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Surface Exploration and First Conceptual Model of the Dallol Geothermal Area, Northern Afar, Ethiopia

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ABSTRACT

The Dallol geothermal area is located in the Danakil depression in Northern Afar in Ethiopia. The area lies in the lowest part of the NNW trending rift valley at about 100 m b.s.l.. No volcanism has been observed in the area and the nearest volcano occurs some 30 km to the south. The rock succession consists of salt strata that reaches below 1000 m depth. Dallol Mountain is an updomed salt structure which has suffered some erosion and is considered younger than 30.000 y. A 1.4 km wide circular subsidence structure is found on top of Dallol, probably formed as a result of voluminous salt outflow from below issued from the margin of the structure. Lower volume, more viscous and domelike formations seem to form at a similar time. This is followed by the emergence of geothermal activity which is confined to two locations. The main one is found within the subsidence structure and is characterized by salt pillars, circular shaped intense steam and gas outlets and then geothermal pools. The second area is at the Black Mountain southwest from Dallol. There the geothermal activity is expressed as a geothermal pool, inactive salt pillar structures and then effusion of boiling bischofite flows. Buried graben faults are postulated to underlie these geothermal locations and are proposed to provide the upflow channels of the geothermal system. The geothermal activity shows extreme variation in activity which changes even on weekly basis. Geochemical character of the geothermal fluids shows supersaline composition of the surface fluids ranging from 370 to 750 x 10^3 ppm. Hydrogen and oxygen isotopes in the geothermal manifestations indicate a mixture of groundwater and a deeper subsidiary hydrothermal system. Reservoir temperatures estimated through the various gas thermometers suggest 280-370°C in the underlying geothermal resource.

1. INTRODUCTION

Dallol is located in the Danakil depression in the northern part of the Ethiopian Rift valley (Fig. 1). The environment in which the high-temperature system at Dallol is emplaced is unique in the world as it shows a complex relationship between a thick succession of salt, supersaline fluids and an underlying heat source.

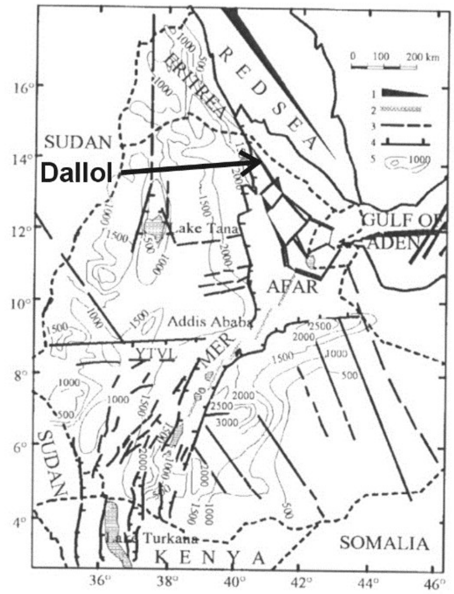

Figure 1. Structural map of Ethiopia showing 1) The major oceanic crust expansion axis, 2) Axis of continental rift, 3) Rift transversal structure, 4) Major fault, 5) Elevation contour of the outcropping Precambrian basement rocks (Abebe, 2000).

This paper describes the results of a geological and geochemical field study done in a short reconnaissance survey (Franzson and Óskarsson, 2011) followed later by a three-week long detailed field mapping in early 2012 (Franzson and Helgadóttir, 2012, Franzson et al. 2012). A geophysical MT survey was run by ISOR staff concurrently to the geological mapping the results of which are not dealt with here (Vilhjálmsson et al. 2012). The emphasis of the study was to establish the presence of a high-temperature reservoir in the area, and to produce a conceptual model of the geothermal system based on the data acquired.

The paper first describes the main stratigraphical and tectonic features in the Dallol area, the updoming structures, salt flows and last but not least the geothermal features found in the area. Lastly a conceptual model of the system is presented. This work was done at the request of NGI (Norsk Geoteknisk Institute), Yara and Ethiopotash Ltd. which were seeking an evaluation of the geothermal potential of the Dallol geothermal system in association with future potash mining activity in the area.

2. GEOLOGY

2.1 Geological setting

The Dallol area lies in the northernmost part of the Danakil depression in Northern Afar. The depression is a huge and complex NNW striking rift/graben structure, with an elevation difference of well over 2 km and with Dallol lying at about 120 m b.s.l.. WNW trending transform faults cross the rift valley one of which cuts through Dallol. The main slope of the graben is heavily downfaulted metamorphic basement from which large river deltas extend. The central part is about 10 km wide flat lying salt plain. No volcanic rocks are exposed at Dallol and the nearest are found south of Lake Assale some 30 km from Dallol. The salt formation is largely formed during periodic sea transgression from the north as well as flooding events derived from the adjacent highlands. The last sea transgression occurred some 30.000 y ago (UNDP, 1973), which puts age constraints on the Dallol formation. The thickness of the salt succession deduced from drillhole data surpasses 900 m. Data from 2D seismic studies indicate a considerable thicker succession, especially underlying Dallol Mtn. (UNDP, 1973, Vigo et al., 2012, Loske, 2012). Further evaluation of the 2D data suggests a major 3-4 km wide buried NNW oriented graben formation, which boarders Dallol Mtn to the east and west. A panorama photo of Dallol is shown in figure 2 and an overall geological map of the Dallol area is shown in figure 3.

Figure 2. Panorama towards Dallol Mountain seen from southwest. Vertical scale exaggerated. Black lines indicate apparent dips of updomed layers. Approximate location of Dallol "crater" is marked on picture. Black Mountain is seen in the foreground, and the light coloured bischofite to the right.

2.2 Dome structures

Dallol Mountain is an elliptically–shaped updomed structure with a long axis striking ENE-WSW and rises some 50 m above the surrounding salt plain (figure 2). The exposed dome strata show structures identical to those on the salt plane. The top layer is an anhydrite which forms a reliable marker horizon and also served as a protective cover against erosion from precipitation. This layer may indicate that the updoming occurred during a time when anhydrite formed the top layer of the saltplane. The geological map (figure 3) shows the overall circular strikes and dips of the formation. The formation is heavily fractured and field study shows these fractures either filled with anhydrite breccia or dark unconsolidated soil. They partly show a radiating system, expected as a result of the updoming. Another but smaller updomed structure, the Round Mountain, occurs to the west of Dallol. A reconnaissance study of the area shows radial dip out from a center in the eastern side of the Mountain. The proposed outer margin of these updomed structures are shown in figure 3 and this would indicate that these would have created a damming effect to the southward migrating flood water, and further explain the preferential salt erosional features in these parts of the dome structures. The age of the updoming is not known, but is assumed to be younger than the last major sea incursion, which occurred some 30.000 y ago.

2.3 Subsidence structure, salt flows, black domes and mud craters

About 1.4 km wide subsidence structure is observed on the eastern half of Dallol Mountain. The depth of the bowl is about 20 m from the rim. The crater boundary is best observed in the northeast part where the top anhydrite layer is seen changing dip from a few degrees towards northeast to a few degrees to southwest into the subsidence structure. No faulting is observed indicating that this is caused by gentle flexing of the salt strata. Dense circular fractures are seen from satellite photo delineating the circumference of the crater (figure 3). The floor of the subsidence is flat (see figure 7) except in the southwest quadrangle, where black domes and geothermal features are found. The floor is assumed to be salt precipitation from a periodic lake formation, and suggests that the original subsidence may have been larger in the central part. No fractures are seen in the floor formation indicating cessation subsidence in that part. There are indications of a dome structure forming as a precursor to the subsidence.

The main updoming event that created the Dallol Mtn shows a strata of salt deposition from evaporated seawater incursion originating from the north. **The salt flows** discussed here are low viscosity salt fluid extruded from fractures that circumference the subsidence bowl. These upflow channels are most pronounced in the north, east and southeast, but minor in the west and absent in the southwest as seen in figure 3. The low viscosity is observed by the smooth surface at extrusion site and the ability to fill in narrow cracks of the underlying rock. It is of interest to observe that no spattering effect is seen at these outflows, which is surprising considering the high gas content of all upflows. Similar upflow (bischofite) may be presently evidenced at Black Mtn in the southwest as discussed below (figures 2, 8). Evidence is found in flow channels of these being voluminous in the beginning but diminishing with time. The flow area shows no evidence of a time break which infers that this occurs as a single event. The overall thickness of the flows is uncertain, but probably within meters, though depending on the underlying topography. The largest part of the flows occurs outside the depression indicating that the latter may have formed at the latter stages of the event. The floor formation inside the depression is seen encroaching on the flows indicating younger age (figure 7).

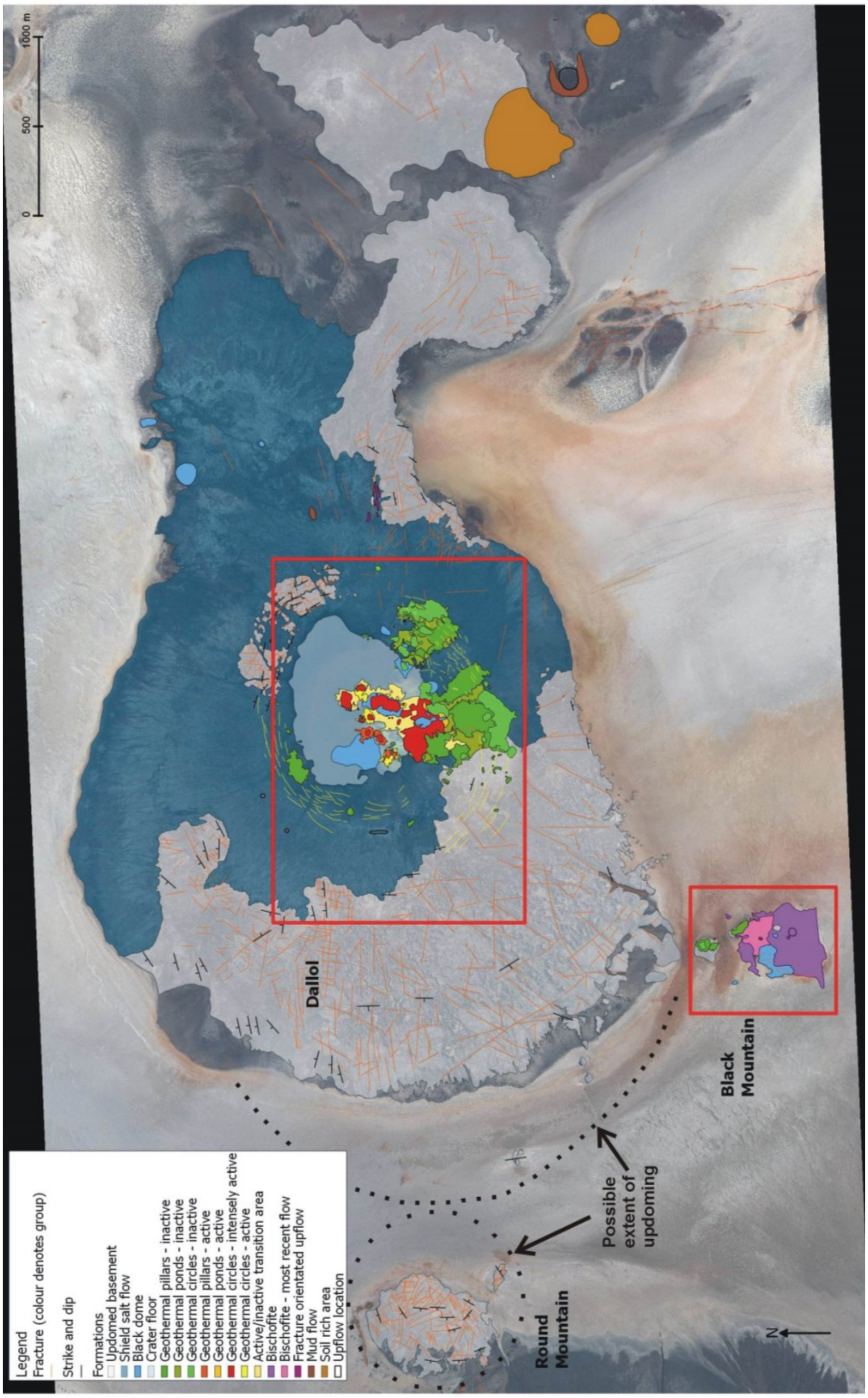

Figure 3. Geological map of Dallol. The squares indicate figures 5 and 9. See text for further information.

Black domes are small volume highly viscous salt extrusions. The type area is the Black Mtn. to the southwest of Dallol Mtn. These usually are from a few tens of meters in diameter up to about 300 m in extent and less than 15 m in height (figures 2, 3, 4, 5), which contrasts greatly with the low viscosity saltflows. Strong flow lineation and internal folding further confirms the high viscosity. They show variable crystallinity which seems to relate in places to the hexagonal jointing which in turns implies that these extrude as a hot fluid. The black nature of the rock is due to the abundant haematite in the halide. In some of these the last part of the extrusive is white halide without the haematite. Wide gaspipes up to 50 cm in diameter pierce through the formations (figure 4) illustrating the high viscosity and the association of gas as a part of the extrusive process. Beside the Black Mtn, these formations are mainly found in the southwest quadrangle of the depression. Similar formations were also identified east of Dallol but closer studies have to be done to confirm their common origin. Age relation of shield and black dome flows is not clear and may be of the same age. It is of interest that they are spatially different where the latter are most abundant in the southwest quadrangle of the depression, in an area where shield flows are largely absent. This implies a genetic link. Furthermore the location of the main geothermal upflow is similar to the location of the black domes.

Figure 4. Top of a small domal structure in the southern part of the Dallol subsidence. Note the relatively large gas pipes cutting through the formation and the joints which may indicate the cooling and contraction while consolidating. Field notebook in the lower center of figure for scale.

Mud craters were located at two locations, the more spectacular one was found some 3,5 km WSW of the depression, and the second one at the lower eastern slope of Dallol. The former has an outer diameter of about 250 m and an inner one of about 100 m, and rises about 15 m above the surroundings. This resembles closely an effusive crater seen in the volcanic environment, but instead of molten magma these are salt fluid columns spouting and spattering leading to a crater formation. The flow from the crater is thorough an opening towards east. Beside the crater formation the force of the eruption may be seen by salt boulders up to a meter in diameter embedded in the crater wall. The salt is soil rich as is also found in the surrounding salt plain and in that way identified as derived from that eruption. The second crater, located east of Dallol, shows similar character, and is older than the succeeding shield flows.

2.4 Geothermal manifestations

Geothermal activity in Dallol presents itself in a different way than in most other places in the world. Geothermal features are confined to the subsidence structure at Dallol and the area around Black Mtn. An exception is a single small inactive manifestation occurring in the middle of the slope east of the depression. All geothermal features are superimposed on the salt flows and black domes confirming a younger age.

2.4.1 Geothermal features within the subsidence structure

The geothermal locations and types are shown in figure 5. These are of three main types; pillars, circular manifestations and acid pools. The name **pillar** is put forward here, and is circular column of variable circumference and forms as a salt deposition from a supersaline upflow as shown in figure 6. These are most commonly found at the margin of the depression and seem dominantly associate with the circular fractures of the depression. They often are found in groups and seem to cease growing at a similar elevation, which is interpreted as being due to the hydrostatic balance of the underlying system. They originate from small central boiling upflow which cause halide precipitation on emergence at the top of the pillar. A common feature to most of these pillars is that after the precipitation episode the salt becomes perforated by pipes of gas/steam preferably on the top but also on the side. Pillars are also found in the more intense geothermal activity, but show a stronger colour variation in active/inactive stages probably due to increased iron content of the fluid. The second main geothermal type is the **circular manifestations** (figure 7). These appear to be the most intense upflow and have a variable diameter ranging from a few meters to over a hundred meters. These show also a similarity with the pillars in that they are controlled by episode(s) of deposition (surface boiling) followed by exsolution and disintegration. This is due to lowering of water table and increased steam/gas flow. The central part of these manifestations, which originally were dominantly halide become gradually more anhydrite and sulphur rich (c.f. figure 7). The third type are the **acid lake deposits** (figure 8). These are fluids mainly derived from a mixture of the groundwater and the geothermal upflow. The fluid shows extremely low pH value (-0.74). The main acid lake during our first visit was about 1500 m^2 but fluctuates rapidly. Evaporation may play a role in this change but other factors must also contribute such as changes in surrounding groundwater pressure and perhaps changes in the geothermal upflow. We observed changes of a few tens of centimeters over three weeks during our second visit, and a recent Google satellite picture shows a similar sized lake in the western part of the crater, that was dry during our mapping in 2012. The area shows drastic colour changes depending on the water table, where colours change from light to reddish colours when water level drops to below surface and then returned back to former colours when water table rises again. No evidence was found of fluid flow-off from the area, which considering the vigorous geothermal manifestations, implies that the underlying geothermal reservoir is steam dominated. Evidence is found of **vigorous gas outlets**, both within the geothermal manifestations as well as in the western part of the depression. These are expressed as holes in the ground but usually without much surrounding debris. Accounts are of periodic dust clouds appearing in the area and is assumed to represent such outbursts

A ground temperature survey was done. Boiling temperature of about 109-111°C was found widely throughout the active area. Erroneous and lower temperatures were recorded where the thermometer failed to reach down into the water table. Intense boiling sounds were also used as a mapping guide in this respect.

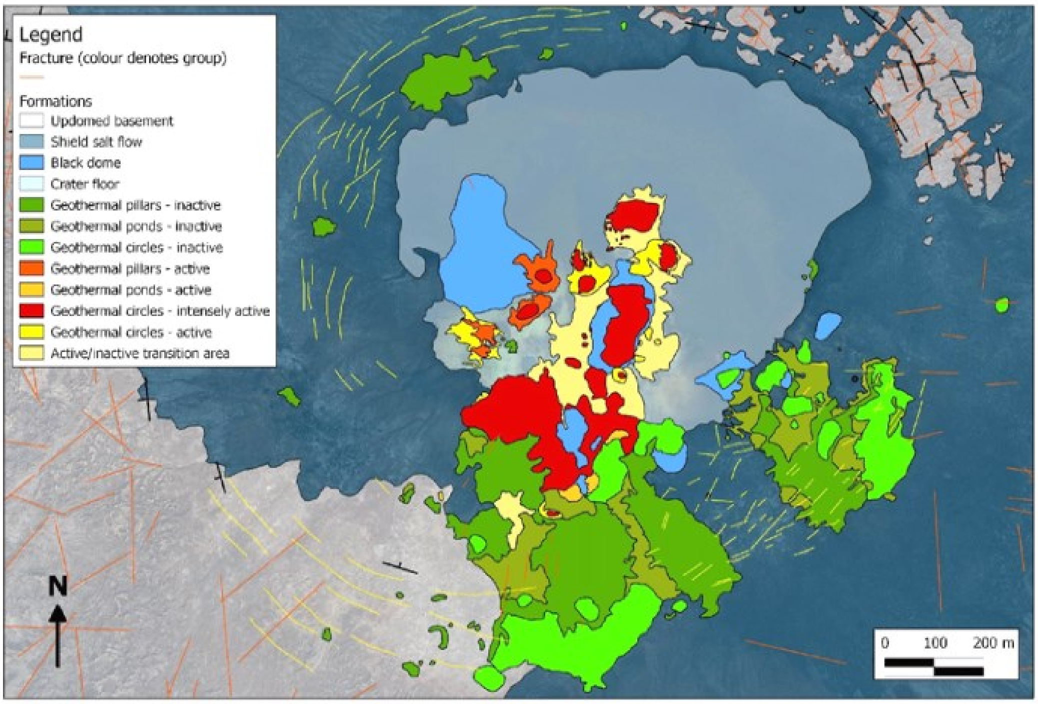

Figure 5. Geological map of the subsidence structure at Dallol. Active geothermal manifestations are shown in yellow and red colours, whereas inactive areas are marked with green colours. North towards left on figure.

Figure 6: Impressive inactive salt pillars located at the southern part of the subsidence structure.

Figure 7: Relatively circular manifestation within the floor of the depression, with exsolved and pulverized central part. The dark formation in the background are the "shield" salt flows issued from the margin of the crater.

2.4.2 Black Mountain

The geothermal features in this area are somewhat different from that found at Dallol and is shown in figure 9. The main geothermal location is the supersaline 71°C **Black Pool** located at the northern end of Black Mtn. Reports are of a phreatic "eruption" just over a 100 m to the northwest. These were to some an indication of a volcanic activity, but no evidence is found there of volcanic material, but a levelled out circular feature is seen in the salt plane at this location, and is interpreted here as being caused by a vigorous geothermal eruption rather than a volcanic one. Small pillar like structures are observed to the north of Black Mtn. mostly though presently inactive. In June 2011 and early 2012 episodic effusion of supersaline fluid occurred some 30 m southeast from Black Mtn. and precipitating bishophite. Temperature measurements were done indicating up to 140°C (Sundara Moorthy, pers comm). These have continued as observed from a recent Google image. The apparent surface size of the geothermal area is about 0,3 km^2.

Figure 8: Acid lake with salt deposition inside the subsidence structure. Small salt pillars seen in the background.

2.5 Analysis of rock samples

A total of 84 samples from the various salt structures were analyzed by XRD, especially those related to the effusive salt formations and geothermal precipitations. Out of these, 70 showed halide as the dominant mineral. Anhydrite was the most common subsidiary mineral, and other minerals that mostly showed up as traces included gypsum, carnalite, jarosite, bischofite, sylvite and thenardite. The iron oxides, which dominantly were found in the salt and dome flows was mainly hematite and some magnetite. Sulphur was commonly found in the geothermal scales. It is of interest to note that no sulfides such as pyrite was found.

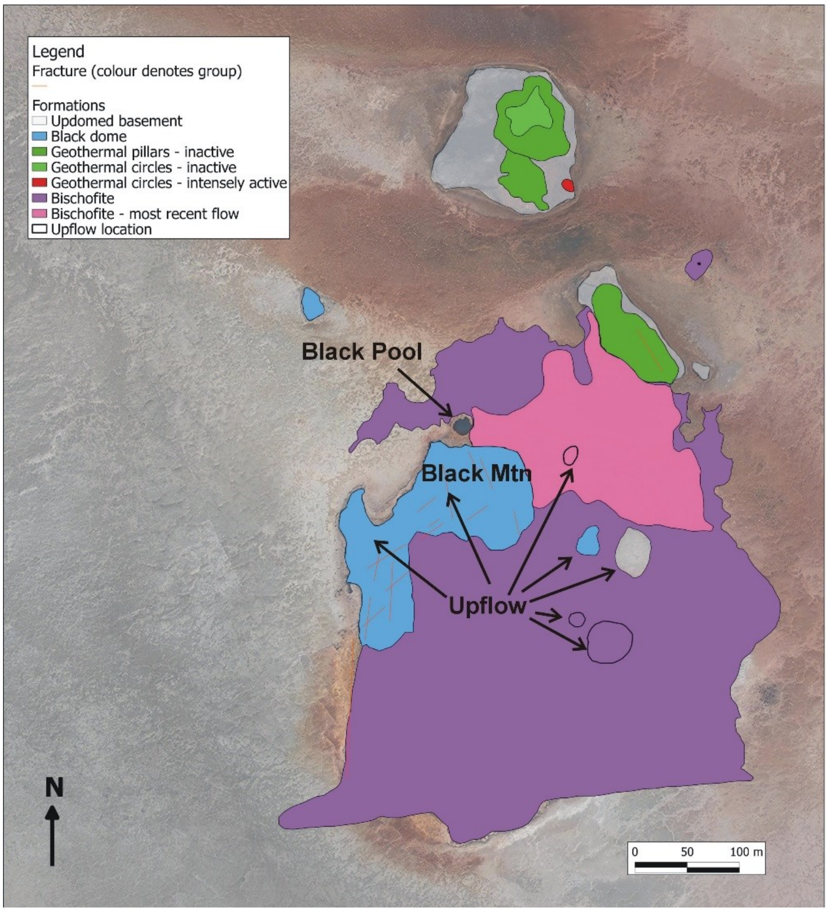

Figure 9. Geological map of the Black Mtn. area presented on top of a satellite image. See index map on figure 3 for location.

3. FLUID GEOCHEMISTRY

The surface waters at Dallol and surroundings have very high salinity (TDS>350 g/kg) and pH ranging from moderately acidic to extremely acidic (pH<0) liquid. The composition of the liquid is mainly controlled by the amount of the various salts and minerals in the surrounding rock and the acidity, which again is cotrolled by the upflow of the gas through the liquid. Mercury is found in much higher concentration in the pool in the depression and is explained as originating from the underlying steam upflow. Steam samples collected from two fumaroles were used to estimate the reservoir temperatures using gas geothermometers of Arnorsson and Gunnlaugsson (1985). H_2, H_2/Ar and CO_2/H_2 geothermometers indicate temperatures of 280-290°C whereas CO_2, H_2S, H_2S/Ar and CO_2/N_2 predict 340-380°C. The former estimate was considered a better estimate, but the great flux of CO_2 could be caused by degassing of underlying magma source which can complicate that interpretation.

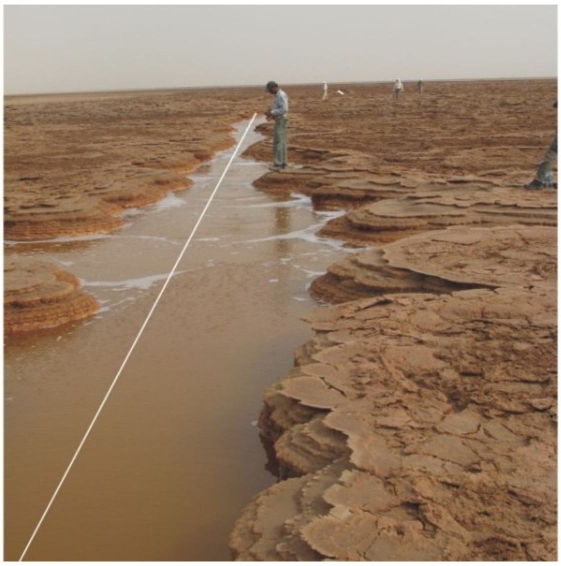

Figure 10: A northerly tectonic fracture on the saltplane southeast of Dallol with vigourous gas upflow.

Isotope data (figure 11) strongly indicate that the surface water and fumarole steam have different origins, the former being meteoric whereas the latter stems from the underlying geothermal reservoir. The sample collected from a clear brine pool close to Lake Assale, some 20 km south of Dallol falls neatly on an evaporation line from the local groundwater (represented by a water sample from the field laboratory) and the samples from the green pool on Dallol Mountain and an acidic yellow pool south of the mountain also seem to be at least partly meteoric water, but both show considerable oxygen shift from the meteoric line indicating mixing with geothermal steam and/or reaction with rock or sediment. The deuterium content of the condensate sample from the fumarole, however, is much lower than that of rainwater, insisting that it has a different origin. Indeed, the sample falls neatly on a mixing line between local precipitation and a suggested primary magmatic water (Taylor, 1974).

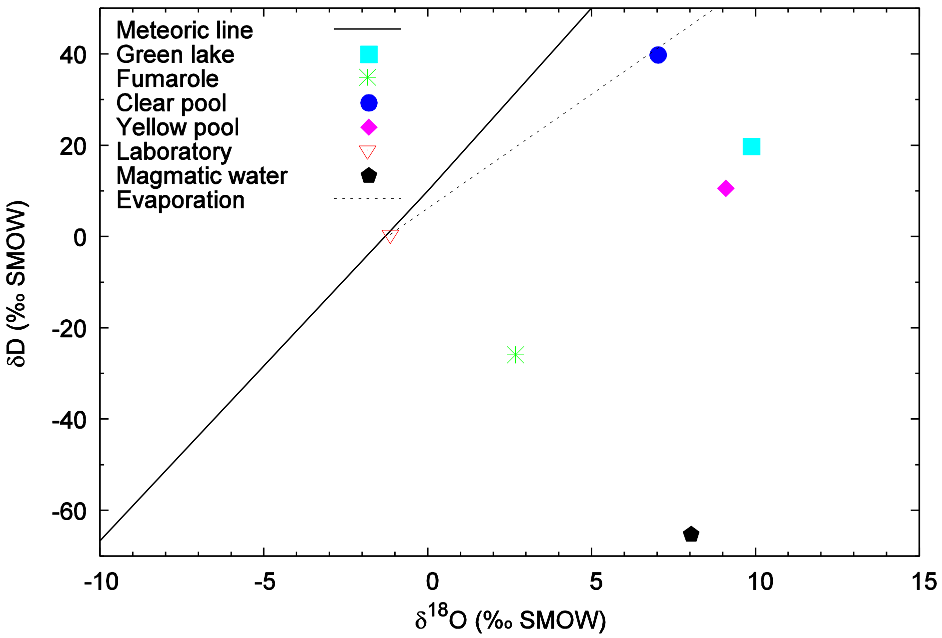

Figure 11: Stable isotope ratios in samples from the Dallol area, along with the meteoric water line, an evaporation line for the water from the river fans and a hypothetical primary magmatic water.

4 DISCUSSION

Dallol is situated within the deepest part of the Danakil depression, bordered on either side by heavily NNW striking downfaulted metamorphic basement. WSW striking transcurrent faults dissect the rift structure, one of which is postulated to intersect the Dallol area. A thick succession of salt strata has accumulated in the central part of the basement, due to seawater intrusions from the north, the last one dated at 30.000 y. Periodic freshwater flooding from the surrounding highlands also occur. There is an absence of volcanic rocks at Dallol and the nearest volcanic area is some 30 km to the south. The absence may be due to less crustal uptake of magma and/or that the salt strata forms an effective magma trap. Considering the presence of the rift structure it seems natural to assume intrusive activity at depth. The thickness of the salt strata is at least 900 m as observed from boreholes. A 2D seismic survey done in the area (De Vigo 2011) indicates that the succession is considerably thicker. It also delineates large NNW striking graben faults, one of which underlies the Black Mtn area, and another one with a large downthrow to the west underlying the eastern part of the Dallol Mtn just east of the Dallol subsidence structure. It is postulated here that the upflow structure of the geothermal system may relate to these graben faults, and perhaps enhanced by the crosscutting of the WSW transform faulting.

Figure 12 shows six sketches illustrating the geological history of the area and the first conceptual model of the geothermal system. *Sketch 1* shows the pre-Dallol updoming stage depicting a thick salt strata formation and buried graben structures as deduced from Ergosplan (2012). The thickness of the salt succession is not assessed here except that it probably is more than 1 km, especially in the central part of the graben due to the subsidence. *Sketch 2* shows the Dallol updoming. The cause of the updoming is tentatively suggested being due to a magmatic intrusion at depth. The time of the updoming is not known but assumed to be <30.000 y. No evidence is found of a geothermal system being formed, either at Dallol or the Spherical Mtn dome to the west. *Sketch 3* shows a time interval of erosion of the updomed structure, while salt deposition continues on the surrounding salt plane. *Sketch 4* indicates the emplacement of a magmatic intrusion, either below or inside the weak salt structure, and forming the heat source to a geothermal system. Release of volatiles and the access of groundwater to the intrusion triggers a geothermal system which migrates upwards through buoyancy and causes renewed updoming in the central part of Dallol Mtn. The initial breakthrough of the system is evidenced by the voluminous salt flows which rapidly drain the underlying geothermal fluid pocket and cause a deflation seen as the subsidence structure (*sketch 6*). The black dome structures are postulated to extrude at that time, but the exact relation with the salt flows is still uncertain, except they tend to be located in areas of less salt flows and within the area of the most intense geothermal activity. The geothermal system changes from fluid to steam dominated system, possibly due to diminished inflow of water towards the heat source, which is the present stage.

Figure 13 shows how we envisage the present state of the geothermal system. At depth the reservoir is steam dominated, as envisaged by the high heat flow but very limited discharge. The fluid geochemistry suggests that the surface waters are groundwater but diluted and heated by the underlying steam zone. The geothermal pillars are more dominating at the margin of the depression often showing clear relation with the marginal fractures. These also show less iron staining than those within the more intense part of the geothermal area which may indicate their peripheral location and closer contact with the groundwater system. The circular geothermal manifestations are found in the most intense part of the geothermal area. These show apparently higher heat and gas flow, and do not show much evidence of rapid salt deposition as would be expected if the upflow was fluid dominated. The dominant steam and gas flow results in higher degree of perforation and pulverization of the salt scale.

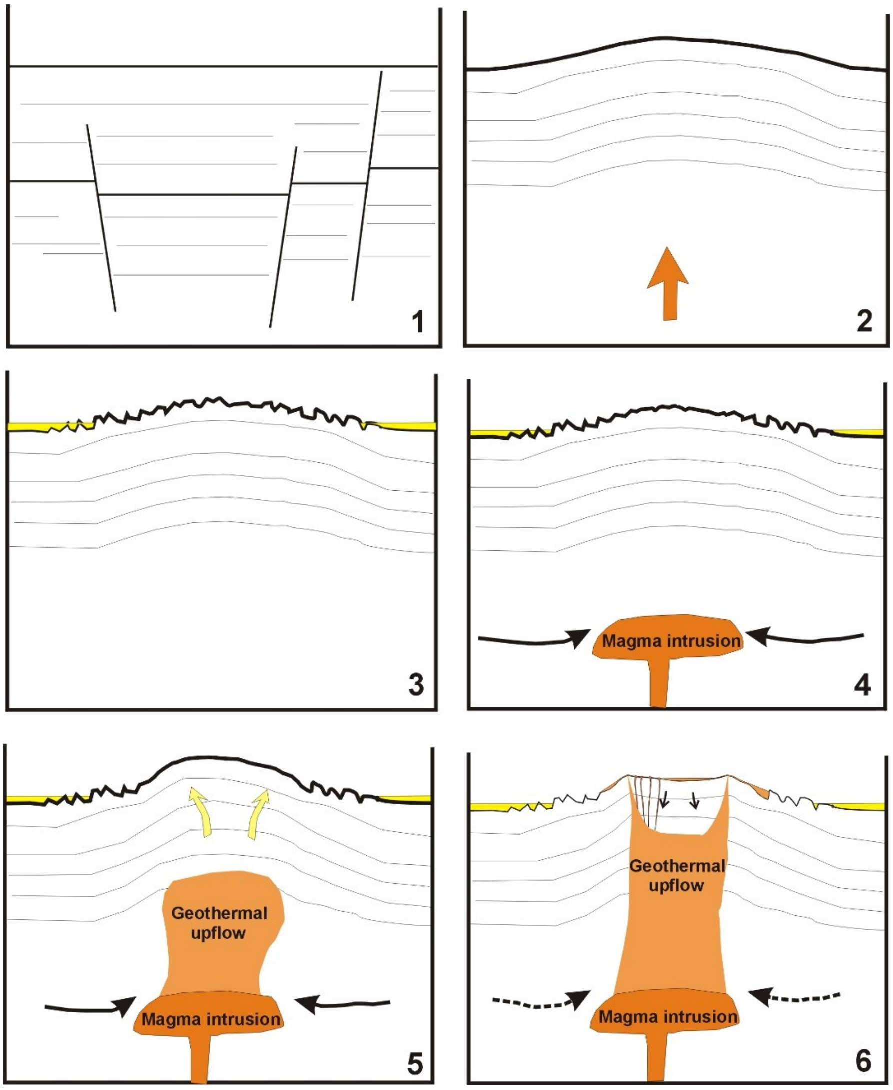

Figure 12. Schematic chronological sketches of the proposed formation of the Dallol geothermal system. See text for further explanation.

The geothermal features of the Black Mtn area to the south west of Dallol is interpreted to be related to a buried graben fault observed from the 2D seismic (Ercosplan 2012, Loske 2012). The area has an overall northerly alignment. Magnetic and gravity survey indicate an underlying anomaly which has been suggested to result from an intrusive body at depth in the order of one kilometer (UNDP 1973). This may therefore indicate a separate geothermal upflow to that of Dallol. The reported phreatic eruption from 1928 is assumed to represent a vigorous water/steam column. The present outflow of bischofite is linked to geothermal activity and may origin from dissolution of thick bischofite sequence at shallow depth (Ergosplan 2012). The black dome appears to be a precursor to the geothermal activity, similar to that observed up in the Dallol subsidence structure.

An estimate of the areal extent of the underlying geothermal system is assessed from; about 0.3 km^2 area of Black Mtn, about 1,2 km^2 extent of the geothermal area at Dallol. Both are regarded as vertical upflows from a deeper resource. A number of holes have been drilled the area around Dallol. Most of them have a gradient equivalent to 35-50°C/km. Two wells about 4,5 km north of the Dallol subsidence structure show, however, anomalous gradient equivalent up to 140°C/km. both of these wells are just west of the eastern graben boundary, the same as underlying the eastern part of Dallol. If one assumes that these three areas belong to a single reservoir at depth, the size of the reservoir may be in the region of 10 km^2.

The lifetime of a high-temperature system in a volcanic terrain is highly variable but usually estimated to last for a similar amount of time as the lifetime of the respective volcanic system which are in many cases a few hundred thousand years. The time constraint for the Dallol system is based on circumstantial evidence. The last sea transgression is estimated about 30.000 y and assumed to have occurred prior to the Dallol updoming episode. This is followed by an episode of erosion in Dallol and after that we have the sequence of salt flows and black domes and then the geothermal activity which is superimposed on the former. The salt flows and the black domes show a very limited erosion and dissolution compared to the older salt strata of Dallol indicating a very young age. Furthermore no cyclic behavior is seen in the presently active area, rather a continuous change towards a more intense geothermal activity and more steam dominated conditions. Judging by the comparison of the satellite images during the last 10 years, the geothermal manifestations seem to be spreading from the southern part of the depression into its central part. Our intuition is that the age of the surface manifestations is a few hundred rather than a few thousand years. That, however, does not exclude the possibility that the deeper reservoir may have been evolving for a much longer time.

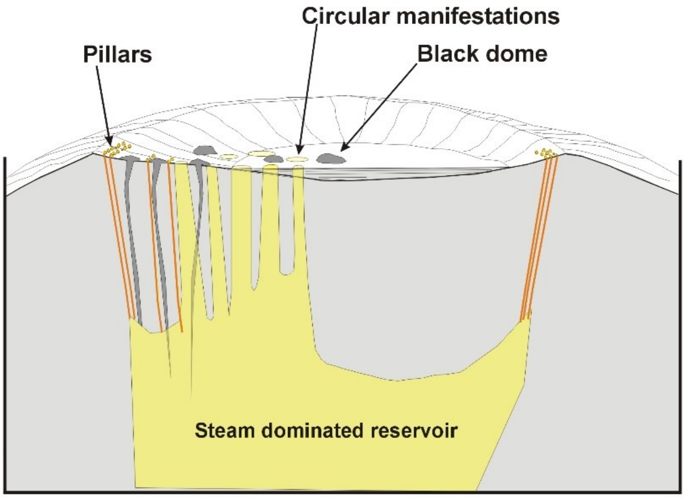

Figure 13: a sketch illustrating the proposed relationship between geological structures geothermal manifestatons and the underlying geothermal system. See text for further explanation.

The fluid and isotope geochemistry indicate two types of fluids; one related to groundwater of the region and the second related to a deeper steam dominated resource. The depth to the lower boundary of the salt succession is a critical point to consider with respect to the utilization of the geothermal resource. A reservoir placed in a salt strata will produce supersaline geothermal fluid which will be very challenging to mine due to the intense scaling. However, such utilization difficulties may become less sever, if a lower salinity reservoir exists within the underlying metamorphic basement. The thickness of the salt strata is therefore of great importance when considering the harnessing of the Dallol geothermal system. Environmental issues regarding the uniqueness of the geothermal area will also have to be assessed in this respect.

5 CONCLUSIONS

The following are the main conlusions:

- The Dallol is located within the deepest part of the NNE-trending Danakil depression and coincides with a WSW transcurrent fault. The succession is made of >1 km thick salt strata. Updoming of the salt strata created the Dallol and Spherical Mtns, probably less than 30.000 y ago.
- Igneous intrusions are believed to have been emplaced at > 1 km depth creating a heat source to a geothermal system.
- The emergence of a geothermal system at the Dallol Mtn is preceded by large volume salt flows, small volume black dome structures and a subsidence structure. The geothermal system within the subsidence consists of large pillar structures, circular intense steam manifestations and acid supersaline lakes.
- Both Dallol and Black Mtn geothermal anomalies are believed to connect at depth to large graben faults, the former to the eastern fault and the latter to a fault defining a western boundary.
- Geochemical evaluation of the fluid and steam samples show compositional contrast, where fluid samples show evidence of groundwater origin, while the steam samples show indications of originating from a different source. Gas geothermometers indicate temperatures surpassing 280°C.
- The age of the geothermal system at surface is estimated to be in the order of hundred years rather than thousands and is progressing towards a steam dominating one.

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