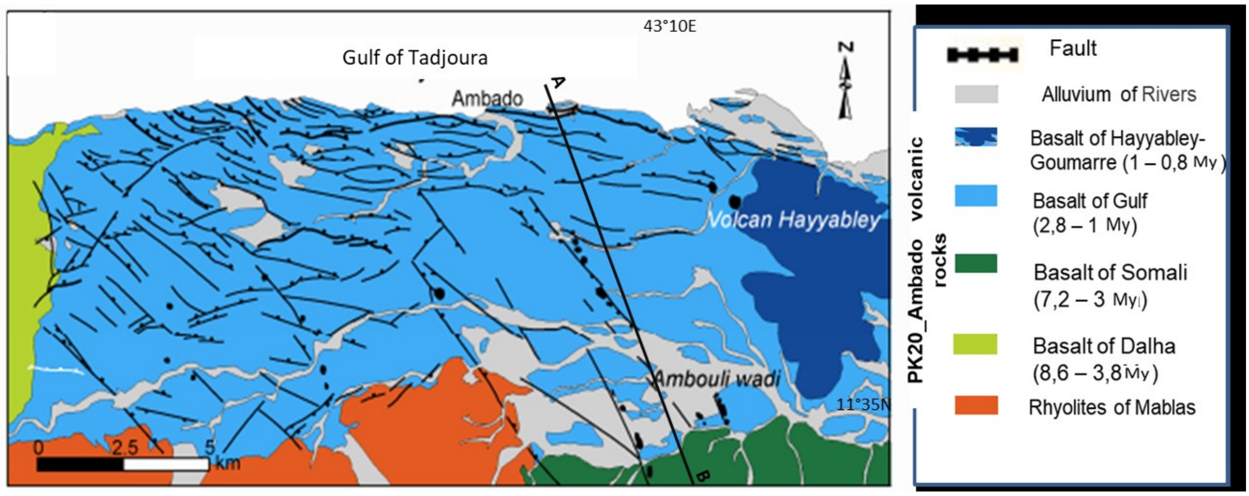


Figure 3: The geological map of PK20-Ambado and the surroundings (From present studies and that of Daoud et al., 2008).

3.1.1 Rhyolite of Mabla

The rhyolite of Mabla is the oldest formation of the study area that was set up in the Miocene in the southwest. Some rhyolitic flows cover the basalts of Dalha. The white rhyolite is very light and very altered.

3.1.2 Somali basalt

The Somali basalt is only found in the southeastern part of the Republic of Djibouti (Figure 3). This series is dated 7.2 to 3 Ma and their emplacement seems to be along emissive fissures with a direction of N160° (Red Sea). The Somali basalt would be the last emissions of the system in extension of direction of the sea, before the abrupt change due to the opening of the Gulf of Tadjourah, there is 3.5 My following direction E-O (Chessex and al.1975). This basalt is unconformably outcropping on the Dalha basalt stack and in places on the tilted Mabla rhyolite.

3.1.3 Dalha basalt

The Dalha basalt is dated from about 8.6 to 3.8 Ma outcrops to the southwest of the study area. This unit consists of a sequence of lava flows, with intercalations of rhyolites, trachytes and detritic deposits. A more or less pronounced angular discordance is found on the highly eroded Mabla rhyolites. There is also intercalation between ignimbrites and detritics. This series narrows northward as the Gulf approaches, this would locate the emissive fissures at the current location of the Gulf.

3.1.4 Gulf basalt

The Gulf basalt dates from 2.8 to 1 Ma and is the most widespread formation in the PK20- Ambado study area. All the basalt in the Gulf is based on Dalha basalt and the Mabla rhyolite which forms the relief of the "Bour Ougoul" massif. The Gulf series consists mainly of basaltic flows with sedimentary formation intercalations (red clays and conglomerates). The thickness of this formation reaches at least 70 meters (Jalludin et 10 al. 1990), with the gulf basalts overlying with unconformity the Somali basalt and the Dalha basalt in the west.

3.2 Structural Geology

3.2.1 Faults and Fracture

Regional faults have previously been mapped in the area e.g. (Daoud et al., 2008). PK20_Ambado is affected by a network of normal faults which are mainly N80°E-N110°E, i.e. EW, parallel to the Gulf of Tadjoura. The latter are intersected by a minority of the faults which are N20°-N70° directions, i.e. NS. This network is post-dated by onlapping Gulf Basalts which are in turn dissected by Gulf-parallel faults, and older than the Hayyabley volcano to the East. As we can see in Fig.4, these faults are synthetic natural faults which delimit a succession of horsts and dissymmetrical grabens, collapsed in the direction of the Gulf towards the North.

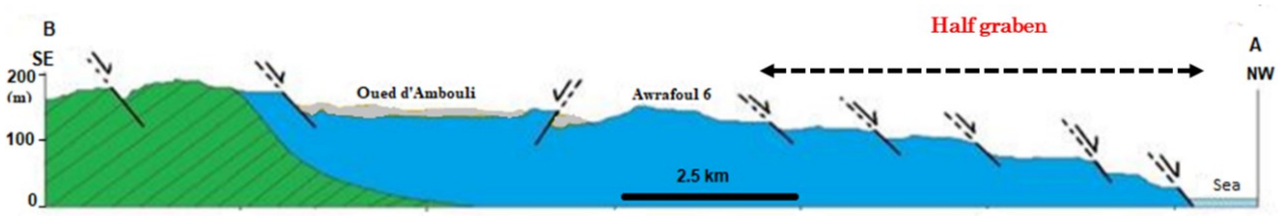


Figure 4: Cross section showing the general organization of volcanic formations structure along a transect whose trace is shown in Fig.3.

3.2.2 Eruption Centers or Volcanic Vent

The Hayyableh volcano is the youngest volcanic unit post-Tajdoura Gulf basalt in the PK20_Ambado aera. It was apparently never investigated despite the obviously unusual characteristics of its basaltic lavas. It is a 5x10km elleiptic edifice, with a NNW-SSE trending axis. This volcano has a shield-like and rather flat morphology, and culminates at 147 m. The total thickness of lava flows is estimated to be 120m and its volume estimated to be approximately 0.6-0.8 km^3 despite the rather large aerial extent of these lavas (Daoud et al., 2008). The eruptive vents of the Hayyableh volcano are no longer identifiable, possibly because of the strong anthropic imprint and constructions of Djibouti city suburbs: They are thought to be located at its summit zone, while aerial photograph data suggest radial emplacement of the lava flows away from this summit (Fournier et al.,1982).

3.2.3 Fissures, Inferred Faults and Lineaments

The results from the rose diagram have shown that most of the faults in the study are oriented in the NE-SW direction (fig. 5). The results correlate well with the field observations as well as literature. The origin and evolution of this structure and its morphological expressions are however not clearly documented.

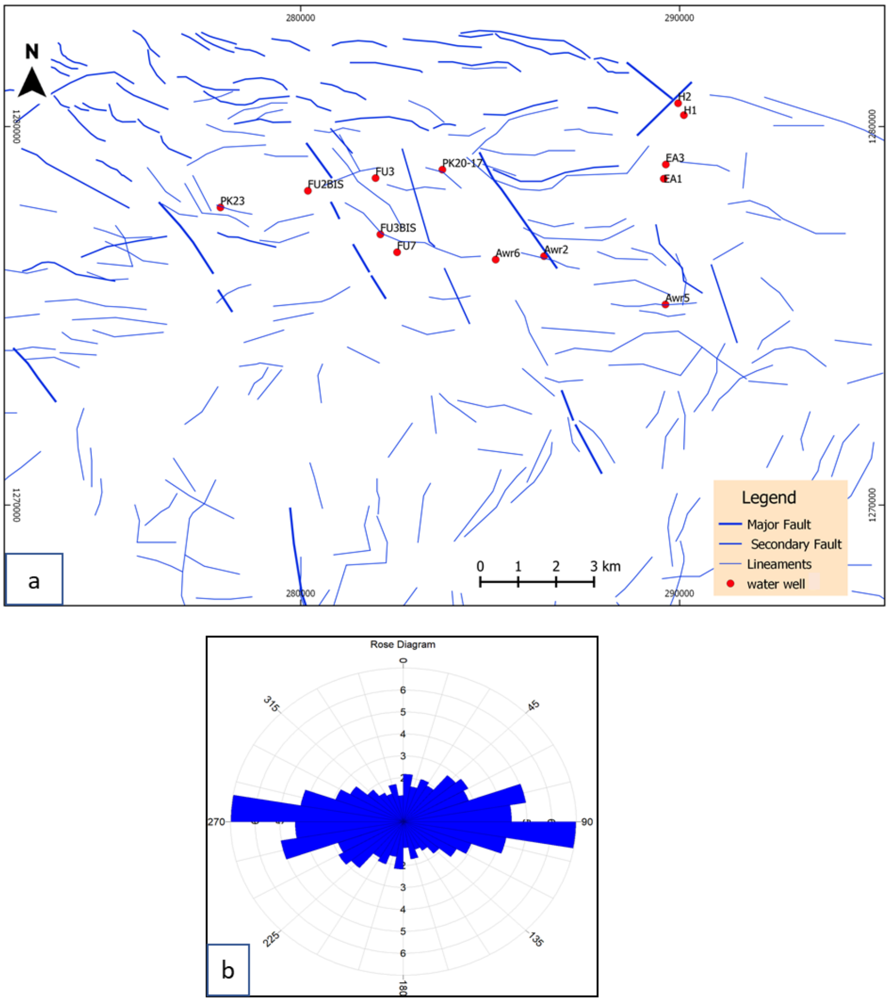


Figure 5: a) Map of the fault obtained from Aster image b) Rose diagram of Fault.

3.2.4 Fault density

Fault density makes reference to the total number of faults per unit area, thus areas with more faults per unit area are considered as high fault density areas hence high-density zone while those with few or less faults per unit area are considered as low fault density areas hence low-density zones. Faults are important in geothermal studies because they are considered as potential permeable zones where thermal fluids flow from the reservoir at depth to the upper levels. The results from the fault density analyses showed that the study area has high, medium and low fault density zones (Fig. 6). When bore hole temperature points of known locations were plotted on the map, it was shown that the groundwater thermal anomaly occurs in high and in medium density areas. We suggest that the groundwater thermal anomaly is controlled by these faults oriented NE-SW. Fault density is used in geothermal exploration to locate highly fractured areas that are assumed to be associated with geothermal reservoirs at depth. As such, several studies have shown that areas with more faults and cracks are considered high fault density areas. Furthermore, these areas are considered as having more potential and being targets for geothermal drilling (Prabu et al., 2013, Anderson et al., 2013 and Wibowo et al., 2010).

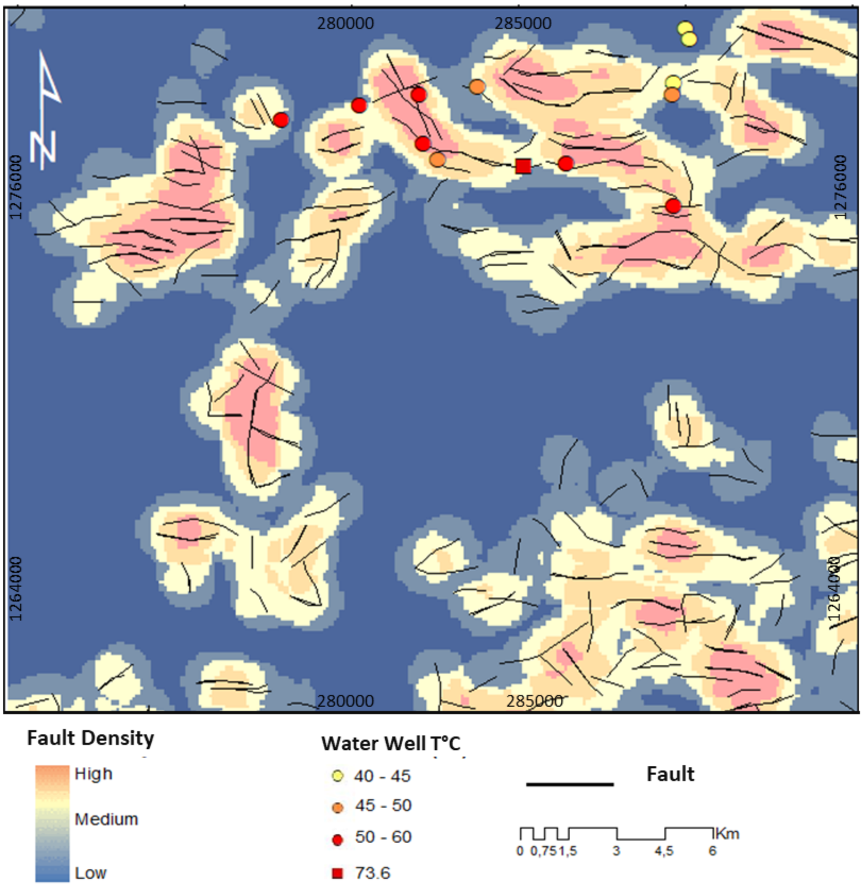


Figure 6: Map showing the correlation of the density of faults and the temperature of borehole water.

3.3 Hydrothermal Alteration Mapping

The results of the Band ratios of 2/1, 5/3 +1/2, (5+7)/62 from ASTER showed the possibility of 2 alteration indicators: iron oxides appear green and clay minerals as yellow-beige (Fig. 7). However, some small zones appear dark which is indicative of habitation in Fig. 7. The iron oxides are a result of the precipitation from weathering and the clay minerals are either a result of hydrothermal fluid or weathering. So, from geothermal point of view, the high temperatures are probably associated with a geothermal system below.

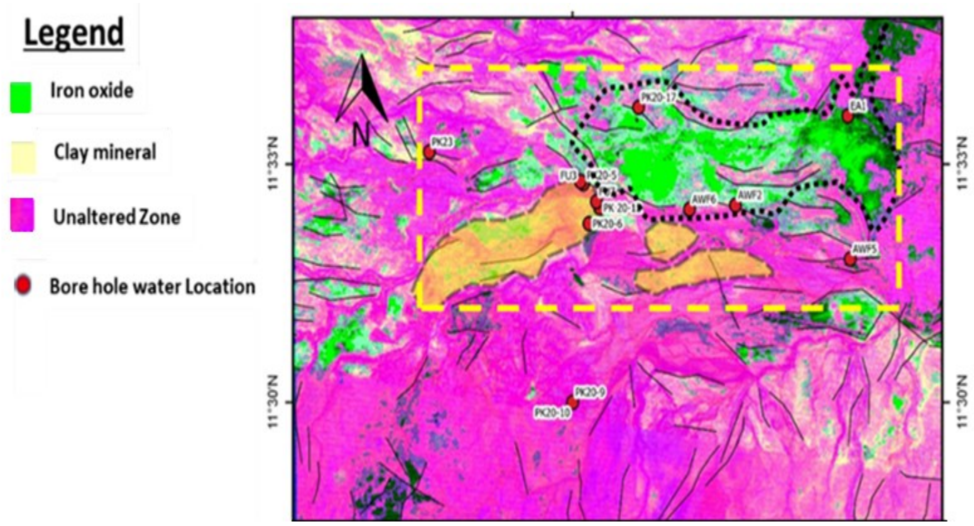


Figure 7: Image the bands 2/1, 5/3 +1/2, (5+7)/62 showing possible Iron oxide and clay minerals. The red circle shows the location of rock samples analyzed by XRD.

3.4 Petrography

In the study area, volcanic rocks are well exposed. The rock samples were collected from the surface in the PK20 prospect site and its thin sections were studied. Four representative samples of different rock types will be present of which 2 are fresh and at least 2 are altered. The trachybasal (PK3) shows that the main phenocryst phase is olivine and plagioclase. The groundmass is glassy with plagioclase microlites, clinopyroxene and orthopyroxene (Cpx and Opx) (Fig. 8a). The basalt (PK9) shows plagioclase crystals, clinopyroxene and orthopyroxene (Cpx and Opx) within a fine-grained groundmass (Fig. 8b). The basanite (PK4) shows that the phenocrysts are fully replaced by smectite and cristobalite and that the groundmass is mostly exposed plagioclase laths (Fig. 8c). The rhyolite (PK5) shows the quartz and the plagioclase is replaced by smectite (Fig. 8d). Smectite is the clay mineral with the lowest formation temperature. It is formed from the alteration of glass or primary minerals like olivine, plagioclase and forms directly from water-rock interaction. It is fine-grained, greenish to dark in the rock. It has brownish warm colours in plane polarized light (ppl). Smectite is an indicator of temperatures lower than 200ºC.

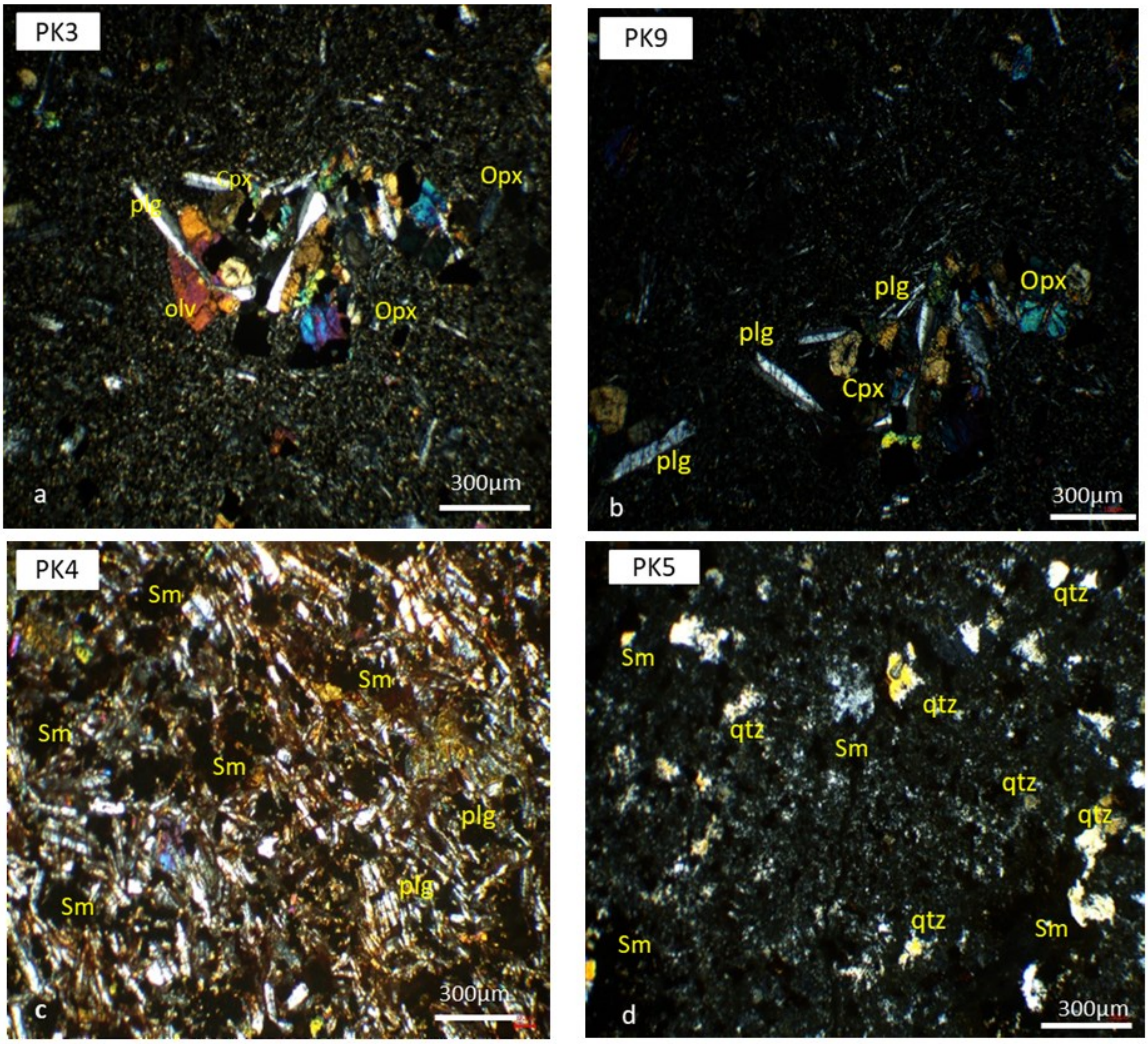
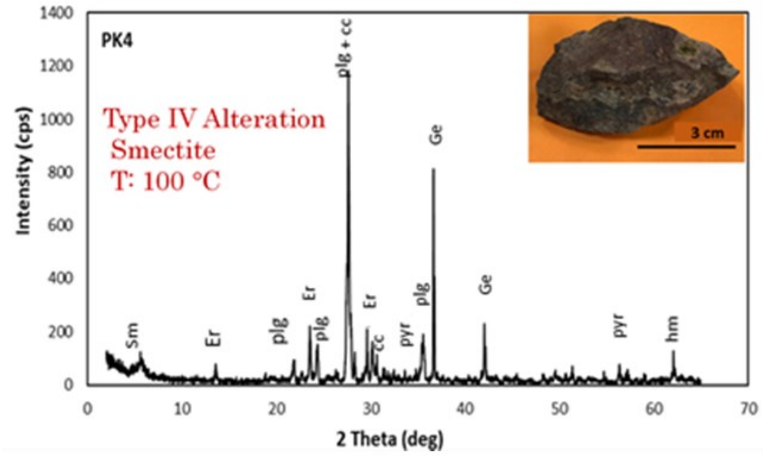


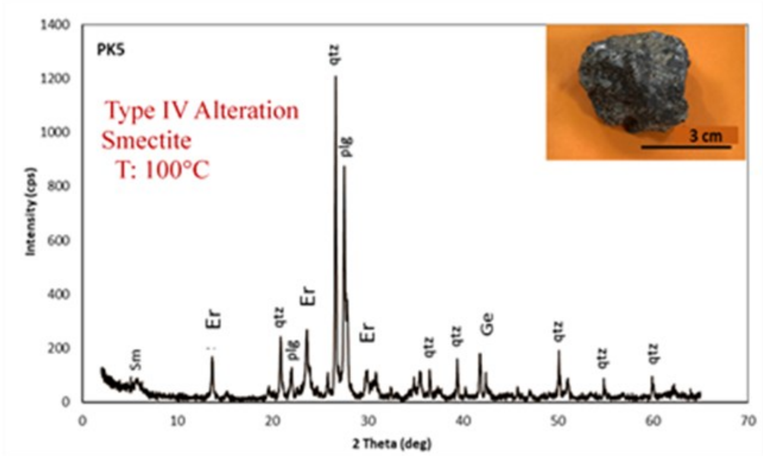
Figure 8: Petrography images (XPL), a) (Pk3) shows plagioclase (plg), clinopyroxene (Cpx) and orthopyroxene (Opx). b) (Pk9) show same mineral of PK3. C) Basanite (PK4) shows S and plagioclase (plg). d) Rhyolite (Pk5) shows quartz (qtz) and clay minerals.

3.5 X-Ray Diffractometer (XRD)

The results of XRD laboratory analysis shows the presence of smectite, goethite, pyrite, erionite, calcite, hematite as alteration minerals in the collected rock samples at PK20-Ambado area (Fig. 9). According to Hayachi (1973), we classify the mineral alterations found as type 4 and that the existence of smectite is indicative of a formation temperature between 0 and 100 ° C. We deduce that the altered minerals found in PK20 indicate the low-temperature hydrothermal alteration of 100° C. Four samples among the fourteen samples analyzed show only the presence of smectite clays. The XRD result of these samples (PK4 and PK5) presented below agrees with the results of petrography showing the presence of smectite. Smectite occurrence identified in samples PK4, PK5, PK7 and PK8, is an important phyllosilicate unique to hydrothermal systems, was a significant indicator of geothermal activity (Heasler and al.,2009). Further, it generally formed a low-temperature event. Results of the alteration map (Fig. 7) from the aerial image are consistent with mineralogical data obtained from XRD studies of the samples taken near the anomaly zone.



Sm: Smectite, Ge: goethite, pyr: pyrite, Er: erionite, Cc: calcite, Hm: hematite



Sm: Smectite, qtz: quartz, Ge: goethite, pyr: pyrite, Er: erionite

Figure 9:XRD diffraction of two samples taken from surface among fourteen samples. PK4 shows the coexistence of Sm: Smectite, Ge: goethite, pyr: pyrite, Er: erionite, Cc: calcite, Hm: hematite. And PK5 shows the coexistence of Sm: Smectite, qtz: quartz, Ge: goethite

4. CONCLUSIONS

The study at PK20-Ambado revealed the presence of fault networks and a good relationship between the high-density faults and the thermal anomaly. Hydrothermal alteration at PK20-Ambado was revealed based on the presence of smectite, goethite, pyrite, erionite, calcite, hematite. These alterations were formed by hydrothermal fluid flowing upwards under the condition of a high water-rock ratio and through highly permeably rocks controlled by geological structure. The results of this study showed that the Ambado_PK20 geothermal field has an intermediate seated reservoir with temperatures ranging from 100 -130°C. This energy can be converted to electricity via binary power plants and the exhausted brine can be used directly for other applications.

REFERENCES

Barberi, F., Ferrara, G. (1975). Structural evolution of the Afar triple junction. In: Pilger, A., Rösler, A. (Eds.) Depression of Ethiopia. Schweizerbart, Stuttgart 1, 38-54.

Barberi, F. & Varet, J. (1977). Volcanism in Afar, small scale plate tectonics implications. Geol. Soc. Am. 88, 1251-1266

Daoud M.A., Barrat J.A. (2008). A LREE-depleted component in the Afar plume: further evidence from recent basalts of Djibouti.

Fournier, M., Gasse, F. (1982). Carte géologique de la République de Djibouti à 1:100 000. Djibouti. ISERST. Ministère français de Coopération, Paris.

Gasse, F., Fournier, M . (1983). Carte géologique de la République de Djibouti à 1:100 000. Djibouti. Notice explicative. ISERST, Ministère français de la Coopération, Paris.

Manighetti, I., P., T., Courtillot, V. (1997). Propagation of rifting along the Arabia-Somalia plate boundary: the Gulfs of Aden and Tadjoura. J. Geophys. Res. 102, 2681-2710.

Schilling, J. G. (1973). Afar mantle plume: rare earth evidence. Nature Phys. Sci .242, 2-5.