Another geothermal site in North-Eastern Afar:
Harak (Bidu woreda, Afar regional state, Ethiopia), that marks
the southernmost extension of the Danakil Sea 110m bsl

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Key words: Danakil sea; surface manifestations over 100°C, 100m below sea level; mud
volcanoes

ABSTRACT

Several geothermal sites have been identified in Afar, the only place on earth where an oceanic
rift is developing within a continent. Active spreading segments, plus central volcanoes at the
crossing of regional faults with transverse structures, have been shown as major geothermal
targets. In northern Afar, the Danakil Sea results from lithospheric spreading, with crustal
thinning through normal faulting since Miocene and even separation through recurrent diking
along the volcanically active axial ranges during the last My: Erta Ale Range, and south of
Lake Afdera, the twin Alayta and Ta’Ali ranges. North of the Erta Ale range the salt plain
develops at an altitude of -125m (bsl) over more than 120km with the presence of two identified
geothermal sites: Dallol and Alid (the last in Eritrea). To the West of Tat’Ali range, the plain
lying at the foot of the Danakil block, surrounded by former coral reefs and beaches along the
0 m line appears as apparently marking the southernmost extension of the Danakil sea, as the
altitude becomes positive south. However, west of this plain, to the South of Tat’Ali range,
separated by a thin horst, a long graben called “Harak” extends over 50km, with a width
narrowing from 10 km north to 3km south, at a negative altitude (averaging 80m bsl and down
to less than 110m bsl in several locations). A recent exploration allowed us to discover here a
significant southern extension of the Danakil rift that has until now not been described. As for
the salt plain, this surface is flooded in the wet season. A salt-lake, surrounded by salt-crust
surfaces extends over circa 6 km² in the southern half of this graben. Along a 5 km long N-S
alignment, numerous thermal manifestations are observed, resulting from steam convection
through open fissures remobilizing the superficial wet and dry sediments, and producing a
variety of geothermal features : active mud volcanoes, colorful salt concretions as in Dallol,
steaming holes and cracks, and phreatic explosion craters. Temperature reaches 115°C in the
mud volcanoes. Observation of the surface surrounding these manifestations clearly shows that
thermal events affected the surface over a wider area, along active faults and open fissures. To
the south a wide recent basaltic field, emitted from the same axis, shows an active magmatic
heat source. This paper describes the geology and propose a preliminary conceptual geothermal
model. At present, the area is poorly accessible through a 15 km hazardous track that crosses
two successive horts and grabens with a few difficult passages even with 4WD vehicles. It is
scarcey populated (6,950 p.), with Tio as main centre, a village along the N-S asphalted road
at a distance of 105 km from Sardo and 80 km from Afdera. The discussion is engaged by
AGAP and APDA with the community on how to better valorize the site: valorize this
exceptional natural site as such, or consider a geothermal development including the salt
extraction.
1. Introduction

The northern part of the Afar depression, also called “Danakil depression” develops in North-Eastern Ethiopia and South-Eastern Erytrea (Figure 1) It is the most desrtic part of these countries, extending along the southern extremity of the Red Sea, separated by the “Danakil Horst” a hilly area (also called “Danakil Alps” but named “Arrata” by the local Afar population). A wide salt plain extends over more than 120 Km from the Gulf of Zula (15°30’N) to the surrounding of Lake Afdera (12°30’N), with numerous well-identified volcanic and thermal manifestations observed along its axis, trending NWW-SSE, parallel to the Red Sea.

This paper describes a new geothermal site, which was not known as such, and never described in the literature, despite several geological and geothermal investigations engaged in the region since the year 1967 (Tazieff et al. 1972; CNR-CNRS, 1973; Barberi et al. 1970; UNDP, 1973). It is located along the southern extension of the Tat’Ali – Mat’Ala range, identified by Barberi et al. (1972 ) as one of the spreading axis of the Afar rift, a fact which has been précised y successive investigations, notably geophysical (seismicity and direct measurements of plate motion with GPS (Beyene & Abdelsalam, 2005; Bosworth et al., 2005; Calais et al., 2006; Mc. Klusky et al., 2010; among others).

Along the axis of a N-S trending graben, 50 Km long and 10 to 3 Km wide, named “Harak”, filled by recent quaternary sediments, with a floor below sea level (down to -120m, Figure 2), numerous surface hydrothermal manifestations are observed, lying along a fault line (in fact an open fissure), observed along the graben axis. This paper describes this newly identified geothermal site, which add a new perspective for AGAP (Afar Geothermal Alternative Power Co) and APDA (Afar Pastoralist Development Association), in view of socio-economic developments of interest for the people living in the area. Besides local uses, it may also be of interest for electricity production, as the electric line linking Sardo and Semera to Makale and Dallol through Afdera is being built at a short distance from the site.

1. Geological environment

The Harak basin is located in the depleted area part of the northern apex of the Afar triangle. The area is characterized by recent quaternary geological formations only: volcanic products (lava flows and hyaloclastites) and sedimentary infilling, detrital, marne, lacustrine, evaporitic
and aeolian (sand dunes and thin dust) along a graben extending along the NNW-SSE (i.e. Red Sea) direction. The graben is narrow north (in Eritrea) and widens southwards, where the Red Sea simultaneously narrows. This results from the anticlockwise rotation of the Danakil Block, a continental microplate which separates the Afar depression from the Red Sea (Sichler, 1980; Figure 3).

![Figure 2: Relief map of the Afar triangle, with the toponymy of the main units cited in the text. The Harak graben is seen in deep green south of Tat’Ali range. NNW-SSE NW-SE trending Axial Ranges (dominantly basaltic spreading segments) in blue. Central silicic volcanoes in red. Lakes in white. Miocene granitic massifs in red over yellow. Transverse ranges of the margins in thick black.](image)

Figure 3: Map of the Afar Triple Junction showing GPS velocities with respect to Nubia and focal mechanisms (lower hemisphere projections) from Harvard catalog, 1976–2009; topography and bathymetry from SRTM30 PLUS (from McKlusky et al., 2010). Active plate boundaries, with axial ranges acting as spreading segments (in thick red), transform fault zones (dotted arrows) and fracture zones (dotted red line) from Varet, (2020a).

A rather symmetrical geological sequence and tectonic arrangement is observed on both sides, with (Figure 4):

- A Precambrian basement (resulting from the Pan-African Orogeny) and its Mesozoic cover (a sequence of Triassic sandstones, Jurassic limestones and Cretaceous...
sandstones) being thinned by normal faulting at the foot of the main Nubian escarpment. These pre-rift units were also intruded and partly covered by basalts trap-series in the Oligo-Miocene when the whole Arabo-African continent was subject of a wide uplift before the separation or the Nubian, Somalian and Arabian plates (Varet, 2020b).

- A detrital unit, of red to yellow colour, therefore called the polychrome formation, also found on both sides with successive terraces inclined towards the depression, resulting from the intense erosion of the down-faulted basement and cover, ranging in age from Miocene to present.

- Marine sediments, observed on both sides of the depression, all along the near zero line, with either former beaches, with beautiful flat urchins and other fossils, or coral reefs, also rich in various fossils. These were dated 120,000 years BP (Lalou et al., 1970).

- The floor of the depression is filled by a sault plain, which resulted from the evaporation of the Danakil Sea, circa 50,000 years BP (Bonatti et al., 1971). Gypsum and pulverulent limestones deposits also show the presence of successive phases of evaporation and lacustrine episodes.

- Salt lakes are observed North (Lakes Karum and Bakili) and South (Lake Afrera) of the Erta Ale range (Bonatti et al., 2017; Figure 2).

- Volcanic units, of recent quaternary ages (ranging from a few hundred thousand years to present-day) are observed along the axis of the depression, fed by dikes of NNW-SSE directions. This recurrent diking along well-identified axis were considered by Barberi & Varet (1977) as presently active spreading axis, that is the geodynamic equivalent of Mid-Oceanic Ridges (MOR). The geochemistry of these dominantly basaltic lavas was shown to be also similar to MOR basalts (MORB). This interpretation was later confirmed by various authors on the basis of successive geophysical surveys (Calais et al., 2006).
- We should note that, in parts of these ranges, the volcano-tectonic evolution allowed for the development of central volcanoes, with a differentiation process by crystal fractionation at shallow depths which resulted in the formation of a magmatic sequence ranging from transitional basalts to iron rich intermediates (ferro-basalts and dark trachytes) up to rhyolites. This is of interest in a geothermal perspective as it implies the existence of magma chambers, i.e. shallow magmatic heat sources.

- In fact hydrothermal activity is observed, mainly as fumaroles and steam vents (along the open faults and fissures of the axis of spreading), and also as hot-springs (near the lake shores).

As a whole, the general environment is favorable for the development of geothermal systems. Several sites were considered and studied as such, in particular Alid in Eritrea (Lowenstern et al., 1997), Dallol (Varet et al., 2012) and Tat’Ali or Dabbahu in Ethiopia (Nabro et al., 2016), but none were yet developed. This relates to the access conditions, rather poor until recently. But the situation is changing: an asphalted road now links Sardo and Semera (capital of the Afar Regional State) to Mekele and Dallol, and electric lines are now being built along these communication axes. These allow to facilitate the export of local products (Potash, Salt, Manganese, Gold, animal husbandry) and to favor poles of local economic development. Besides Afdera, several villages and small towns develop along these axis, with hotels, restaurants, schools, hospitals, etc. Harak is now part of this environment.

2. Description of the Harak geothermal site and preliminary conceptual model

The Harak graben controlled by N-S symmetrical normal faulting, extends south of the Ta’Ali axial range, forming a southern tectonic extension for the Mat’Ala shield volcano, itself seated along the Tat’Ali rift axis (Figure 4). Mat’Ala is a basaltic shield volcano, topped with a circular caldera, 3 Km wide and 500m deep, where fumaroles are observed. It is slightly older than the Tat’Ali lava fields extending west along faults and open fissures releasing steam vents, and considered as a geothermal target by Gardo & Varet, (2018). It connects with the Tat-Ali caldera, which itself is elongated along the same sub-N-S direction as the Harak graben and Mat’Ala volcano. To the West of Tat’Ali range, the plain lying at the foot of the Danakil block, surrounded by former coral reefs and beaches along the 0 m line was until now considered as the southernmost extension of the Danakil sea, as the altitude becomes positive south, and no more trace of the presence of marine deposits is observed.

However, west of this plain, to the South of Tat’Ali range, separated by a thin horst, a long graben called “Harak” extends over 50km, with a width narrowing from 10 km north to 3km south, where it progressively dies. The floor of the graben, filled with recent flat-lying sediments, lies at a negative altitude, averaging 80m bsl along its axis and down to less than 110m bsl in several locations. That is an altitude below Afdera lake level and similar to the wide salt plain north.

Hence, in a recent exploration we discover here a significant southern extension of the Danakil rift that has until now not been described. Up to 100m thick white sediments deposits are observed, stick along the bordering faults of this graben, offering good geological sections of marine reefs and later evaporitic deposits, than would justify detailed studies by sedimentologists allowing to precise their age and depositional conditions (Figure 5).
Figure 5: Satellite image of the Harak graben, with its grey-green floor below sea level. The deeply faulted stratoid series (in black) on both sides are covered by white sediments on both sides below the zero altitude. To the west, the Sodonta plain is filled with evaporitic sediments (pulverulent limestones and gypsum). It contoured by the asphalted road seen (while curvilinear line) in the middle of the image.

As for the great salt plain north, this surface is eventually flooded in the wet season (although yearly rains are getting more seldom), as it is fed here by wide hydrographic basin extending south over circa 200km$^2$. A salt-lake, surrounded by salt-crust surfaces extends over circa 6km$^2$ in the southern half of this graben. Along a 5km long N-S alignment, numerous thermal manifestations are observed, resulting from steam convection through open fissures affecting the graben axis (Figure 6 & 7), remobilizing the superficial wet and dry sediments, and producing a variety of geothermal features (as outlined below) eventually named “little Dallol” (name of the site affected by spectacular hydrothermal manifestations in the middle of the Great Salt Plain):

- Active mud volcanoes (Figure 8)
- Steaming holes and cracks (Figure 9)
- Chimneys and domes (Figure 10)
- “Dallol like” Green, yellow and red salt concretions (although smaller in size and extension, Figure 11)
- Phreatic explosion craters (averaging 20m and up to 200m wide for the largest, Figure 12),
- Various other kinds of thermal manifestations (Figure 13)

Temperature measurements indicate 100°C at the surface of the dry steam vents, and even higher values (up to 115°C) in the mud volcanoes. Observation of the surface surrounding these manifestations clearly shows that even more important thermal events affected the surface over a wider area, along active faults and open fissures of the same N-S direction. The seasonal flooding is reshaping yearly the landscape of these geothermal features. As a consequence, a variable landscape will be observed from year to year.

To the south the graben dies while crossing the Ela rhyolite centre topping the faulted stratoid series. To the South-East, a fairly recent basaltic lava flow covers a 120km x 40km wide surface, called Maska (see Figure 3). This flow was emitted from a spatter cone that formed along the same fault line as the Harak graben. As a consequence, the Harak graben, which was thought to be “purely tectonic” in a first view, appears to be magmatically active with an active diking along its axis, not expressed at the surface in its lowest-altitude section, where thermal manifestations are the most spectacular. The geothermal system is therefore not only tectonically controlled, but is also linked with shallow magmatic heat source.
Figure 6 (left): alignment of hydrothermal manifestations along the Arak graben floor. Figure 7 (right): thick sedimentary deposits stuck against the Eastern major fault scarp, and covering he tilted blocks along its foot (satellite images from Google Earth pro.)

Figure 8: some Harak’s active mud volcanoes, toping an explosion crater, below (Photos J.Varet, 2020)
Figure 9: Some of Harak’s dry or wet steam vents (Photos J.Varet, 2020)

Fig. 10: Hydrothermal chimneys and domes at Harak (Photos J.Varet, 2020)
These new observations do not only open geothermal development perspectives but also raise a new picture for the understanding of the geodynamics of the Afar region. It shows that the transform fault zone south of Ta’Ali, Afdera and Alayta do not accommodate the whole extension concentrating in the Manda Harraro rift segment south, but that residual extension still persists eventually linking Ta’Ali and Manda Inakir axial ranges (Audin et al., 1990; Varet, 2018, and Figure 13).

As a whole, besides its exceptional “text-book” value as a natural active hydrothermal site, Harak area also appear as a site of high geothermal value, with:

- a magmatic heat source,
- a fractured reservoir in the basaltic stratoid series, and
- a sedimentary cover that allows surface leakages due to open fissuring and steam release, either continuous (fumaroles and mud volcanoes) or discontinuous (phreatic explosion craters).

The area deserves further detailed field investigations, implying geology, fluid geochemistry and geophysics (gravimetry, micro-seismicity and magneto-tellurics), allowing to quantify in 3D the presently qualitative geothermal conceptual model.
3. Social environment and socio-economic perspective

Harak is located at a distance of 10Km East from the Sardo - Afdera asphalted road at a distance of 105 km North from Sardo and 80 km South from Afdera), which in fact links Mekele and Dallol to Addis Ababa and Djibouti. The drawing and quality of this road makes it more convenient than the older road passing along the plateau through Dessie. The traffic is therefore increasing fast with several villages and towns along the road developing with hotels, restaurants, garage, schools and health facilities. It facilitates the export of salt mined in the great salt plain and produced by the salt pounds which developed around lake Afrera. The traffic is expected to increase even more when the direct link from Afdera to Dallol - being built through Dodom plain along the western side of Erta Ale range - will be completed, providing an access to the mineral port under construction in Tadjourah for the potash and other mines north.

The village of Tio (or Téo) located on the eastern side of the highway is the departure point for a 4WD track that allows to reach the Harak hydrothermal site. The 15 km track crosses two successive horsts (basalts of the stratoid formation partly covered with gypsum deposits) and grabens (filled with unconsolidated evaporitic and eolian sediments), with a few difficult passages along faults.
The Harak population is pastoral, with 6,950 people spread over the area, and Tio as main centre, where access conditions and local guides should be looked for, allowing to reach the geothermal site, until now rarely visited, except by the few tens families living permanently there there, as the plains surrounding the salty graben axis are rather green with permanent pasturelands.

The discussion is being engaged by AGAP and APDA with the community on how to better valorize the site: keep it as a natural feature, to be eventually protected and valorized as such. This pedagogic site could be organized for visitors in a form of eco-tourism that would benefit to the local community. This should not refrain from engaging a scientific study of the geothermal resource in view of a local geothermal development including water and energy production, facilitating the salt extraction and export along an improved access road.

4. Conclusion

The “discovery” of this new geothermal site, “unknown” until now despite geological and geothermal surveys, open a new perspective, besides the sites already considered by AGAP at Tat’Ali and Dabbahu. Given the limited technical capabilities of AGAP at present, a partnership is being considered with the Geological Survey of Ethiopia (GSE), who shared with AGAP the last field mission allowing to recognize these sites, and plan complementary surface studies at Tat’Ali. Dabbahu (now called Era Boru, see Gardo & Varet, 2020) will also be considered as a new road is being built that should cross trough this wide geothermal area at present of difficult access. The Harak site adds another perspective which should now be considered with the local communities, as well as with the Afar Regional State authorities, regionally and locally.

From a pure and basic geological point of view, this open a new vision of the Danakil Sea, which extended 50 Km more to the South than considered until now. These new observations show that the Ta’Ali axis of spreading do not abruptly stops south of Mat’Ala crater, but still undergoes active extension further south. The Maska recent basaltic lava field, considered as a late manifestation of the Afar stratoid series, should be looked as part of this rift axis which appears as really tectonically, hydrothermally and magmatically active.

Acknowledgments

The authors thank APDA, AGAP, Géo2D, GSE, and local communities at Téo for their support in the identification of this new geothermal site.

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