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# Geological and Hydrothermal Alteration Mapping of the Doffen Geothermal Prospect and Adjacent Western Escarpment (Ethiopia)

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## ABSTRACT

Geological and surface hydrothermal alteration mapping was conducted at the Doffen Geothermal Prospect located in the extreme southern part of the Afar Depression and the adjacent western escarpment. Mio-Pliocene basement rocks of the rift floor are the flood basalts of the Afar Stratoid Series and the ignimbrite succession of the Nazret Group, both extensively exposed to the northeast and southwest of the study area respectively. During the Plio-Pleistocene a marginal rift basin parallel to the western escarpment accumulated fluvio-lacustrine sediments with intercalated basaltic lava and felsic pyroclastics (Kessem-Kebena Formation). The area along the extensional axis of the rift (Wonji Fault Belt) is affected by intense Quaternary faulting and central rhyolitic and fissural basaltic volcanism. The Doffen Volcanic Complex (DVC) is such a center which produced intermediate and peralkaline rhyolitic lava between 1.7 and 0.2 Ma with an estimated volume of erupted material of about 25 $km^3$. The volcanic center is dissected by a series of normal faults which formed a graben and divided the center in two peaks with the northern part of the graben marked by a historical basaltic volcanic eruptions.

Active hydrothermal manifestations in the study area occur on the northern and southern parts of the DVC. The manifestations on the northern part of the center are hot springs, hot ground and fumarolic activity with kaolinized ground marked by sulfur mineralization, intimately associated with the recent basaltic aa flows. Fumarolic activity also occurs on the southern flank of the center together with dry mud encrusted rumbling pool on the southern adjoining plain to the center and warm spring activity controlled by the local hydrogeology. Fossil hydrothermal alteration represented by travertine deposits found along the foot of the western escarpment, and also associated with the fluvio-lacustrine sediments attest to the presence of a more widespread hydrothermal activity related to higher water table conditions of the pluvial periods of the Pleistocene. Localities of deep-rooted widespread fossil hydrothermal alteration are found controlled by the tectonic structures that dissect the DVC.

Previous gas geochemical study has indicated subsurface temperatures in excess of 250ºC in the vicinity of the DVC. XRD mineralogical analyses of hydrothermally altered samples showed the presence of secondary minerals comprising of kaolin, illite, chlorite, smectite, pyrophillite, hematite, pyrite, silica, calcite, anhydrite, allunite, native sulphur, bicarbonate salts and rare aluminosilicates. Hydrothermal mineralogical assemblage in most samples indicates an altering fluid with temperature in excess of 150ºC and acidic pH and a noncondensible gases with high $H_2S$ / $H_2$ ratio and an affinity to gases from an active volcanic system. The Mio-Pliocene ignimbrite succession, which is widely exposed along the escarpment presumably, makes the reservoir for the prevailing hydrothermal system(s) and hence the western escarpment area requires a focused investigation. It is recommended that a proposed shallow temperature gradient survey consist of at least one drill well at each of the northern and southern part of the DVC to determine the direction of hydrothermal fluid circulation and make plausible isotherms over the magmatic system that determines the thermal budget.

## 1. INTRODUCTION

Geological and surface hydrothermal alteration mapping of the Doffen Geothermal Prospect is conducted as part of an ongoing follow up study to utilize geothermal resources from the more than a dozen prospects in the Main Ethiopian Rift (MER) and Afar Depression (AD). The study area is located in the southern AD or the northern extreme part of the MER and includes the adjacent western escarpment and is enclosed between 9º15’ and 9º30’ N - long. and 39º45’ and 40º00’ E - lat. geographic coordinates and is situated along the Addis Ababa - Djibouti trunk road (figure 1). The western part of the study area making the rift escarpment is faulted by a series of faults and slopes down from the highest elevation of over 2000m a.s.l. to an average elevation of 750 m a.s.l. in the rift floor. The Doffen Volcanic Complex (DVC) rises 300 m above the surrounding rift floor to 1055 m a.s.l. Awash River, which flows in the general northeast direction parallel to the western escarpment with its tributaries such as Kessem, Kebena and Tunfeta, drain the study area. A warm climate with a mean annual temperature ranging between 20°C and 30°C with daily maximum temperatures as high as 35°C in the rift floor and annual precipitation between 400 and 1200 mm is typical of the study area (EMA, 1988). The land along the escarpments is cultivated for short duration crops combined with a pastoralist subsistence farming whereas a primarily traditional pastoralist land use and commercial mechanized agricultural systems are wide spread in the rift floor.

In many geothermal areas hydrothermal alteration associated with fumaroles and acid sulfate springs is typically preserved for shorter period of time than from alkali chloride springs. An increasing order of resistance to weathering is soluble salts, kaolin and other clays, anhydrite, pyrite, calcite, aragonite, and silica sinter. On the other hand silica sinter is almost exclusively deposited at the ground surface whereas the products of acid alteration pervade much country rock below the surface. Mapping fossil hydrothermal manifestations therefore provides information on the nature of the altering fluid, duration and age of the thermal activity, the existence of geological structures, which might have controlled circulation of hydrothermal fluids and an overview of the size of the geothermal field. Two 1:50,000 scale topographic base map subsheets and 1:60,000 scale aerial photos were used to prepare the geologic maps. All active and fossil hydrothermally altered grounds (fossil altered grounds, hot grounds, fumaroles, mud pools and hot springs) were

located on the map in addition to observations on the type and aerial extent of the altered grounds. 40 rock samples were collected for petrographic study of the major geologic map units from the study area. 8 samples were collected from products of hydrothermal alteration and mineralization for physical mineralogical analyses (XRD). Untreated bulk powder samples from the hydrothermal alteration samples were analyzed on an x-ray diffractogram (SIEMENS - D8 Advance model, Serial No D8-01/08-340) in the Central Geological Laboratory (GSE).

Among the earlier regional geothermal exploration work in the area is the joint GSE-UN technical team reconnaissance study (UNDP, 1973) including infrared surveys conducted in a broader area covering the whole of the MER and AD. Subsequent studies conducted in selected prospects including the study area showed that the DVC erupted considerable volume of pantelleritic lava from numerous eruptive centers and that petrologic studies indicate the existence of a magma chamber at a depth not exceeding 4-6 km (ELC, 1987). Active tensional tectonics is evident and responsible for the N-S trending graben structure that dissected the central part of the DVC and also rejuvenated volcanicity with a sub-historic basaltic effusion. Several active hydrothermal manifestations (fumaroles and hot springs) exist within the graben with an impervious cap rock and possibility of an effective recharge from the highlands.

Fluid geochemical survey showed that the waters present in this area are alkaline bicarbonate and chloride type of waters with relatively higher content of sulfate. Various chemical geothermometers (such as Na/K; Na-K-Ca) indicated reservoir temperature in the range of 105-145°C. Geoelectrical survey indicated a resistive basement characterized by medium to high resistivity which represents the rift floor basalts (Afar Stratoid Series) is overlain by a conductive unit probably corresponding to the sedimentary sequence (Kessem-Kebena Formation) or a combination of a sedimentary sequence and the underlying Nazret Group, which potentially make the reservoir rocks. An intermediate unit between the surfacial and the conductive unit is presumed to correspond to lavas of the DVC with an upper unit characterized by medium to high resistivity representing the recent alluvial products. A gravimetric survey showed that the resistive basement has been strongly dissected by tectonism with step like structures, with narrow horsts and grabens mostly oriented N-S to NNE-SSW (ELC, 1987).

## 2. GEOLOGY

Regional geologic studies show that pre-Tertiary rocks while outcropping on both the northwestern and southeastern plateau and basement horsts in the southern and central parts of the MER are not represented in the area. The only non-volcanic formations are the widespread volcanogenic fluvio-lacustrine sediments of Plio-Pleistocene age. Within the continental scale graben of the MER and southern AD a discontinuous belt of Quaternary volcano-tectonic activity making the axial spreading zone(s) of the rift known as the Wonji Fault Belt (WFB) were the focus area for geothermal resources utilization. The WFB have several easterly transversally displaced segments with each segment being a host to at least one major rhyolitic volcanic center. The DVC is one such center on one of the northern sectors of the WFB and has produced significant quantities of felsic lavas. In addition to the regional thermal anomaly related to the lingering magmatism associated with crustal extension in the region, locally concentrated magma chambers feeding both fissural and central volcanism are likely to be present all along the WFB. The following major rock units were mapped in the study area and are shown on figure 2 placed at the end of this manuscript.

### 2.1 Pre-rift Basalts (Tb)

Exposures of pre-rift basalts are found on the western escarpment in deeply incised river gorges such as Kebena and Tunfeta rivers and faults of high vertical displacement along the escarpment. Miocene basaltic volcanism in the region consist of a tholeiitic flood basalt succession with intercalated felsic products particularly near the upper part, known as the Alaji Group with a K-Ar age range between 25-23 Ma in the region (Chernet, 1995). This unit is overlain by central shield forming alkaline basalts formed particularly in the vicinity of the rift escarpments known as the Tarmaber Group with K-Ar ages range between 15-10 Ma. Such aphyric, jointed and spheroidally weathered basalt flow units with intervening scoriacious soil horizons are exposed on ridges descending to the rift floor in the extreme western part of the study area.

### 2.2 Nazret Group (Nn1, Nn2 and N)

The Nazret Group consists of several ignimbrite flow/cooling units of predominantly Pliocene age with interbedded air fall ash, rhyolite flows and domes and minor basaltic lava. Numerous centers along the rift margin that are now obscured by volcanoclastic sedimentation are proposed to have erupted these voluminous pyroclastic products. (Kazmin, 1979). On the western part of the study area along the escarpments are exposed a series of ignimbrite flow units belonging to this group, intensely dissected by sub-parallel NNE-SSW trending faults which show flexuring and displacement of fault blocks in an antithetic sense both to the east and west. Thickness as large as 250m has been reported, even though a much more thicker succession of ignimbrites should be expected in the rift floor. However in the study area a thickness of about 100m were observed along the river gorges on the escarpment. Near Gorgo township greenish grey, lithic, crystal rich ignimbrite showing columnar jointing and a thickness of about 20m overlies a massive yellow tuff over 30 m thick with a glassy bottom. In some localities the Nazret Group ignimbrites unconformably overlie an inclined bed of a massive brown silty clay layer with a thickness of up to 10m, which directly overlies the pre-rift basalts (N).

### 2.3 Afar Stratoid Series ($N_{1\text{-}2}$ab)

Pliocene flood basalts of the AD known as the Afar Stratoid Series (ASS) crop out on the southeastern part of the study area along the main Addis Ababa – Djibouti road. In this road exposure the ASS basalts are moderately weathered, jointed and vesicular with vesicles and joints filled with secondary calcite. The ASS flood basalts have a thickness greater than 1000 m in the region and probably constitute a significant portion of the crust in the AD. The ASS basalts are dissected by a series of NNE-SSW trending faults and in the southeastern part of the study area make a basement horst in which adjacent grabens are filled by fluvio-lacustrine sediments.

### 2.4 Fluvio-lacustrine Sediments (NQ – Kessem Kebena Formation)

Fluvio-lacustrine sediments (silty clay, sandstone and sandy conglomerate) are found exposed between the western escarpment and the active spreading axis of the northern MER (WFB). The succession of fluvio-lacustrine sediments

with intercalated basaltic lava flows and felsic tephra (ash, pumice and ignimbrites) was accumulated in a marginal graben that acted as a sedimentary depocenter in a shallow lacustrine and fluvial environment. In the study area the sediments have a thickness of up to 100 m and an average thickness of 60 m in many sections. It is probable that the southern bounding fault structure of the basin is related to the southern AD escarpment. Furthermore part of this sedimentary succession is correlable to sediments found east of the DVC exposed along river gorges on the southeastern part of the study area. These sediments have been dated using the K-Ar and 40Ar/39Ar methods on intercalated volcanic products (pyroclastic ash and basaltic lava) to yield ages between 3.7 – 1.0 Ma (WoldeGabriel et al., 1992).

**2.5 Quaternary Basalts (Qb1)**

Volcanic activity in the vicinity of DVC was initiated by an extrusion of olivine basalt lava and scoria along two sub-parallel NNE-SSW trending fissures to the east and west of the center. These basaltic extrusions appear to be precursors to the nucleation and growth of the DVC and to the west of the volcano contain hyaloclastite members. The partly contemporary nature of the basalts to the fluvio-lacustrine sediments shows the long persistence of structurally controlled mafic magmatism in the region. More proximally to the DVC magmatic differentiation processes of related basalts have resulted eruptions of trachybasalts (Qtb) considered to represent the initial phases of volcanism at the center. Near the northern central part of the DVC plagioclase mega-porphyritc variety of basalt is exposed which suggests deep seated differentiation processes of the Quaternary basalts may have given way to subsequent more felsic, differentiates.

**2.6 Doffen Volcanic Complex (DVC)**

The DVC is one of the felsic volcanic complexes situated on one of the northern sectors of the WFB, which hosts Fentale Volcanic Complex (Gibson, 1974) to the south. The volcanic complex appears to be located in a graben close to the western escarpment. Volcanic activity at the center was initiated in the Pleistocene period by a tracy-basaltic lava flow that is now exposed on the eastern and western flanks of the center. This is followed by a predominantly pantelleritic rhyolite flow and dome formation during the middle Pleistocene which built the main volcanic massif. A major extensional volcano-tectonic activity in the region created a NNE-SSW trending graben about 5km wide across the central part of the volcanic massif. Resurgence of volcanic activity later created two rhyolite domes on the eastern part of the volcano.

Quantity of erupted magma from the center is estimated to have a volume of 20-30 $km^3$ that is less by one order of magnitude as compared to its southern nebhouring center of Fentale (>100 $km^3$). However the presence of a felsic magma chamber below the volcanic center is evident from the persistence of volcanic activity at the center for over one million years. It is noteworthy that the prevalence extensional tectonics may favor injection of basaltic magma from the mantle and may affect the stability and geometry of existing felsic magma chambers. And hence like at Fentale recent / historical activity is represented by scoriacious and aa basaltic volcanic activity and may make the existence of magma chamber questionable. The influence of volcanic activity from the center appear to be spread out over an elliptical area with a longer axis perpendicular to the rift axis and a maximum diameter of about 7km. This radius of influence is much smaller as compared to the nearly circular subsidence structure, which accompanied the formation the Fentale Volcanic Complex with a diameter exceeding 50 km. Deep seismic experiments in the northern MER southern AD has identified a number magmatic segments which nearly correspond to the northern sectors of the WFB (Maguire et al., 2003) and may suggest a subsidiary (if not parasitic) nature of DVC to Fentale.

2.6.1 Quaternary trachy basalts (Qtb)

Circumscribing the western flank of the DVC and to the south of the center dark grey locally vesiculated trachy-basalt (mugearite) lava flows crop out on structural highs covering several tens of kilometers and are dissected by a series of sub-parallel NNE-SSE trending fault scarps. These trachy-basalts are associated with scoria cones and cinder cones to the west of the younger felsic domes of the DVC. Samples from this typically dark grey, vesicular, weakly banded, lava representing the earliest activity from the center yielded K-Ar of 1.7 Ma (Elc, 1987).

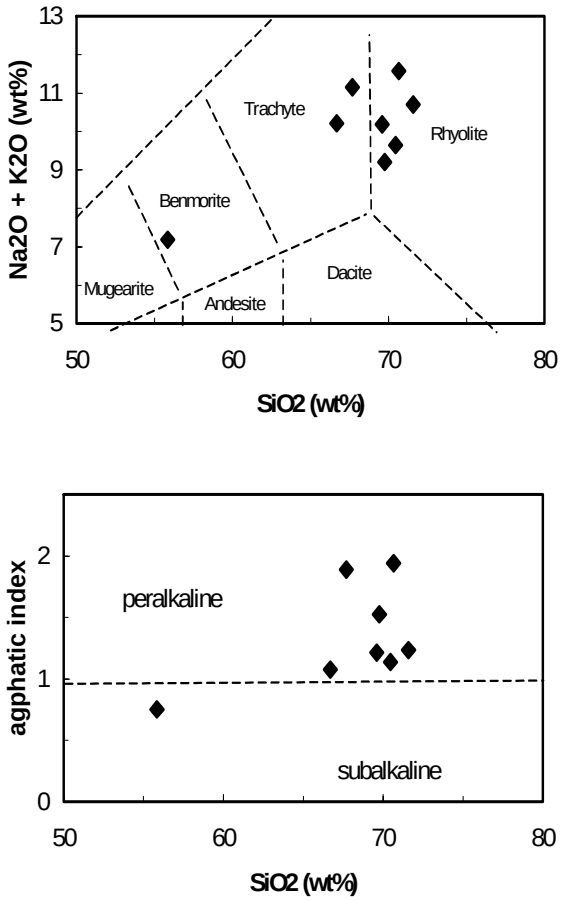


**Figure 3: Total alkalis and agphatic index plotted against SiO2 (wt%) to show the geochemical features of the Quaternary felsic lavas of Doffen and Fentale volcanic complexes (data from Cherent, 1995).**

2.6.2 Quaternary Rhyolites (Qr1)

Rhyolite flows and domes, which constitute the main part of the DVC predate the formation of the NNE-SSW trending graben structure, which affected the central part of the center. Geochemically most of the felsic products from the center are peralkaline (rhyolites and trachytes). The lava are dark grey, vesicular and exposures several meters thick can be found on fault scarps forming the graben. The

rhyolites are extruded from morphologically well preserved edifices with radially coalescing viscous lava accumulating over tens of square kilometers. Three rhyolitic volcanic edifices (i) Western (ii) Northwestern (iii) Eastern can be identified at th DVC from photo-geologic studies. A fourth center which probably produced minor pyroclastic products and had an accompanying collapse structure had been down thrown into the northern floor of the central graben structure and coincides with the area where recent basaltic extrusions, intense alteration and solfatara activity are found. A more detailed account of the eruption history from the center and each edifice has been given (Elc, 1987) and a K-Ar age of 0.5 Ma has been obtained from a rhyolite lava from the Western edifice.

2.6.3 Quaternary Rhyolites (Qr2)

Two rhyolite domes covering a few square kilometers are localized to the northeast and southeast of the eastern edifice and represent the latest felsic volcanic activity from the DVC. Their well preserved and youthful morphology together with the relation of the flows to preexisting flows from the eastern edifice suggests their recent age of formation. More over the flows were not affected by the NNE-SSW trending fault systems that may indicate that the domes postdate the tectonic activity, which created the central graben.

2.6.4 Holocene Basalts (Qb2)

In the central northern part of the DVC where the graben structure joins the surrounding plain recent basaltic lava and scoria (some of which is confirmed to be not more than a century old, Elc, 1987) are wide spread. This volcanic activity occurred from numerous structurally controlled vents which produced basaltic aa flows and scoria and cinder cones with total thickness nearly 10 meters on a related fault scarp. At the northern part of DVC (near the abandoned plantation camp) are found numerous scoria cones and layered scoriacious basalt and basaltic lapelli with intervening discontinuous vesicular lava flows exposed along a fault scarp.

### 2.7 Recent Alluvial Sediments (Qal)

Along many waddis in the central and western part of the study area are exposed layered alluvial sediments consisting of a lower yellowish brown silt and sand overlain by an agglomerate layer with well rounded boulders and cobble outwash a few meters thick and having an overall thickness of about 10 meters. In the vicinity of the low lying floodplain of Awash River, the widespread alluvial sediments are capped by a grayish brown organic rich alluvial soil which has enabled large scale mechanized farming in the area. Quarrying for construction material of these sands is being undertaken in some of the waddis and riverbeds.

## 3. HYDROTHERMAL MANIFESTATIONS AND ALTERATION

### 3.1 Northern Part of DVC

(a) The most profuse active hydrothermal manifestation in the area is found in the graben in the northern part of the DVC. The graben appears to have been overlapped by a circular volcanic depression possibly a small basaltic crater with a diameter of about 500m and the center marked by recent basaltic aa flow. Four major zones of intensive hydrothermal alteration and activity are exposed on the bounding scarps. Each zone of alteration has an area of nearly 100 $m^2$ except the northeastern one that has an area of about 30 $m^2$. Fumarolic activity has altered the country rock into yellowish and pink clay with disseminated native sulfur particularly in the western zones. Low pressure and hissing fumarolic vents are found with sinter and travertine deposits found in cavities and joints in the less altered scoriacious and aa basaltic lava. Clay from the eastern zone shows a moisture absorbing property when rubbed between fingers due to the presence of hygroscopic salts (NaHCO3?). Weak fumarolic vents are also found in the vicinity of Doffen plantation town emerging from within the scoriacious basalts unit. These fumarolic vents appear to be offshoots of the main zone of fumarolic activity and do not show even superficial hydrothermal alteration.

(b) Two major areas of hot spring activity are found north of DVC. The first group of springs are located on the plain north of DVC a few hundred meters northwest of the Doffen plantation town. These springs discharge warm water (~50˚C) that flows into a nearby swamp and no appreciable flow outside the area. The other group of warm springs emerge from the base of the NNE - SSW trending fault making the western bank of Lake Debhile. Except the presence of algae both hot spring localities do not show appreciable hydrothermal alteration or precipitation in their vicinity. Northeast of the DVC warm springs are also reported to emerge from the alluvial soil along the banks of the Awash river, but are flooded by the river during most seasons in the year. The other type of hydrothermal manifestation is wide spread warm ground found in many localities near the northern part the DVC.

### 3.2 Southern part of the DVC

Fumaroic activity is found on an east facing fault scarp making the southwestern side of the DVC. Moderate pressure fumarolic vents making hissing sound with surrounding brick red clay with siliceous crust altered hot ground cover the scarp about 10 m high. About 2km due south from this location along the same structural line south Tunfeta Wadi a dry mud pool with an underground hissing and bubbling sound is found covered by a crust of dry and cracked mud a few meters in diameter. From local reports, the pool gets wet and fills with viscous bubbling mud during seasons of elevated water table. The vicinity of the pool over an area of some 200 sqm is surrounded by hot ground covered by barren sand.

Other types of hydrothermal activity to the south of the DVC include numerous low-discharge warm springs along the banks of Kebena river north of Yallo cotton plantation. Temperatures between 50 and 55˚C were reported for these springs (Chernet and G/Egzeabhere, 1983). Other types of hydrothermal activity in the study area include travertine deposits along the western escarpment, which are also found associated with the fluvio-lacustrine sediments attest to the presence of a more widespread hydrothermal activity related to higher water table conditions of the pluvial periods of the Pleistocene.

### 3.3 Hydrothermal Alteration

Besides the observed alteration found with active hydrothermal manifestations, many localities of fossil hydrothermal alteration controlled by the tectonic structures, that dissects the DVC, are shown on the map (figure 2) eventhough sampling of the sites was not possible due to the difficult access. The most important zone of active hydrothermal alteration is however the wide spread fumarolic activity found near the northern part of the DVC. Detailed mineralogical study of the alteration products was done on about eight samples from the study area.

Most of the samples contain hydrothermal minerals consisting of kaolinite, illite, chlorite, smectite, pyrophillite, hematite, pyrite, quartz with its various polymorphs, calcite anhydrite, allunite, native sulphur and rare ferromagnesian silicates and feldspars (figure 4). A systematic sampling and rigorous mineralogical analysis would have enabled to identify zonation on certain mineralogical criteria, which may indicate migration of the focal point of hydrothermal activity and variation(s) in temperature and chemistry of the altering fluid. Peculiar to the study area as applies to the hydrothermal mineralogy is the occurrence of wide spread disseminated native Sulphur, with anhydrite and gypsum with the secondary clay minerals on the northern part of the DVC. The presence of illite and chlorite show that the temperature of the altering fluid is in excess of boiling temperature and could range between 150-250 ˚C. The presence of Kaolinitc clays shows an acidic pH of the altering fluid. The presence of Sulphur may suggest the presence of a volcanic system with high $H_2S$ / $H_2$ ratio.

## 4. CONCLUSIONS AND RECOMMENDATIONS

The presented scientific data show that the vicinity of the DVC has a magmatic heat source manifested as recent felsic and mafic volcanism, geological strata that provide a suitable reservoir and cap rocks and an effective recharge from precipitation on the northwestern plateau. Notwithstanding that Doffen geothermal prospect has qualified as high priority for a more detailed study including geophysical studies, the work outlined above is far from complete to fully understand the nature of the hydrothermal system(s) in the study area. The following points need to be considered for follow up geologic and hydrothermal alteration studies to be conducted. [1] More systematic sampling with secondary hydrothermal alteration samples being collected from a grid of pits to be dug within the zones of alteration having a depth some 30-50 centimeters. [2] More detailed XRD study to qualitavely and quantitatively investigate the clay minerals (i.e. 2-20°, 2 theta, air dry, heated, glycolated) to identify distinct mineralogical zonation using other secondary minerals as additional hydrothermal alteration index minerals and establish a suitable mapping criteria for continuing similar works. [3] More field traverses are required in the vicinity of the western escarpment to establish the stratigraphic relation between the Mio-Pliocene volcanic and related sedimentary successions, which make the reservoir rock of the prevailing hydrothermal system. [4] If follow up geoscientific studies to be conducted in the area get a support from shallow temperature gradient survey it is recommended at least one well be drilled on each of the hydrothermal fields on the northern and southern part of the DVC. This provides important subsurface temperature gradient data which helps establish a direction of hydrothermal fluid circulation in the area and a relationship between the deep convective hydrothermal fluid and shallow hydrologically controlled thermal features.

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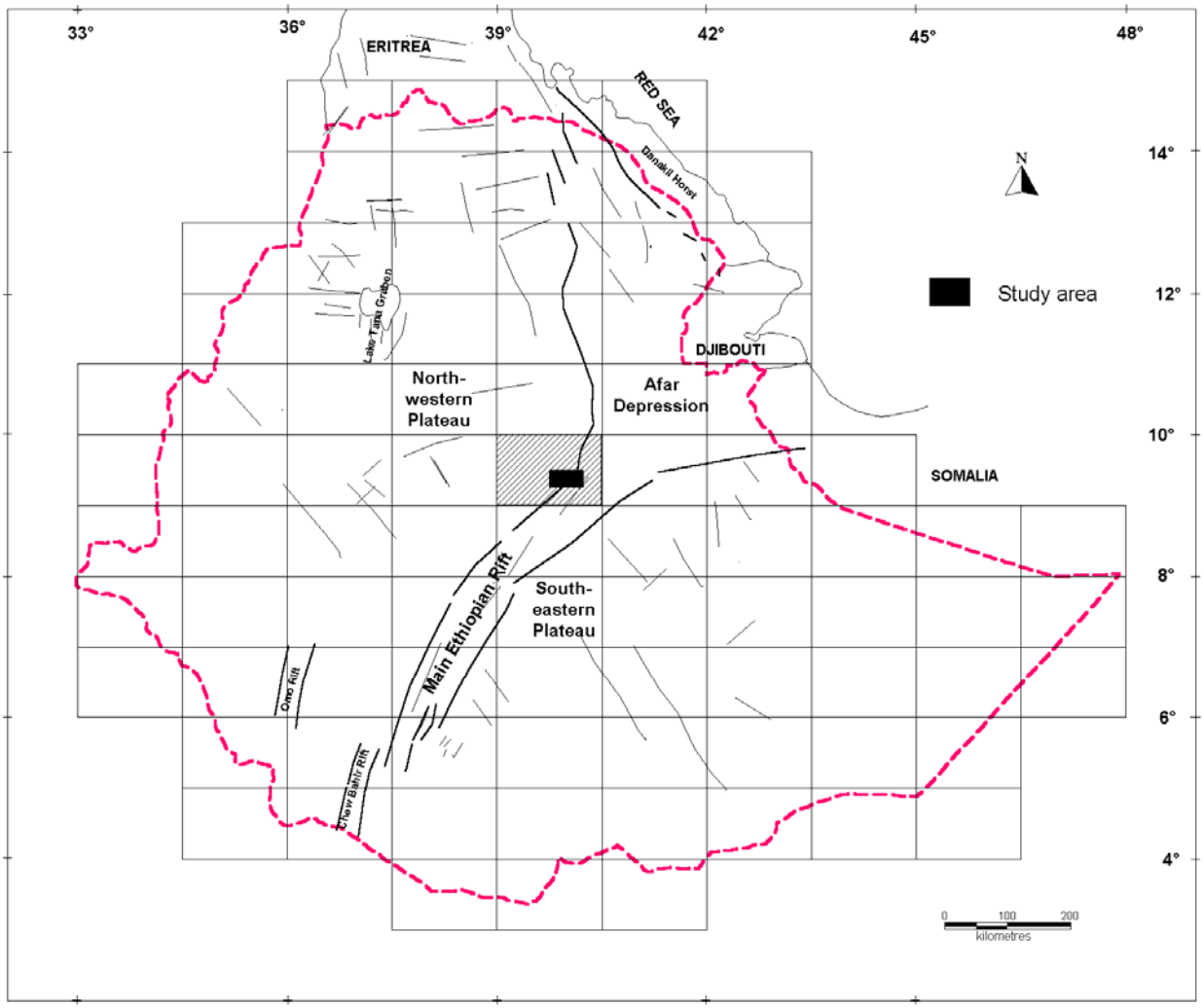


**Figure 1: Location map of the study area. (zoom in to 150-200%)**

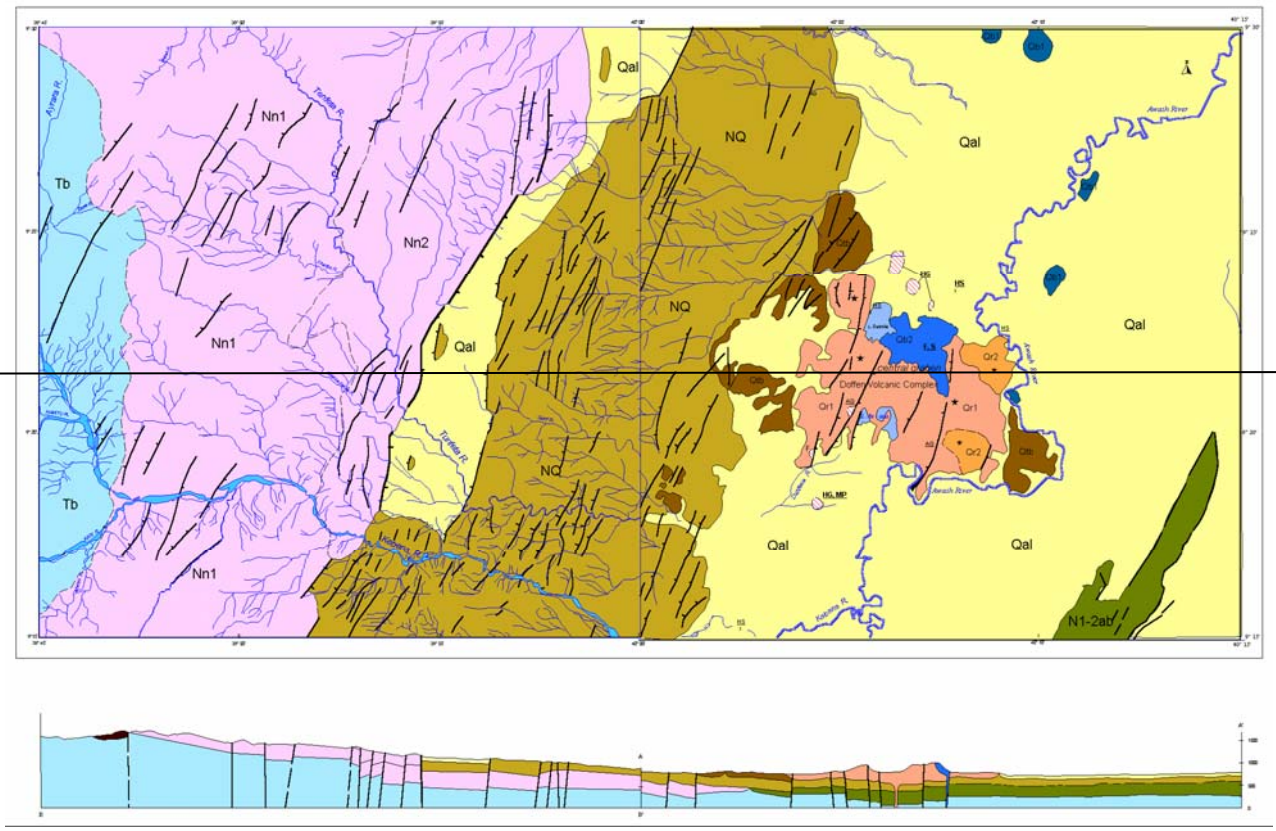


**Figure 2: Geological map of the study area, (text for deatail). Hydrothermal features: G - fossil hydrothermal alteration, HG - hot ground, F - fumaroles, S - solfatara, HS - hot spring, MP - mud pool.**

LEGEND

VOLCANIC UNITS

Holocene

Qb2 - Recent basalts associated with scoria cones

Qr2 - Resurgent rhyolite domes of the Doffen volcanic complex,with youthful features and post date graben subsidence.

Pleistocene

Qr1 - Rhyolite domes and flows forming the main Doffen volcanic complex. Hypersthen hornblende rhyolite.

Qtb - Trachybasalt (mugearite) lava flows forming initial volcanic activity of the Doffen volcanic complex.

Qb1 - Vesicular and amygdyloidal flows with associated scoria cones and hyaloclastite deposits

Pliocene

N1 - 2ab - Afar stratoid seres - flood basalts of the Afar rift floor, seriate porpyritic (labradorite augite) basalt forming the Afar rift floor and later affected by intense faulting.

Nn - Nazret group - welded ignimbrite and ash flow tuff, with rhyolite domes and rare interbedded basalt flows.

Oligocene Miocene

Nb - undifferentiated trap basalts alkaline basaltic lava flows from central shield forming centers on the rift shoulder (Tarmaber group) weathered aphanitic basalt with intercalations of welded ignimbrite near the upper part (Alaji group)

SEDIMENTARY UNITS

Holocene

Qal - Alluvial silt, sand and gravel

Plio - Pleistocene

NQ - Kessem Kebena formation lake sediments,silty clay,sandstone,and calcite cemented conglomerates, withpumice,ash flow and basalt flow intercalations (3.7 - 1 Ma )

Pliocene - Miocene

N - Undifferentiated intertrappean sediments (siltstone with interbedded ash flow tuff )

Geological contact (broken if inferred)

Fault (broken if inferred )

Crater / Major volcanic edifice

Hot Ground / Altered ground

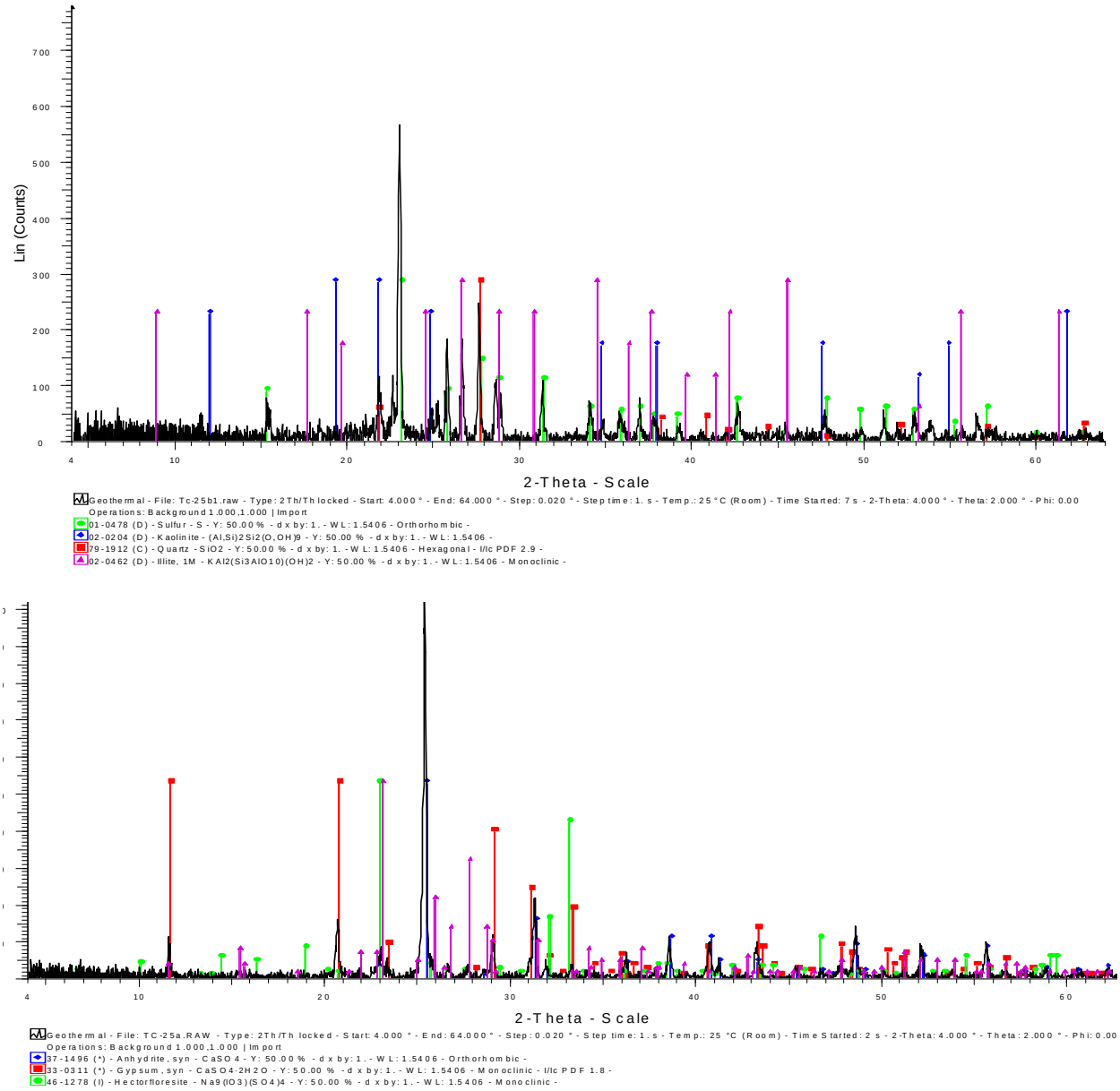


**Figure 4: Selected XRD pattern of hydrothermal alteration samples from the northern Doffen hydrothermal area. Note prominent peaks for illite, kaolinite, quartz, anhydrite and sulphur that indicate acidic alteration.**