

Preliminary study on geology, mineral potential and characteristics of hot springs from Dallol area, Afar rift, northeastern Ethiopia: implications for natural resource exploration

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ABSTRACT

Dallol area is located in Afar region of northeastern Ethiopia. From west to east, the geology of the area is characterized by: i) Neoproterozoic metavolcanics and metasediments, ii) Quaternary alluvial fan deposits and red beds, iii) a transitional zone of mud and salt mixture, and iv) evaporites, which consist of rock salt (commonly halite and potash) and sulfur/sulfides. The metavolcanic-sedimentary rocks of the area are sheared and locally affected by pervasive chloritization, silicification, and carbonatization as well as quartz-carbonate veining suggesting that it has a good potential for orogenic gold mineralization. The around 5 m thick alluvial sediments of Gehartu and Musely Fans are also favorable for the occurrence of placer gold deposits. This study reveals that industrial minerals such as kaolin and mica are also encountered in the Dallol area in addition to the already known sulfur and salt deposits. In surrounding areas of mount Dallol, hot springs of varying temperature and extent are being erupted forming semi-circular to circular ponds. In this study, two types of hot springs, light-yellowish and yellowish brines are recognized which are contaminated with mud. Field observations show that both brines have indications for the presence of oil as sensed by greasy feelings. To know the general compositions of the hot springs and test the presence of liquid hydrocarbons, 8 water samples were collected and analyzed for major element contents, sulfide, sulfate and Total Organic Carbon (TOC) concentrations. The preliminary results show that TOC values are moderately low (94 to 902 ppm). Sulfate (19 to 60 ppm) and sulfide (27 to 111 ppm) concentrations are low except for one sample with higher concentrations for both complexes. Their low sulfide and sulfate content suggest that these compounds are converted into sulfur/sulfide by bacterial reduction of magmatic and/or sea water SO₂ or sulfate. Therefore, the Dallol hot springs are interpreted to be derived from heated groundwater mixed with sulfides/sulfates of magmatic and/or sea water origin. Although low, the up to 902 ppm TOC concentrations in the hydrothermal fluids could suggest the presence of hydrocarbon containing rocks at depth and/or fluid mixing with laterally and/or vertically migrating hydrocarbon fluids. Generally, the Dallol area contains huge metallic and non metallic resources, which warrant detailed exploration and further scientific study.

Key words: Dallol, Hot spring, Rock salt, Sulfur, Mineral resources, Afar, Ethiopia.

1. INTRODUCTION

Located in Afar Regional State, northeastern Ethiopia, Dallol area represents the second lowest water uncovered oceanic crust on Earth with a depth of ~120 m below sea level (reference missing Fig.1). The region is also known for its huge natural resources such as rock salt, potash and manganese deposits (e.g. Tadesse et al. 2003). Traditional rock salt mining has been active in the Dallol area for centuries. Preliminary and detailed exploration surveys for potash deposits were conducted in the 1950's by American and Italian companies. The companies estimated the presence of a 100 Mt of potash. However, the quantity and quality of these resources is not yet exactly established. In addition to the salt resources, hot springs are continuously erupting at different spots of mount Dallol and its surroundings by forming circular to sub circular ponds. They are becoming tourist destinations for visitors from all over the world. There are also sulfur and trace metal deposits at mount Dallol and its environs. Currently, a detailed exploration work is being carried out for potash in the Musley/Dallol area by Indian, Canadian and German companies to properly calculate its reserve and possibly establish a mine that could produce raw materials necessary to produce fertilizers and chemicals. Reconnaissance exploration works for hydrocarbon excluding the study area are also ongoing in different blocks of the Afar rift system. However, scientific research outcomes related to hydrocarbon and mineral resources are limited. This paper presents an overview of the geology and mineral potential of the region, nature and characteristics of the hot springs, which were observed and sampled during field excursions in and around Dallol organized by Mekelle University with an objective of assessing its natural resources potential.

1.1. Accessibility and physiography

The Dallol area is located about 200 km NE of Mekelle, in Afar Regional State, northeastern Ethiopia (Fig. 1). After travelling through the main asphalt road from Mekelle to Agulae town, one has to turn towards NE and drive through a gravel road that takes to Berahle town. Dallol is finally reached after driving consistently in NE direction from Berahle through the gravel road. The geomorphology of the Dallol region is characterized by the rugged and dissected rift scarps in the west, flat lying plains in the center and by the Tertiary Denakil volcanic ridges in the east (Fig.1). Major physiographic features existing on the top of the salt plains are the ~60 m high Mount Dallol, which is interpreted to be formed by an uplift due to existence of magmatic

intrusion beneath and the ~-20 m high reddish grey mountain (locally called Ashale), which is made up of salt and mud mixtures and used as traditional medicine for various diseases by the local people. The Dallol area is characterized by the hot climatic condition with average annual rainfall of 50 to 100 mm and average annual temperature of 25°C to 45°C (Garland 1980).

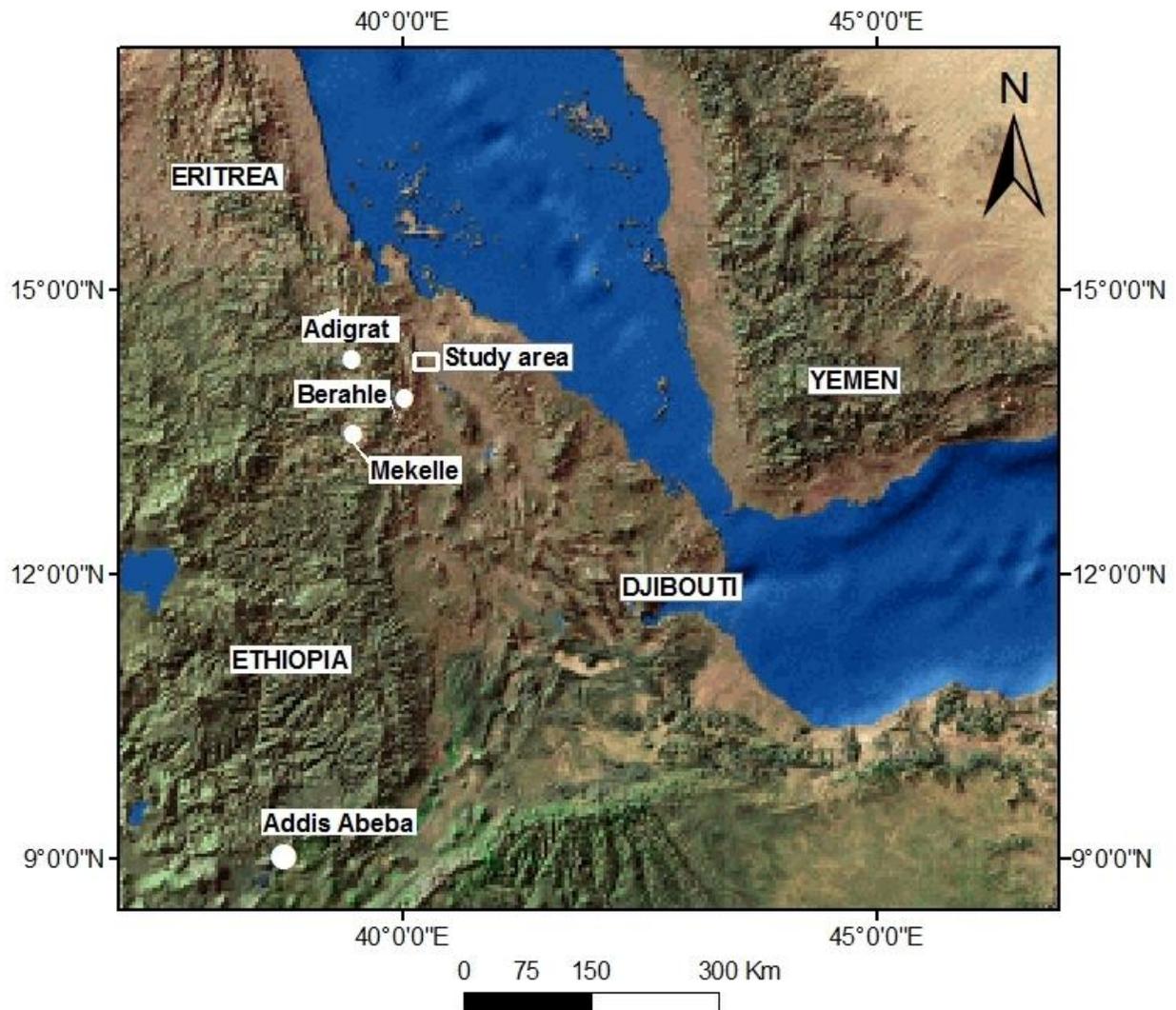


Figure 1. Satellite image map showing the location of the Dallol region (inset rectangle), which lies within the Afar depression.

Drainage pattern of the study area is mainly defined by intermittent small-scale rivers (wadis), which commonly flow from the western highlands towards the Afar depression and red sea. The

Dallol region is very sparsely populated by the Afar people who are nomads and pastoralists. Their main means of living is livestock production and traditional salt mining.

2. REGIONAL GEOLOGY AND TECTONIC SETTING

The regional geological setting of the region is defined by the exposure of Neoproterozoic basement rocks at the western margin of the rift. The basement rocks are of mainly metavolcanic and metasedimentary varieties. They are considered as the southern domains of the Arabian-Nubian Shield (ANS; Davidson et al., 1994; Drury et al., 1994). These basement rocks are overlain by Permian to Palaeogene sedimentary rocks, which were deposited in continental and shallow marine environment. Marine successions were produced during Jurassic transgression of sea by the Indian ocean after the intra-continental rifting caused by breakup of the Gondwana Supercontinent (Davidson et al., 1994; Drury et al., 1994). The sedimentary strata mainly consist of the Enticho Sandstone and Edaga Arbi Tillites at the base followed by 300 to 650 m thick and steep cliff forming Adigrat Sandstone (Beyth, 1972). Up to 700 m thick succession of Antalo Limestone Formation occurs in the middle. This Formation contains an intercalation of fossiliferous limestone and marl units, which in turn is overlain by Agulae Shale and Amba Aradom Sandstone of regressive facies (Bosellini et al., 1997; Beyth, 1972). After completion of the deposition of the sedimentary successions, the region was affected by tectonic uplift and subsequent erosion, which resulted in the formation of a peneplain (Davidson et al., 1994; Drury et al., 1994). This was followed by a rifting that formed the Afar depression and deposition of Quaternary fluvio-lacustrine deposits in the graben (Holwerda and Hutchinson 1968). Elsewhere on the plateau, up to 3 Km thick sequences of flood basalts were erupted continuously 30 ±2 Ma ago and overlie the Mesozoic sedimentary strata (Kabeto, 2010). These flood basalts created a huge pile of layered igneous succession in East Africa and Arabian Peninsula (e.g. in Yemen). Compositionally, they are of basaltic varieties at the bottom followed by andesitic to rhyolitic flows at the top (flows are always volcanic)(Hofmann et al., 1997, Kabeto, 2010). Sr, Nd, Pb, and Hf isotope studies show that they are derived by mixing of three mantle end components, i.e. two enriched and one depleted mantle components (Kabeto, 2010). There are also Younger (10 to 15 Ma) volcanic rocks, which are commonly emplaced in the rift axis. These volcanic rocks are of mainly basalts, ignimbrites, rhyolites, pyroclastic lava flows, scoria and pumice. Locally,

the Tertiary to Quaternary age volcanic rocks are intercalated with fluvio-lacustrine sediments and evaporites (commonly salt and gypsum; Holwerda and Hutchinson, 1968).

3. GEOLOGY AND MINERAL POTENTIAL OF DALLOL AREA

The study area lies in the northern part of the Afar depression (Fig. 1). From west to east, the geology of the area is characterized by: (i) Neoproterozoic metavolcanic and metasedimentary rocks, (iii) gently dipping Quaternary alluvial deposits intercalated with red beds, and (iv) evaporites, which mainly consists of salt deposits (halite and potash) and sulfur especially on mount Dallol and its vicinities (Fig. 2).

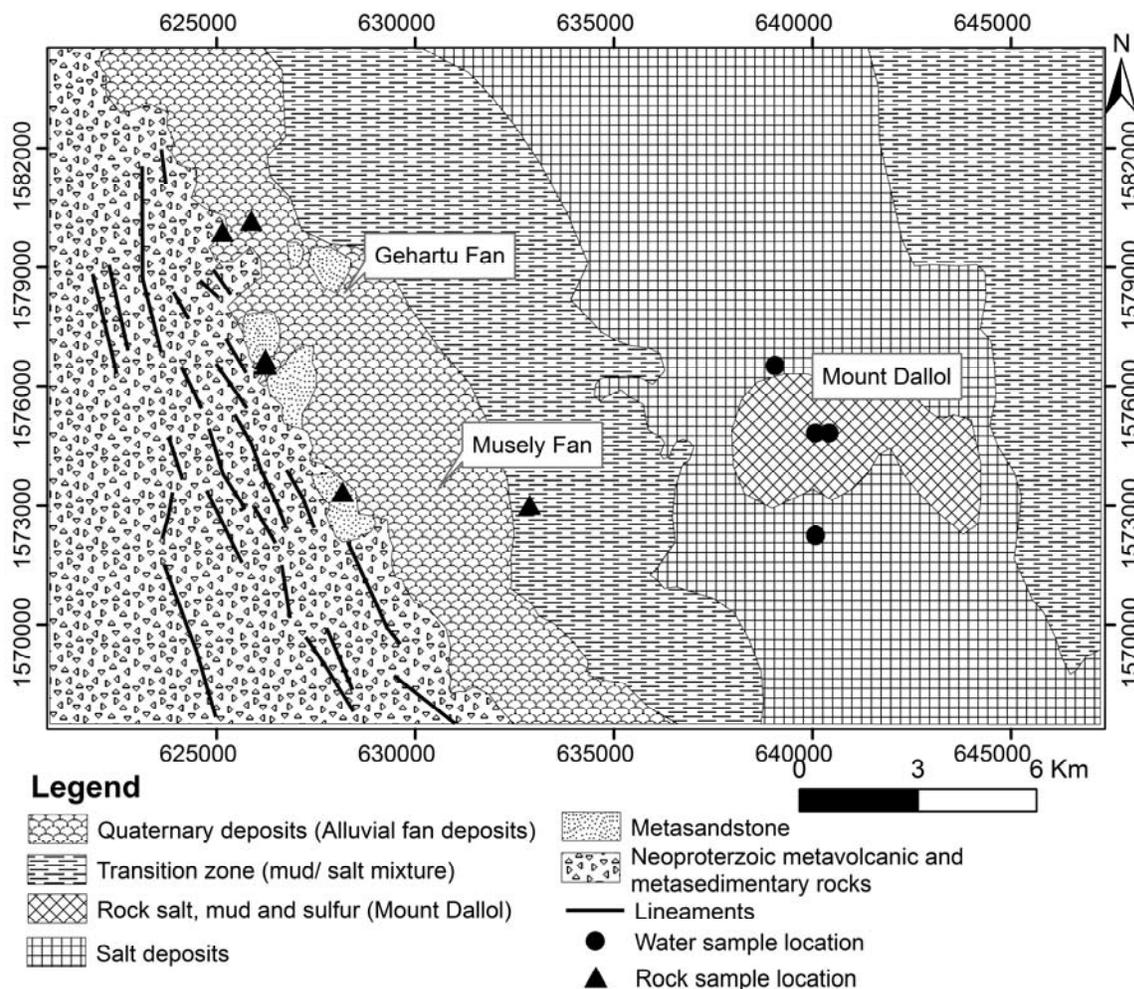


Figure 2. Geological map of the Dallol area. Precambrian rocks are exposed in western part followed by Quaternary alluvial fan deposits. A transition zone of salt/mud mixture brackets the main salt rock, which is exposed at the center.

3.1. Neoproterozoic metavolcanic and metasedimentary rocks

Metavolcanic and metasedimentary rocks are exposed in the western part of the study area (Fig. 2 and Fig. 3a-d). They consist of foliated intermediate to mafic metavolcanic rocks, slate/phyllite, metasandstone, and metalimestone.

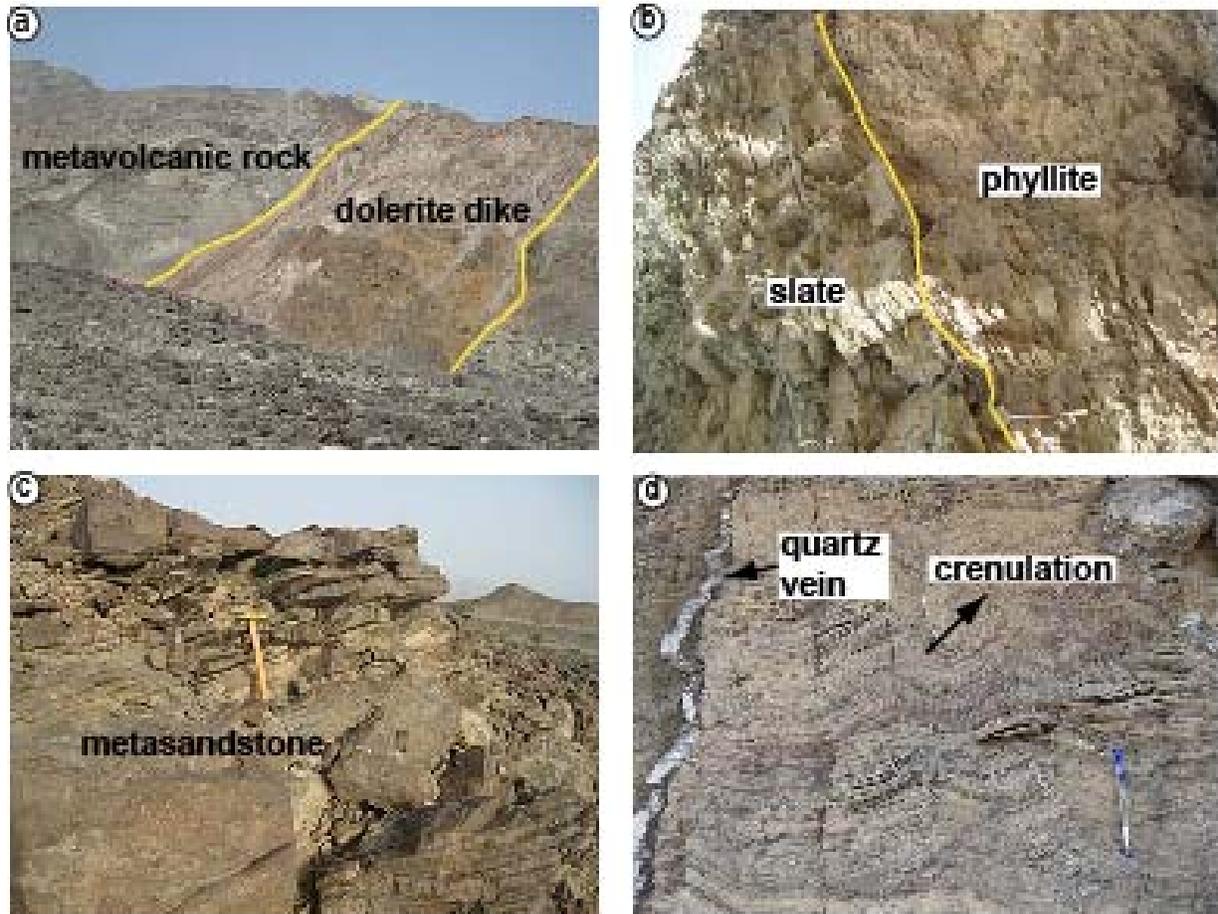


Figure 3. a) North view of the Neoproterozoic metavolcanic rocks, which are cut by dolerite dike; b) Slate/phyllite rocks found intercalated with the metavolcanic rocks; c) Metasandstone exposed at the base of the western margin of the study area; d) Crenulated slate/phyllite, which is cut by quartz vein.

Metavolcanic rocks are greenish, fine-grained and characterized by the presence of approximately N-S trending and 40°SE dipping foliation (Fig. 3a.). They are locally affected by chloritization and cut by doleritic dikes/sills. Slate/phyllite rocks are found intercalated with the metavolcanic and metasandstone (Fig. 3b). They are characterized by slaty cleavage striking N35°E and dipping 27°SE. The slate/phyllite rocks are commonly sheared, which is manifested by nearly E-W trending crenulations and closely spaced quartz veinlets (Fig. 3d). These rocks are

also locally affected by chloritization and silicification. Metasandstone occurs at the base of the scarp adjust to the alluvial fans and are whitish pink, fine- to medium-grained, foliated (foliation strike N20°E, dip 35°NW) and locally hematized. Compositionally, they contain quartz and feldspar, which were overgrown or cut by secondary hematite stains/veinlets, respectively (Fig. 3c). Metalimestone rocks are encountered as patches embedded within the metavolcanic and slate/phyllite rocks. They are characterized by their whitish-gray nature and elephant skin weathering. These metavolcanic-sedimentary sequences of the study area are commonly intruded by aplitic to dolerite dikes/sills.

3.2. Alluvial fan deposits

Alluvial fan deposits occur in central part of the study area, mainly at localities called Gehartu and Musely (Fig. 2 and Fig. 4a and b).

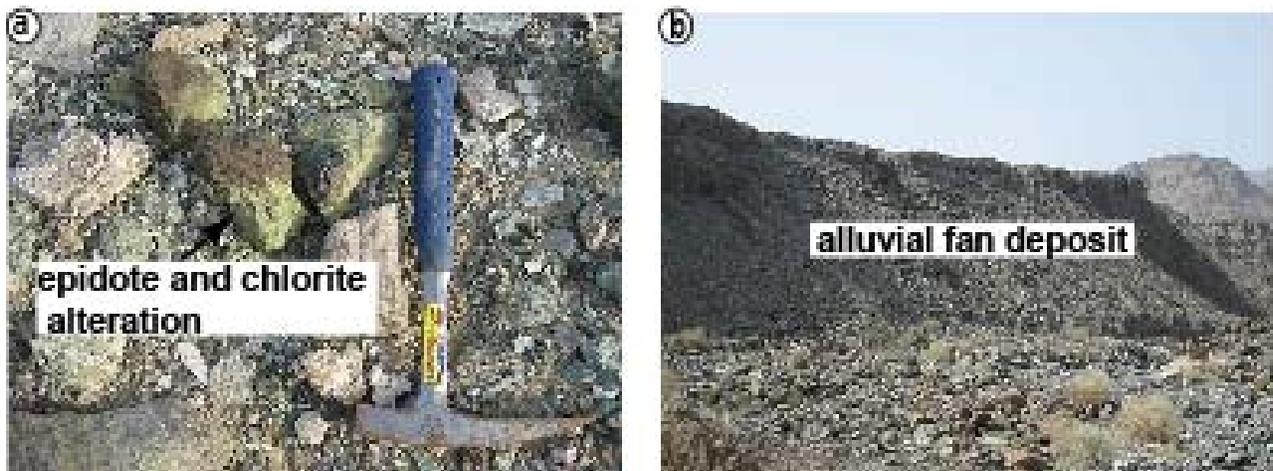


Figure 4. a) Epidotized and chloritized metavolcanic fragments components of the fan, showing the presence of a propylitic alteration zone in the source; b) Showing around 5 m thick alluvial fan deposit at Musely area, which may host placer gold.

They form gently dipping slopes adjacent to the scarp and mainly contain combinations of metavolcanic, metalimestone, metasandstone and sericite-chlorite schist fragments. These fragments are locally chloritized and epidotized. Most of the coarser fragments occur near to the scarp and smaller once near to the salt plains due to decrease of the energy gradient eastwards. The Gehartu and Musely Fans are dissected by branched of rivers, which yielded many braided bars. As estimated from the base of a river cut gully to its top, the thickness of these alluvial fan deposits reach up to 5 m.

3.3. Evaporites

Evaporites are abundant in the Dallol region (Fig. 2 and Fig. 5a and b). They are manifested by the occurrence of sulfur, mud and salt deposits (halite and potash, Fig. 5a and b). The area adjacent to the alluvial fan deposits is dominated by the presence of salt/mud mixtures, which form a transition zone on the western margins of the evaporite zone (Fig. 2). The muds are mainly sandy at the west and become clay and loam towards east. They are affected by primary sedimentary structures such as ripple marks and hexagonal mud cracks. Sulfur/sulfide occurrences are commonly dominant on the crater of mount Dallol and its vicinities giving a rotten-egg smell to the area. Mud and salt deposits are also observed on mount Dallol.

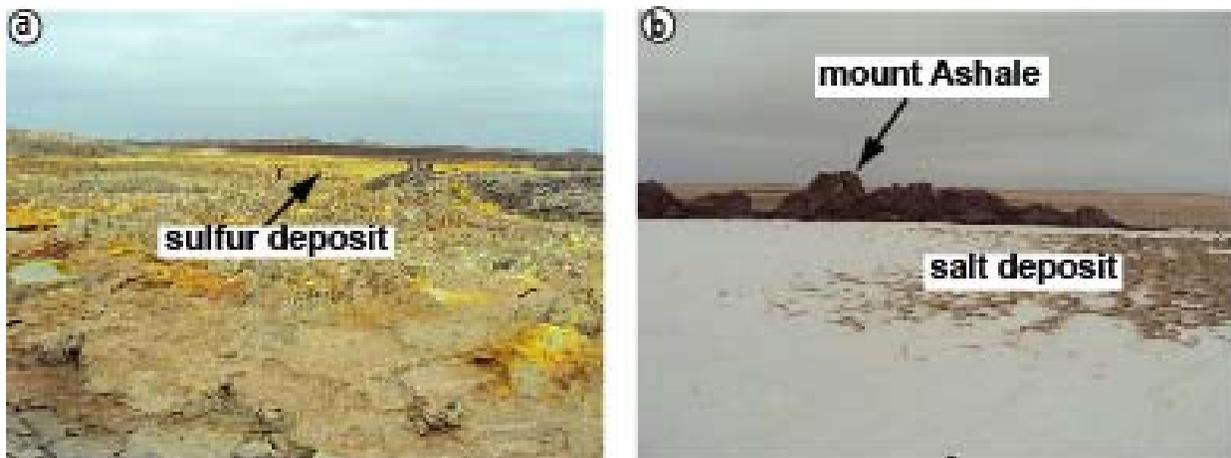


Figure 5. a) Sulfur and salt deposits from the crater on top of mount Dallol; b) Mount Ashale surrounded by younger salt deposit plains.

3.4. Industrial minerals

Industrial minerals such as kaoline and mica are other resources encountered at the Dallol region in addition to salt deposits (Fig. 6a and b). Kaoline deposit was exposed in a gully at western margin of Gehartu Fan and has a thickness of around 5 m. It occurs in the form of sill intruding metavolcanic rocks. From its mode of occurrence, its protolith is aplitic or granitic dike/sill. Within the kaoline deposit, muscovite crystals are observed in the form of disseminations and/or veins. The origin of this mica occurrence is not clear but could be of hydrothermal or pegmatite.

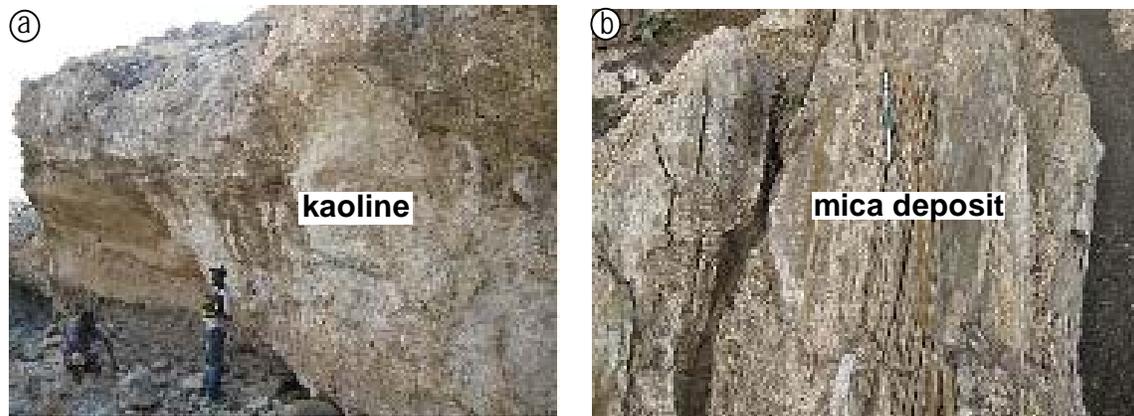


Figure 6. a) About 5 m thick kaoline deposit exposed at the contact between the metavolcanic-sedimentary rocks and Gehartu Fan deposit; and b) Mica deposit adjacent to the kaoline.

3.5. Hot springs

At some spots north and south of mount Dallol, hot springs of variable temperature and extent are being erupted forming semi-circular to circular shaped ponds (Fig. 7a and b). Generally, two types of hot springs are recognized: a light-yellowish brine and a yellowish brine, which is commonly contaminated with mud. Field observations show that both brines show indications for the presence of oil as sensed by greasy feelings and hydrocarbon smell.

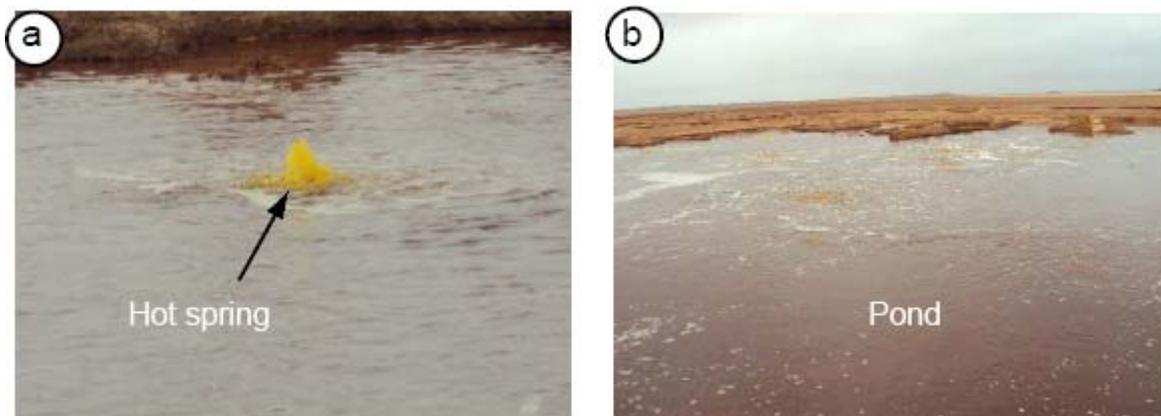


Figure 7. a) One of the continuously erupting hot springs in the Dallol area; and b) Circular to sub-circular ponds formed from the erupting hot springs.

4. ANALYSIS

8 water samples from the hot-spring associated ponds were collected to analyze in the laboratory for their sulfide, sulfate and total organic carbon. EC and pH measurements were conducted in situ while sampling.

The samples were analyzed in the Department of Chemistry, Mekelle University using HACH DR2800 Spectrophotometer with HACH LT200 Digester. Total Organic Carbon (TOC) was determined by applying LCK 381 Kit Method. Using the procedures of this method, Total Carbon (TC) and Total Inorganic Carbon (TIC) are determined independently by converting them into CO₂ by oxidation and acidification, respectively. CO₂ was passed from the digestion cuvette to the indicator cuvette through a filter membrane. The change of color of the indicator is photometrically evaluated. To determine TC, one dose of digestion reagent (LCK 381 A) was added in the TC cuvette. Then 0.2 mL of sample was added. After that the sample containing cuvette was closed with another new indicator cuvette. After fixing the sample containing cuvette with the indicator cuvette, the sample was then placed in pre-heated thermostat (HACH LT 200) with the colored indicator cuvette upwards for 2 hours at 100°C. After allowing the sample to cool to room temperature, TC of the samples was determined photometrically using HACH DR 2800 Spectrophotometer.

Table 1. Chemical composition of hot springs from Dallol area.

| Sample No. /analyte | Location (UTM) | TOC (ppm) | Sulfate (ppm) | Sulfide (ppb) | TDS (ppm) | pH | Conductivity (mS) |
|---------------------|-----------------|-----------|---------------|---------------|-----------|------|-------------------|
| 01 | 0640420/1574973 | 902 | 59 | 60 | 59.4 | 2.09 | 104.1 |
| 02 | 0640420/1574973 | 171 | 19 | 27 | 64.8 | 2.55 | 109.7 |
| 03 | 0640420/1574973 | 112 | 21 | 71 | 79.9 | 2.76 | 123.9 |
| 04 | 0640078/1574973 | 877 | 60 | 102 | 66.1 | 2.25 | 103 |
| 05 | 0640078/1572390 | 36 | 21 | 142 | 110.4 | 3.5 | 183.6 |
| 06 | 0640078/1572390 | 49 | 20 | 111 | 96.4 | 3.62 | 159.1 |
| 07 | 0640078/1572390 | 409 | 117 | 965 | 104.2 | 3.95 | 171.3 |
| 08 | 0640078/1572390 | 94 | 40 | 40 | 109.4 | 3.87 | 57.4 |

Similarly, total TIC of the samples was determined by adding 1 mL of sample into the TIC cuvette followed by closing with another indicator cuvette. The cuvette combination was digested in preheated thermostat (HACH LT 200) for 2 hours at 100°C. TIC was measured using the same photometer after allowing the cuvette combination to reach room temperature. Finally, Total Organic Carbon (TOC) was then determined by subtracting the TC from the TIC values. The analytical results show that TOC values are moderately low and range from 94 to 902 ppm

(Table 1). Sulfate (19 to 60 ppm) and sulfide (27 to 111 ppm) concentrations are also low except for one sample, which has higher values of both complexes (Table 1).

5. DISCUSSION

The metavolcanic-sedimentary rocks in the study area mainly consist of metavolcanic rocks, slate/phyllite, metasandstone and metalimestone suggesting that they are low-grade metamorphic rocks. The nearly N-S or NE-SW strike direction of the regional penetrative foliation suggests that it was formed during D1 deformation by N-S trending compression as discussed by Alene et al. (1998). D1 foliation was locally folded to form D2 crenulation cleavage. Generally, the fabric and nature of deformation of the metamorphic rocks at Dallol is similar to the 850 Ma Tsaliyet and 800-735 Ma Tambien Group rocks of Tigray region (e.g. Beyth, 1972; Teklay 1997; Alene et al., 2006).

The sheared nature of the metavolcanic-sedimentary rocks and associated imprints of hydrothermal fluid flow, which are manifested by chloritization, silicification, and carbonatization of the rocks means that the area has a good potential for orogenic gold mineralization (e.g. Gebresilassie, 2009). The Gehartu and Musely Fans comprise around 5 m thick sediments, which were derived from the aforementioned metamorphic rocks. The presence of such thick sediments within abundant river terraces makes the region suitable for the occurrence of placer gold deposits. The availability of sulfur and salt deposits at Dallol and industrial minerals (mica and kaoline) within the metamorphic rocks clearly demonstrates that the region is endowed with mineral resources as a result of geological processes, which have occurred from Pan African Orogeny to present.

As described above, the physico-chemical properties of Dallol hot springs may also give an insight for hydrocarbon exploration. Literatures suggest that the occurrence of hydrocarbon in a certain oil field depends on the presence of source rocks, which can generate oil under given P-V-T conditions (e.g. Wolela, 2010; Kacewicz et al., 2009). The generated oil is stored in reservoir rocks such as sandstone. This stored oil needs to be capped by impermeable rocks. Source rocks for hydrocarbon are classified as poor, marginal and good to excellent based on their Total Organic Carbon (TOC) contents (Wolela, 2010). Source rocks with TOC content of 0-0.5% are considered as poor, whereas those with TOC concentrations of 0.5-1% are marginal

source rocks (Wolela, 2010). Good to excellent source rocks contain TOC values of >2% (Wolela, 2010). Therefore, up to 902 ppm TOC values in Dallol hydrothermal hot springs lie within poor category of hydrocarbon oil source rocks. In fact, Dallol hydrothermal hot springs are not source rocks. Their low sulfide and sulfate contents suggest that they are derived of heated groundwater mixed with sulfates and sulfides of magmatic and/or sea water origin. The magmatic sulfates could be reduced into sulfur/sulfides by bacterial reduction of magmatic and/or sea water SO₂ or sulfate (e.g. Ohomoto and Rye, 1979). However, the physical properties and presence of the aforementioned TOC content in Dallol hydrothermal fluids may suggest that hydrocarbon containing rocks are present at depth and/or nearby areas. These source rocks could be the fluvio-lacustrine sediments similar to that described by Holwerda and Hutchinson (1968) and/or the Triassic to Cretaceous sedimentary sequences of Mekelle basin, which constitutes part of the western rift scarp (e.g. Beyth, 1972). A hydrocarbon generated from these source rocks is, therefore, likely contaminating the groundwater that resulted Dallol hydrothermal hot springs. The rift related faults/fractures might have served as conduit for lateral and/or vertical migration of the hydrocarbon.

6. CONCLUSION AND RECOMMENDATION

The Dallol area comprises metavolcanic and metasedimentary rocks at its western margin with alluvial fan deposits exposed at gentler slopes. A salt/mud mixture, which is interpreted as transitional zone brackets the main salt deposits at its western and eastern margins. The results of this preliminary study shows that the region has a potential for the occurrence of placer and/or primary gold mineralization and industrial minerals (kaoline and mica) in addition to the already known salt and sulfur deposits. From the physico-chemical characteristics of hydrothermal hot springs and presence of up to 902 ppm concentrations of TOC, it may be suggested that hydrocarbon bearing source rocks may be present at depth and/or nearby areas. Potential source rocks could be the fluvio-lacustrine sediments described by Holwerda and Hutchinson (1968) and/or the Triassic to Cretaceous sedimentary sequences of Mekelle basin (e.g. Beyth, 1972). Generally, the regional geological, alteration and structural setting of the Dallol region combined with the first laboratory results of the hydrothermal fluids from the hot springs suggest that it contains abundant metallic and non metallic resources as well as hydrocarbons. This warrants

detail exploration activities to tap these resources and further scientific studies to understand their genesis.

7. ACKNOWLEDGEMENT

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