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Geological study of Lake Abhe, geothermal field

Samod Youssouf Hassan, Samatar Abdi Mohamed and Hassan Mohamed Magareh

Djiboutian Office for Development of Geothermal Energy (ODDEG)

P.O. Box 2025, Djibouti

samsossi@outlook.fr , ratamas01@gmail.com and hassan_med2@yahoo.fr

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ABSTRACT

Lake Abhé is located in the Afar depression, close to the borders between Ethiopia and Djibouti. The direction of the Gulf of Aden (WWN-EES) predominates clearly thus giving the orientation of the Lake Abhé Graben. The graben is wider in the East and the most collapsed part of the graben is mainly filled in by lacustrine sediments (eg. Gobaad, Le´ado). The origin of the graben and its evolution is evidenced by different fault systems which are of normal types and shear zones. The major faults of the area are the N120° (WNW-ESE) normal faults wich intersect NNW-SSE, N-S, and NE (N30-50°) trending faults and striking and cutting this area in a series of horsts and grabens.

The stratigraphy of the Lake Abhé is composed mainly of volcanic rocks of an age ranging between 3.5 and 1 Ma. The area is characterized by stratoid basalt series, rhyolite, as well as lacustrine sediments of the lake. The stratoid series cover the entire Afar depression and is also well as the dominant geological formation at Lake Abhé.

Most of the hot springs at Lake Abhé are concentrated close to the travertine chimney. The most common direction of the travertine chimneys is E-W along the graben structure but some have N300 direction near the lake. The fumaroles are controlled by the main WNW-ESE fault system. Compared to the thermal springs near Lake Abhé, the fumaroles are characterized by fault breccias and reddish clay.

1. Introduction

This study concerns the geothermal prospect of Lake Abhé, characterized by numerous hydrothermal events in the form of hot springs, fumaroles and travertine. Lake Abhé area is located in the south-west of the country at the western extremity of the Gobaad plain, 90 kilometers from the city of Dikhil. The fieldwork of the Lake Abhé area spans six days. The purpose of the study was to map the geological formations of this region, and the surface

manifestations (hot springs and fumaroles) to determine the relationship with each other. This work enabled us to identify various volcanic and sedimentary geological structures of the region and the tectonic phenomenon affecting them.

Djibouti is adjacent to a triple junction point between the Nubian plate (Northeast), the Somali plate (Southeast) and the Arabian plate. The triple junction of these three plates form the convergence of three rifts also called the Afar Depression:

- The Red Sea (oceanic rift) defines the Arabian plate of Africa.
- The Gulf of Aden (oceanic rift) extends from the Indian Ocean to the Red Sea.
- The East African rift (rift) is the frontier between Nubian and Somalia rift extends to Tanzania.

The recent geological history of this region is the result of the spread of the Gulf of Aden ridge, resulting in the formation of a series of disjointed rift segments in which tectonic deformation and magmatic activity are concentrated. The rift of Asal-Ghoubbet is one of the youngest and most western segments of this ride. It constitutes the onshore extension of the Tadjoura Rift (Manighetti et al., 1997, Daoud et al., 2011). Almost all of the Afar depression (Barbéri and Varet, 1977) is covered by the stratoid basalts, thus partially masking the witnesses of the early stages of rifting, the main manifestations of which are currently exposed to the basaltic traps of the Ethiopian plateaus ~ 30 Ma(Hoffman et al., 1997) and Yemenites 31-26 Ma(Baker et al., 1996a), associated with Afar plume recovery.

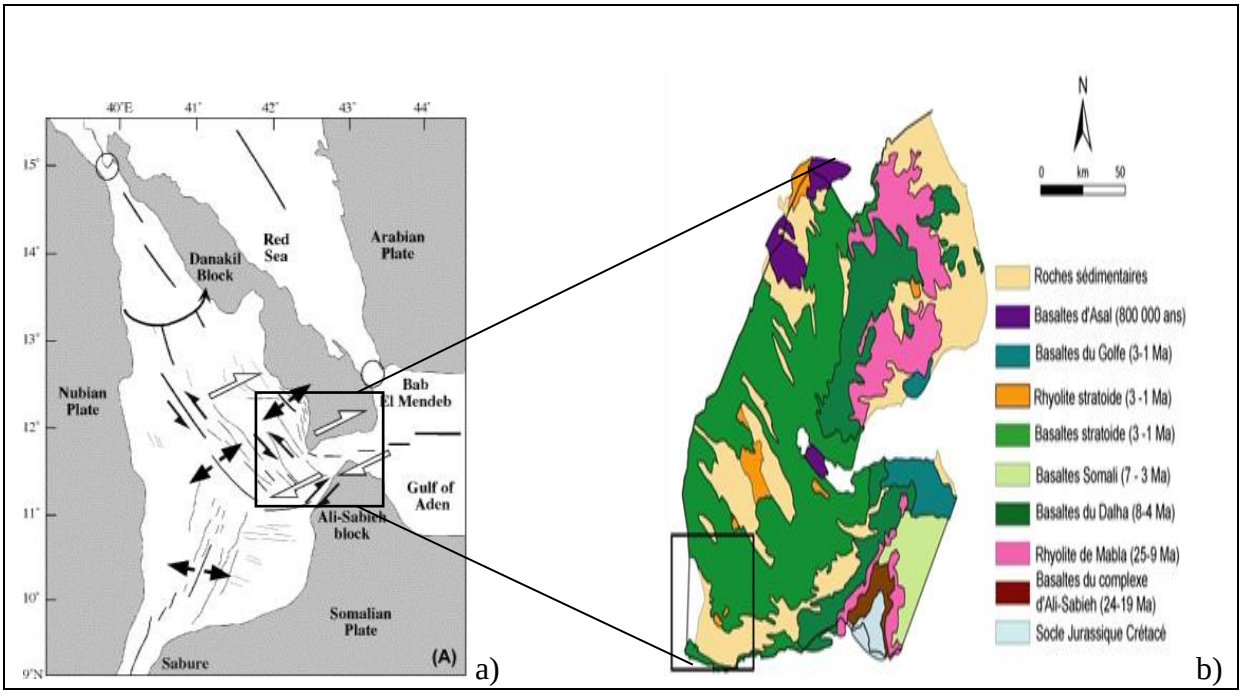

Figure 1: a)Structural map of the Afar Depression showing motions of faults and blocks in the Afar depression. Double-headed arrows designate extension and spreading, open half arrows designate shear couple and solid half arrows show strike-slip motions, (From Beyene and Abdelsalam, (2005). b) Simplified geological map of the Republic of Djibouti. The square shows the study area at Lake Abhé.

The Republic of Djibouti is located in the Afar depression, 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 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).

2. Literature review

The earliest geothermal development surveys in Lake Abhé was carried out by BRGM in 1971. Through these surveys, fluid flow system has been clarified by geological/geochemical survey (BRGM 1971, CERD 2012, ODDEG/ISOR 2015). The BRGM survey proof of the Eritrean steering accidents (NNW-SSE) materialized by alignments of scoria cones testifying to a very recent eruptive phase.

The field work and the first steps of the project are described in reports by Hersir et al. (2016) and Thorbjörnsson et al., (2015). However, the results of the surface exploration survey suggest that the subsurface temperature is not sufficient for electricity generation (ODDEG/ISOR, 2015).

3. Results of Geological setting

3.1 Morpho-structural of the Lac Abhé region.

Lake Abhé is located in the Afar depression, close to the borders between Ethiopia and Djibouti. The lake receives water from the Awash River, within the Ethiopian border. The lake has no outflow on surface and the water level is controlled by evaporation.

The graben hosting Lake Abhé has a particular structure, marked by strong asymmetrical faults. The graben is wider towards the West than the East. The termination of the graben is well developed in Ethiopia. Before the opening of the graben, we can imagine an older relatively high massif, the most resistant part of which would be formed by a base of old traps pierced with rhyolitic domes. Around the plateau composed of all the different basaltic series. The most collapsed part of the graben is mainly filled by lacustrine sediments (Gobaad, Le´ado, etc…). The latter (diatomite, limestone) show the presence of lakes on a geological time scale. At the opening of the graben, the southern part of the region plunges rapidly through a series of half graben faults, while the northern part forms blocks of old basalts and rhyolitic domes (Le'ado, Biida).

Figure 2: Landsat image of Lake Abhé southwest in the Republic of Djibouti. The A (NE)-B (SW) line shows the location of the cross section shown on Figure 3

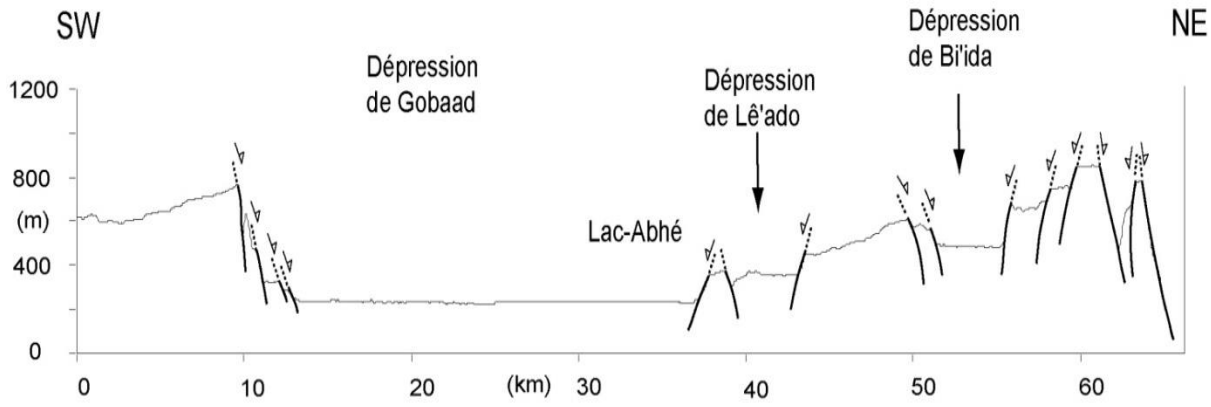

Figure 3: Topographic sections through part of the Lake Abhé region (CERD, 2012)

The graben can be divided in two parts, the Southern part great plain (Gobaad) of 12 to 15 km wide and over 30km from east to west. This graben is entirely filled by lake sediments, fluvial sediments and wind-borne sediments (sand). At the Northern part essentially of traps, we observe low subsidence such as the Le'ado and Biida depression. The origin of the graben and its evolution is manifested by different normal faults and shear zone.

Tectonics manifests itself by several generations of faults:
The major faults in the area are the normal faults with ~N120° (WNW-ESE) strike, cutting this area in a series of horst and grabens.. The vertical release of these faults can reach several hundred meters. They are systematically steeply dipping to the Northeast and to the Southwest. Their orientation changes more or less to East-West strike east of the Lake.
Some NNW, N-S and NE (N30-50°) faults whose play is poorly defined intersect the N120 ° E faults. Subsequent to these structures recent volcanic alignments along NW faults/fissures follow these structures. These effusive alignments are concentrated east of Lake Abhé in an area where the former deformation appears more diffuse.
The alignments of the travertine are in a preferential orientation of N80° E to East-West at the edge of Lake Abhé. The distribution of the travertine chimneys near or within the lake seems

to be controlled mostly by the main structures and where they intersect minor faults or fractures.

3.2 Geological formation and Stratigraphy

The stratigraphy of the Lake Abhé Lake is composed largely of volcanic rocks dated between 3.5-1 Ma. Most of the geological formations outcropping on the Lake-Abhé region belong to the stratoids series (covered over the entire region, this basalt is sometimes altered which changes its colors as well as mineralogy. And also the presence of slag remolded whatever on a cone or on castings.), rhyolite and recent cinder cones, as well as aeolian sediments and lacustrine sediment plating, thus filled by deposition of the sub-lake and the matter carried by the winds. The stratoids series covers the entire Afar depression as well the dominant geological formations at Lake Abhé. In the Study area (southern part of Djibouti), this geological formation has been subdivided into three chronological groups the lower, middle and higher (carte geologique de la région de Dikhil 1:100000). Each set is associated with a basaltic sequence that forms the bulk of the geological formation. However, the base of each set begins in several places by the establishment of hyaloclastite associated with lacustrine sediments.

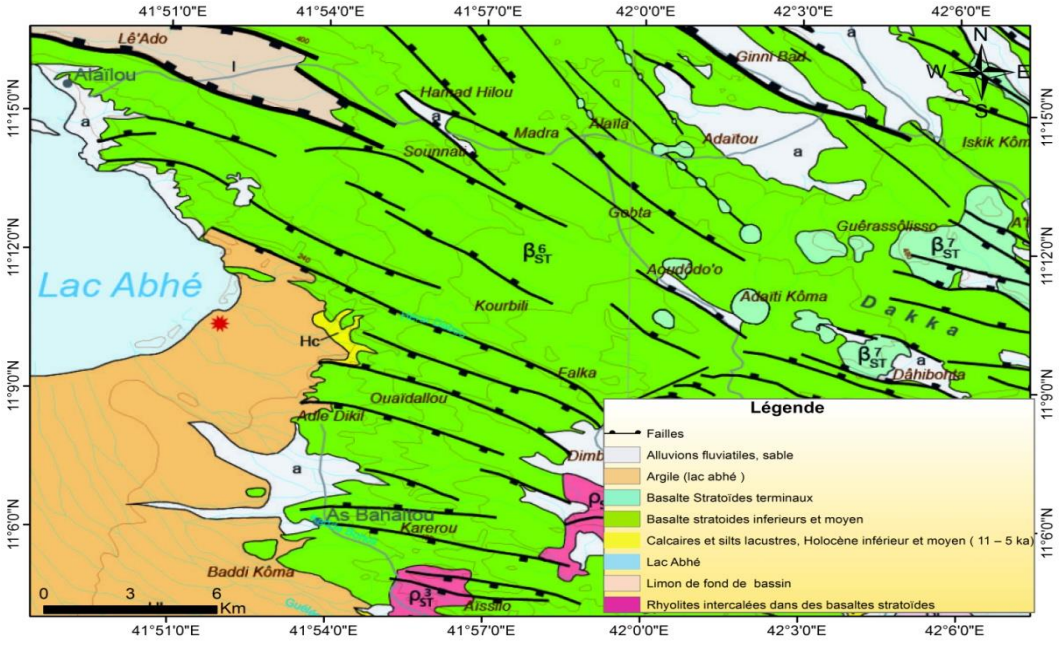

Figure 4: Simplified geological map of Lake Abhé region

And more generally, each set ends with significant rhyolite emissions. The lower set of the stratoid series is the oldest unit in the Lake-Abhé region. This lower set comprises a basaltic series and an acidic series of rhyolite type. The middle set of the strata series is the most important by the extent it covers, the upper set of the stratoid series consists mainly of volcanoes and slag cones, of varying importance, based on the previous unit. The dominant geological formations on the Lake Abhé are mainly of the stratoid series. We notice that there is alternation between basalt and rhyolite, this is due to the different volcanic eruption, but we note that there are two types of basalt according to their age, the ancient basalt (3 Ma) and recent basalt that have different flows. These two eruptions occurred every hundred years and in particular the stratum series cast in general quickly arrived at each other as the rhyolite is thicker than the basalt flows.

4. Geothermal Significance and Discussion.

The interest of this sector is related to the presence of hot springs, whose temperatures reach 100°C, which spring at the base of enormous "chimneys" of calcium carbonate some of which reach 65 m above the current level of lake. In general, the geothermal indices of the Lake Abhé region are divided into 3 categories: hot springs, travertine and fumaroles. In this part the chimneys are still mostly active because they emit hot springs on their foot. Most of the hot springs at Lake Abhé is concentrated close to the travertine chimneys and near the lake. Temperature in these springs varies between 70° C and 100° C. They are all east of the lake (around the travertine chimneys) and occur in the lake sediments. Travertine limestone chimneys close to the lake were formed at the time when the water level in the lake was higher than at present. Most travertine chimneys reach a height of 1-15m and have base diameter of between 5 to 15 m. The largest chimney, most As Bahalto (large chimney) is about 60m high and with about 90m in diameter. The Fumaroles are found at one site (Gamboli), with several steam vents but low flow. These fumaroles are controlled by the main WNW-ESE fault system. Unlike other geothermal manifestations close to Lake Abhé, the fumaroles are characterized by breccia fault and reddish clay. The temperature in the steam range between 98.5°C and 99°C.

The most common direction of the travertine chimneys is E-W along the graben structure but some have N120°, direction. The position of the chimneys seems to indicate that the springs were aligned along the tectonic fractures. From the structural point, these indices are localized doubly collapsed zone undergoes both a subsidence of blocks by EW direction faults, which results in the direction of the graben and N-S slumps caused by N-S faults, indicating the bleachers in the North (Bi'ida, Leado). The tectonic movements of the region are extensive, thus favorable for a convective circulation important for hydrothermal fluids but also the flaws delimiting the graben are of deep nature from where the recovery of old traps. In addition, the presence of active volcanic chain (Dame Ale) of the western shore of the lake is located in a very similar tectonic context.

Previous studies and geothermal prospect of 2015 concluded that the Lake Abhé site is a meduim enthalpy of 110°C to 150°C. In 2015 prospect that the CERD team carried out, they concluded a superficial reservoir of 750 to 950 meters depth, as well as that the companion of 2015 that the ODDEG and ISOR initiates puts in rigor the same results, according to the geological, geophysical and geochemical interpretations.

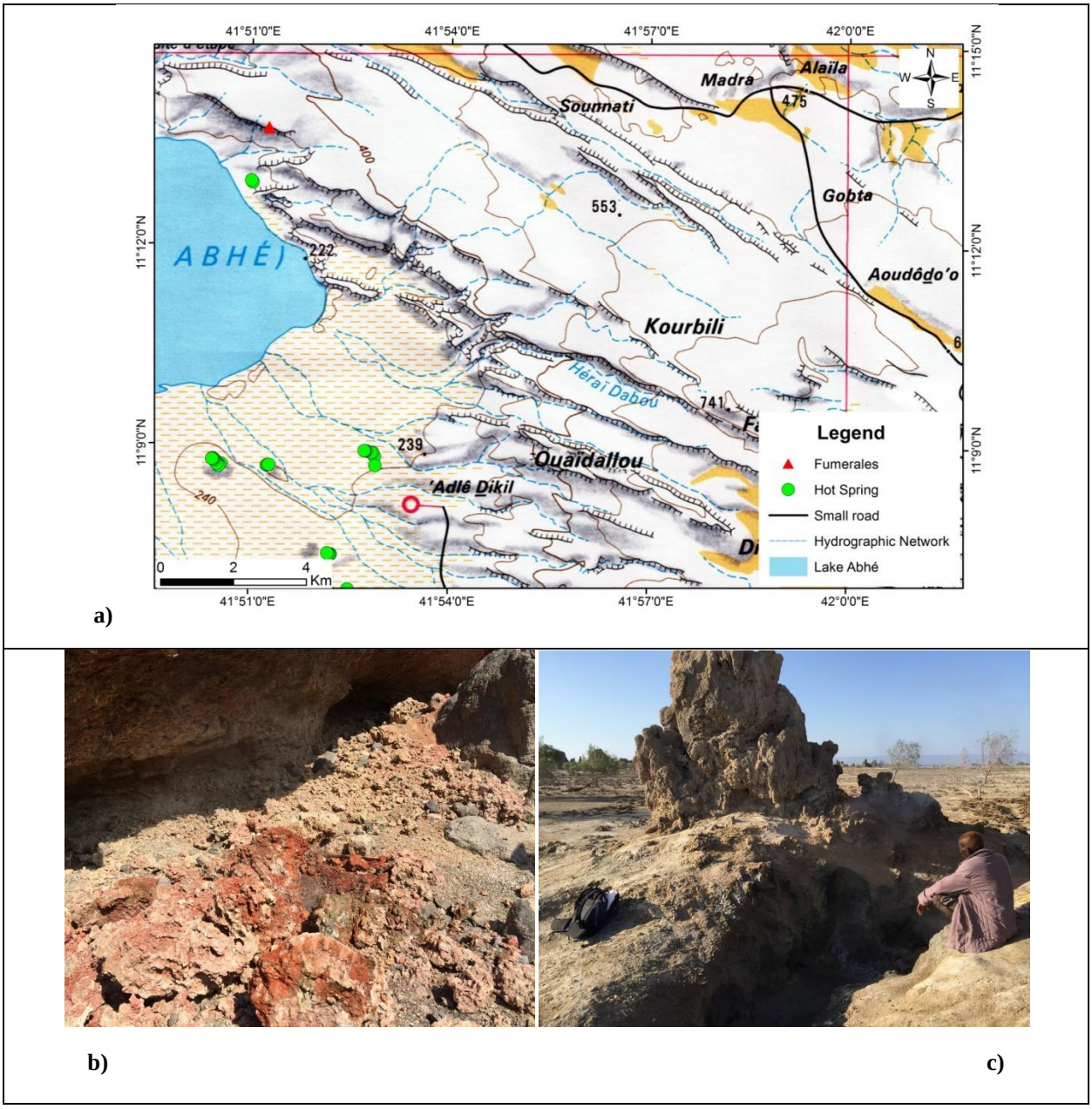

Figure 5: a)Topography map showed springs and steam vents mapped in 2015.*b)* Fumaroles of Gamboli and red clay. Temperature in the vent was 98.7°C. c)Source of hot water that boils with a flow rate of 0.5 L/s. Temperature is 99.8°C.

The geological model of the reservoir is illustrated by underground flows, in addition of that, the flows of cold origins which infiltrate by tectonic fracture and would ascend by heating up to constitute the geothermal reservoir (CERD, Prospect géothermique au site Lac Abhé. (2012)).

5. CONCLUSION

Lake Abhé is an important area in terms of geodynamic context because it is the only place in the world where three rifts meet in an area less than 20 Km. This region is particularly active and unstable with the presence of graben, basaltic flows and rhyolitic flows that come from old volcanic eruptions (3 Ma). The craters are well visible in the area so shows significant volcanic activity the other time in this region.

The lacustrine sediment indicate that the lake had a higher level in the past than now. This is because the stagnation level of the water are clearly visible on the geological formation and travertine. It has many thermal springs located at the foot of travertine and fumaroles that escapes, at the top of some travertine which are aligned along the fissures (faults). This fractures at the bottom of the lake fed by Awash river is the origin of travertines, thermal springs, and fumaroles. The volcano Dama Ali is the only volcano, closest to the Lake where the water during its passage from the subsoil passes next to the reservoir of the volcano thus increases its temperature.

The following are some of the recommendation put forward;

- Fine cartographic study of hydrothermal alterations and their evolutions.
- Conducting further surface studies (geological, hydrogeochemical and thermal) to complete the prefeasibility study.

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