

## **Dabbahu (Teru Woreda) in Northern Afar A major Ethiopian Geothermal Site Leased by AGAP**

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### **ABSTRACT**

AGAP (Afar Geothermal Development Company) is a community-based organization founded in 2015 that aims at developing geothermal sites in the Regional State of Afar. After a comprehensive regional survey, in this region that is characterized by active volcanism and tectonics, the first-priority targets were identified in Northern Afar. The choice of this target results mainly from social considerations. Differing from Southern Afar where the Awash basin provides significant water inflow, Northern Afar is particularly dry, and droughts are significantly increased by the ongoing climate change. The only option is immigration. AGAP considers that geothermal is eventually the most viable solution for the pastoralist communities in the region to continue living on their land and could even ultimately provide climate resilience.

From the reconnaissance study undertaken with the support of Geo2D, two priority targets were identified, out of which Dabbahu (Teru Woreda, also called Boina, meaning fumarole in Afar language) appears to be quite promising and eventually one of the major geothermal sites in Ethiopia.

The Teru plain (which gave the name to the Woreda) lies at an altitude of 330 to 370 metres along the eastern foot of the Nubian escarpment. Filled by sediments over a thickness of 300m, it benefits from the inflow of the meteoritic water along the plateau faulted margin both at the surface and through faulted aquifers. Teru is 60 Km long and 20 Km wide, bordered to the East by the recent basaltic lava flows emitted from the Alayta and Manda Hararo ranges and silicic flows from Dabbahu volcano, and closed South and North by the Ma'alalta and Dabayra volcanic units developed along the Afar margin at the favour of transverse tectonics. This wide sedimentary plain therefore benefits from rather favourable conditions and is covered by a green vegetation for half its surface. It is therefore more densely populated than the surroundings, with circa 120.000 inhabitants.

Dabbahu volcano (toping 1401m) is a wide silicic unit, characterized by a set of obsidian flows and domes ranging from comendites to pantellerites, emitted through N-S fissures in a broad area which appears to be a “leaky transform zone” linking the two-major axial (NNW-SSE) ranges of Alayta and Manda Harraro (two typical spreading axis). This silicic unit is topping a dominantly basaltic shield volcano with all intermediate terms of the differentiation. Both ranges are active with basaltic historic eruptions (and associated volcano-tectonic events) having occurred in 1915 and 2005-2010. This last event also reactivated a rhyolitic

pumice outburst at Da'Ure in the Dabbahu massif. The area affected by these recent domes, south of Alayta and North of Manda Harraro is 24 Km long and 12 Km large, a plateau circa 300 Km<sup>2</sup> wide averaging an altitude of 600m, also the site of steam vents emitted through open fissures of dominantly N-S direction. To the SW of Dabbahu, NNE-SSW trending faults and emissive fissures are also leaking steam along the slope of the shield volcano. These steam vents are largely used by the Afar pastoralists, and in addition to semi-permanent settlers, the plateau area is a place of refuge for surrounding Afar tribes in case of severe draught.

Geochemical and geophysical surveys still need to be carried out on the site, and AGAP is looking for partners to develop this geothermal lease that contain both superficial steam resources to be tapped by shallow wells and deep reservoir for classical high-temperature development. Considering the huge heat source, the important natural groundwater inflow, the high permeability resulting from multiple open fracturing, the huge surface characterized by upflow and outflow, and its active geodynamic location, Dabbahu appears – despite its present remoteness - as one of the major geothermal sites in Ethiopia, if not in the world, with a potential of several thousand MWe.

## 1. Introduction

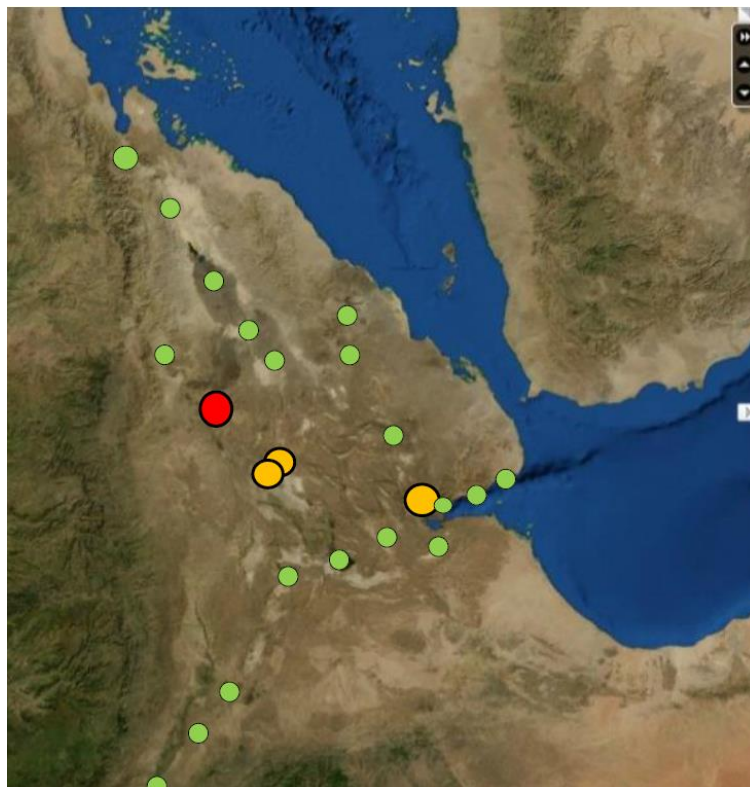
Afar is one of the hottest and driest places in the world. Although it is severely affected by climate change, it is an area where a population has been living since immemorial times, adapting its pastoralist activities to changing environmental conditions. The Afar triangle; a term derived from the name of the local inhabitants, extends over 3 countries (NE Ethiopia, SE Eritrea, and Djibouti Republic); the main surface and the majority of the population being found in Ethiopia. Since the Federal Democratic Republic of Ethiopia was promulgated, Afar benefits from the status of a “Regional State”, with Semara at the centre as its capital.

Within the EARS, Afar displays a particular geodynamic situation, as it is not just the northern extension of the EARS, but in fact part of the Red Sea – Gulf of Aden oceanic rift system, exceptionally emerged there, on the African continent. Afar does not represent the “funneling out” of the MER but a specific area where the MER continental rift system hits the out-cropping Aden-Red Sea ridge (Tazieff et al., 1970, Barberi et al., 1972). The Afar floor (-120m bsl to the north and – 155m bsl to the east) is surrounded by the escarpments of the Nubian plate to the West, the Somalian plate to the South and the Arabic plate to the East, with the Danakil Alps acting as a rotating microplate to the NE in-between the Southern Red Sea and the former Danakil sea (Fig. 1).

Totally flooded by lavas less than 4 My in age, with several - still active since the last 1 My - well defined spreading segments expressed at the surface by basaltic axial ranges, as well as transverse ranges and central silicic volcanoes along the margins (in areas of discontinuities of the basement) similar to those along the MER northern extension (Fig. 2). These various volcanic units provides numerous opportunities for the development of shallow heat sources. In addition, the lithology as well as the intense and active faulting allow for the development of geothermal reservoirs.

As a result, Afar benefits from numerous sites of high geothermal potential – some of them among world's giants - which have been neglected up to now, due to the remoteness of the area, away of from the main axis of development of the climatic better gifted Ethiopian plateau regions. According to the investigations carried by Géo2D, Dabbahu is one of these major geothermal sites, eventually the largest in Ethiopia. It is of interest for the local

population, not only answering their immediate needs, but also because climate change heightens the necessity for new avenues for local development. This is the reason why the Afar Geothermal Development Company (AGAP), a community-based enterprise founded in 2014, registered in Ethiopia and owned by 13 communities of Northern and Central Afar (Nebro et al. 2016) choose this site as one of its priority target.



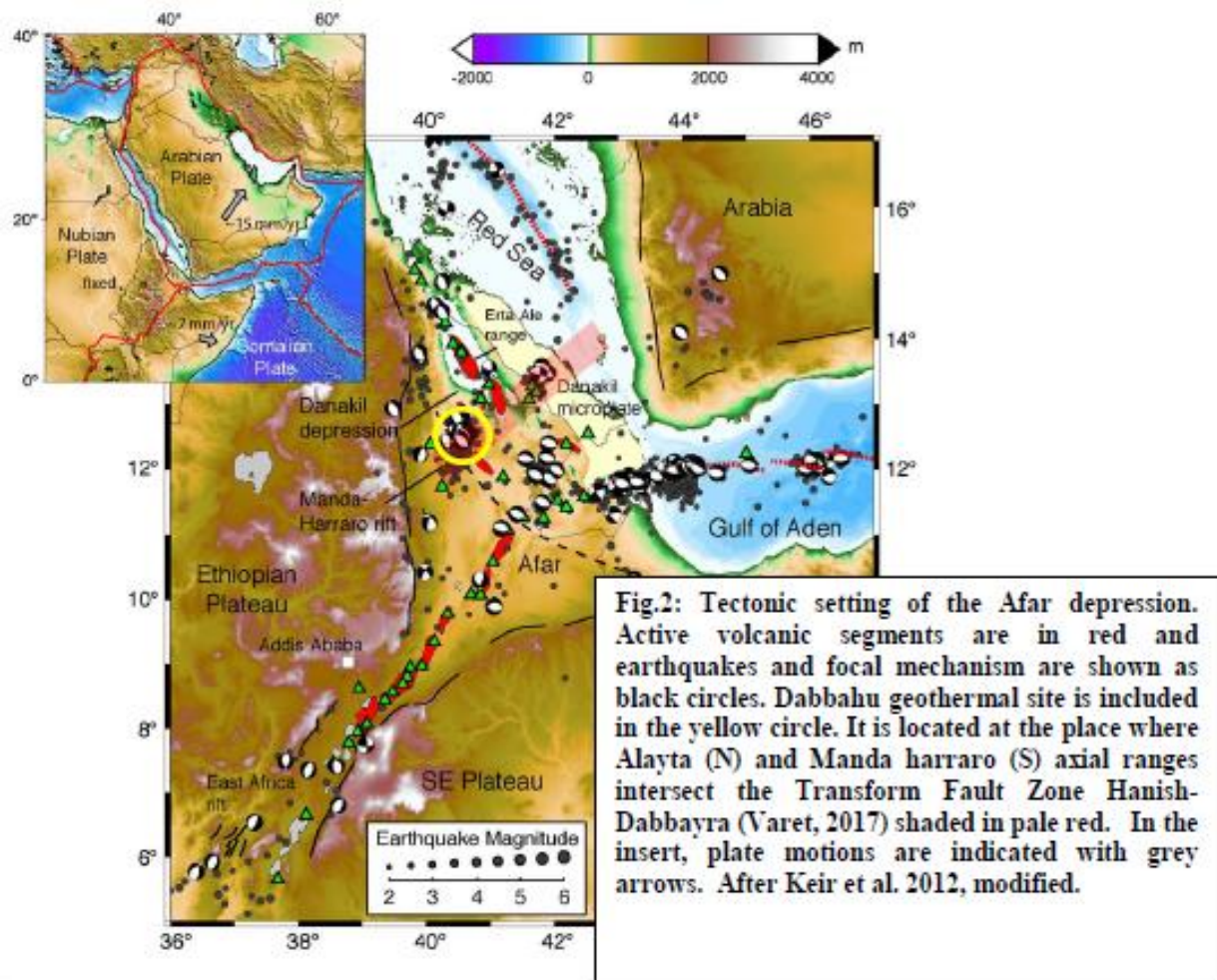
**Fig.1: The « Afar triangle » (in pale colour compared with darker plateaus), a large desert depression covered by recent volcanic essentially bared formations affected by active faulting, also display numerous steam vents. Red dot show the location of the Dabbahu geothermal project proposed by AGAP, whereas the orange dots show the location of the Tendaho projects being developed by the Ethiopian Government and of the Asal geothermal sites (Fiale and Gale Le Koma) in the Djibouti Republic. Other major geothermal sites identified by Géo2D are shown with green dots (including Alid and Nabro in Eritrea and a few sites in Djibouti).**

## **2. A geodynamic environment favouring high enthalpy geothermal sites**

Conditions for the development of high enthalpy geothermal fields were shown to be met in NE Afar when the super-position of 3 geological features was encountered (J.Varet, 2006):

- 2.1. The presence of active spreading segments, with important and recent volcanic activity developed in the “rift-in-rift” structures: the Erta-Ale, Alayta, Tat’Ali, Manda-Harraro and Manda-Inakir axial ranges. From the Asal rift in Djibouti, which connects with the Aden-Tadjoura oceanic ridge, up to Alid (in Eritrea) these ranges allow for the development of significant, shallow magmatic heat sources. The spreading rate varies and reach the highest values in the ranges of central and western Afar (Manda Harraro and Asal, Fig.2).

2.2. The development of transverse faulting crossing through the dominantly NNE-SSW normal and open faults, which frequently correspond to offsets in the scarp of the Nubian plateau as well as between axial ranges, which allow for the development of larger heat sources and fracture permeability in geothermal reservoirs. This prevails in particular for Dabbahu (Fig.2).



2.3. The feeding of the geothermal reservoirs from eventually wide basins developed along the normally faulted and intensively eroded escarpment of the Nubian plateau, with frequent lateral grabens allowing for the infiltration of meteoritic water from the wet highlands into faulted Proterozoic basement, its Mesozoic sedimentary cover (Jurassic limestone and cretaceous sandstone) as well as Tertiary and Quaternary detrital formations. Such hydrogeological environment is particularly well developed at Dabbahu, with the nearby green Teru plain (Fig.3).

### 3. A powerful magmatic heat source and large fractured geothermal reservoir

South of Alayta, a major fracture zone (Varet, 2018) extends from Dabbayara to Dabbahu, Bidu, Dubi and Hanish island in the Red Sea (shaded red in Fig.2 and underlined in Fig. 4). This also marks one of the major offsets of the Nubian basement scarp. It also marks the shift between the historically active Alayta axial range to the north and the Manda-Harraro range

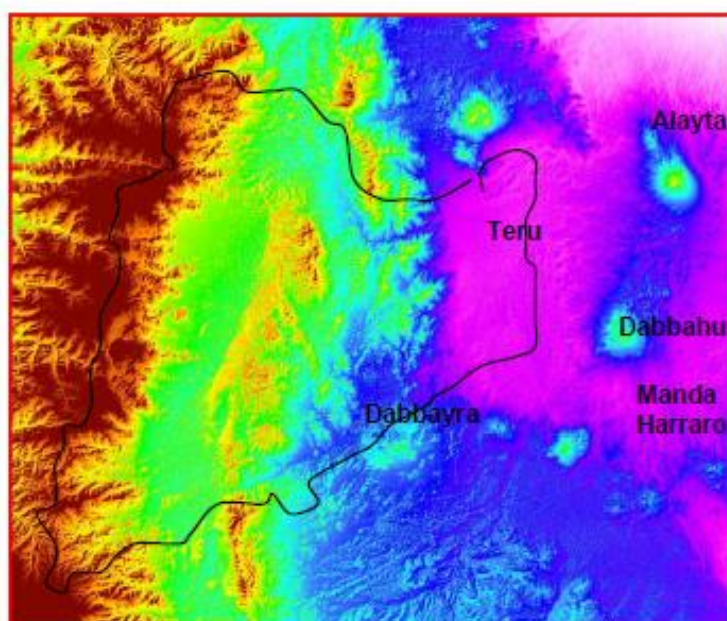


that extends along 120 Km and was particularly active in the years 2005-2010. In the area of transition between these two axial ranges, the Dabbahu recent silicic centre (Barberi & Varet, 1975) developed. This volcanic unit is affected by silicic extrusions over a width of 25 Km, reaches an altitude of 1400 metres (which gave its name in Afar language meaning “the large mountain” and covers a surface of circa 750 Km<sup>2</sup>.

It was initially built on basaltic fissural lavas found all around the volcano which evolved in a shield. The successive feeding of basalts along a set of fissures of N-S direction permitted the progressive identification of magma chambers, allowing the composition of magmas to evolve up to andesine basalts, ferrobasalts and dark trachytes found at the surface of the shield. The volcano was topped by fairly recent rhyolite domes that are aligned along several (up to 7) parallel N-S trending emission fissures, extending from the Manda Harraro axis to the Alayta axis. Although the geochemistry points to a single line of fractionation (Fig. 5), their composition slightly varies with pantellerites dominant at Dabbahu whereas comendites prevail south from Alayta, showing different magmatic units (Barberi et al., 1975). Among the silicic products, crystalline domes and obsidian flows are dominant although subordinate pumice and pyroclastics are also present.

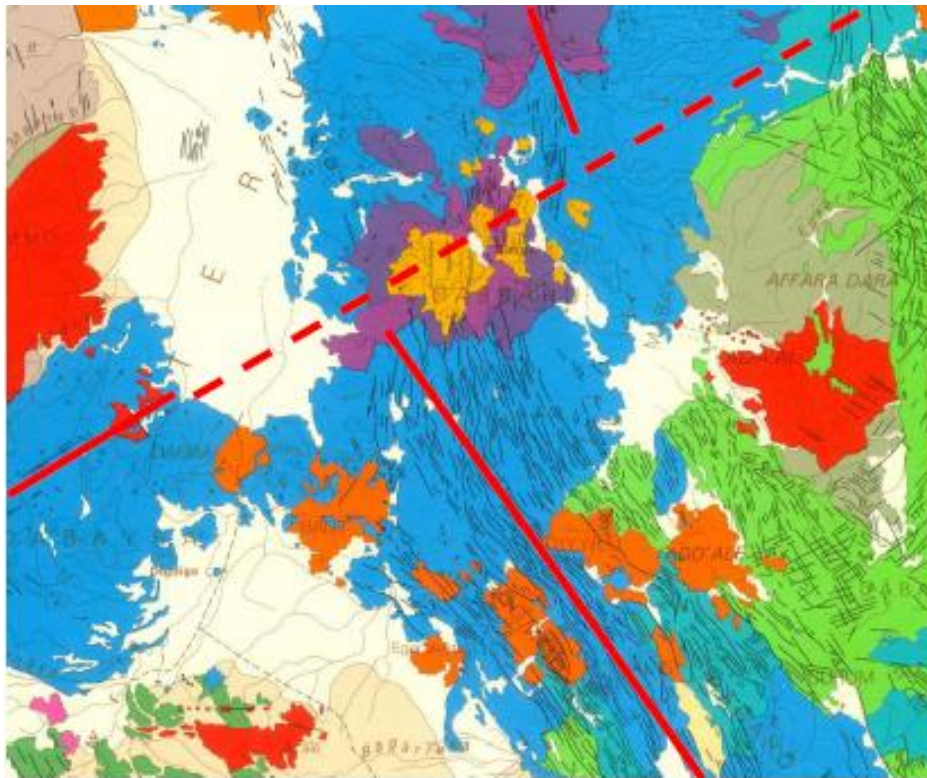
Ages were measured 44 to 10 ka by Barberi et al., 1972 for two obsidians. Field et al. (2013) provided ages of 64 ka for andesine basalts from the shield volcano, whereas younger andesine basalts were dated 33 ka, comendites 30 ka and pantelleritic obsidians younger than 7.8 ka, showing a regular activity from for the last 100 ky.

**Fig.3: Hydrographic basin**  
feeding the Dabbahu geothermal  
site from the Nubian plateau.  
Observe the marginal grabens  
Along the foot of the escarpment.  
NASA/SRTM source, BRGM  
Processing (Varet et al., 2012).

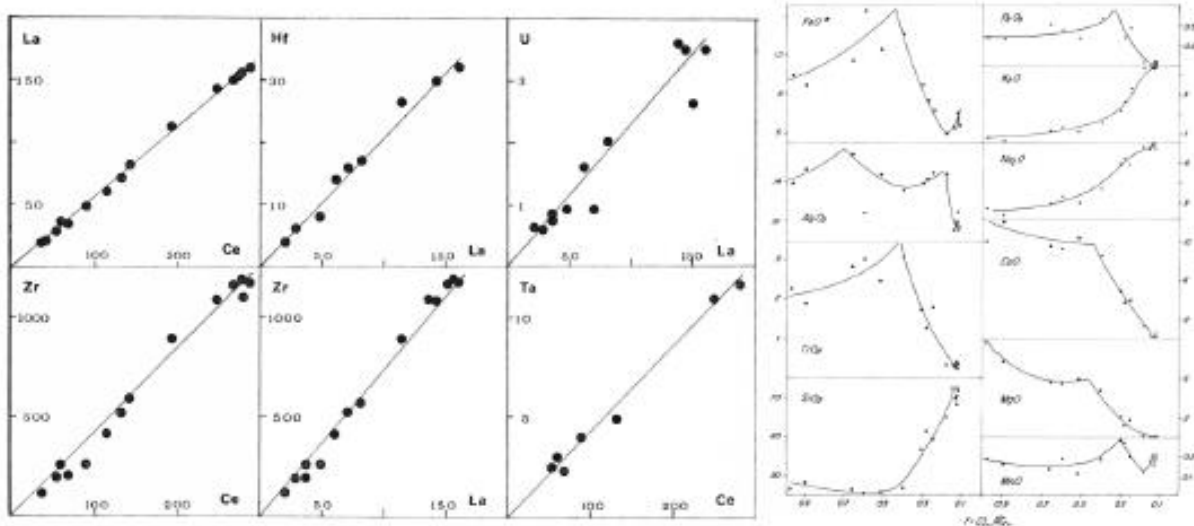


The width of the area penetrated by silicic domes is impressive (22 Km) and - despite a relative dispersion of the emissions along N-S fissures - trends in the ENE-WSW direction of the fracture zone. The length of the emissive fissures never exceeds 8 Km and their precise and limited structural position indicate that they are closely related to the tectonic and magmatic evolution of the underlying strato-volcano. No clear volcano-tectonic evidence however point to a single magma chamber, as no caldera nor summit sink is observed. However, in addition to the several N-S short axis, the existence at depth of a transverse line of weakness is inferred from the distribution of the silicic emission centres and recent

transverse faulting rejuvenated during the 2005 Dabbahu event. As a whole, Dabbahu acts as a leaky transform fault between Alayta and Manda Harraro ranges (Varet, 2018).



**Fig.4:** Geological map of the Dabbahu geothermal site, south of Alayta, and north of Manda Harraro axial ranges. This right lateral offset of the spreading segments correspond with the offset of the Nubian escarpment. Dabbahu is also located in line with the ENE-WSW axis of the Dabayra dominantly basaltic transverse volcanic unit, and mid-way between the two peralkaline granites (in red) of Limmo (on the left) and Affara Dara (on the right) (Varet, 2017).

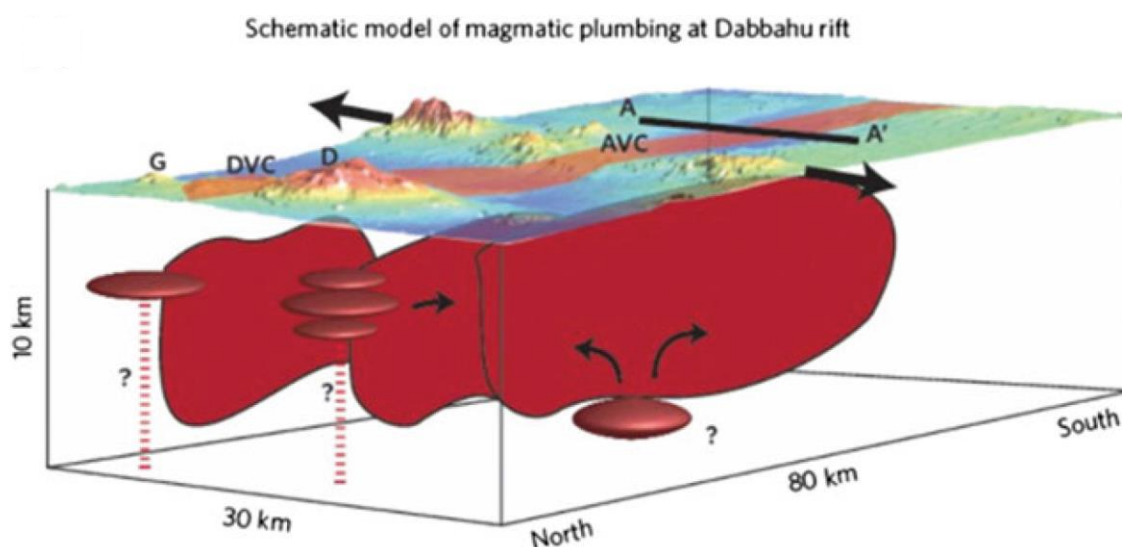


**Fig.5 (left):** Linear correlation for pairs of hygromagmatophile elements in the whole Dabbahu rock series showing the crystal fractionation process from a single magmatic source. **Fig. 6 (right):** Evolution of major elements as a function of the residual liquid fraction (Barberi et al. 1975).

Field et al. (2013) précised the temperature (1200-680°C) and depth (10-15 Km) ranges where this crystal fractionation process occurred. The aseismic zone observed from the 2005-2006 earthquake data allowed to locate the magma storage region at a depth of 2 to 6 Km, whereas abundant earthquakes above 2 Km suggest a fractured roof – and eventually the site of the geothermal reservoir - above the magma chamber.



InSAR modelling of interferograms obtained since the 2005 event allowed to identify an uplift signal of 50 cm, that could be interpreted as a point source at a depth of 3 Km inflated by  $0.022 \text{ Km}^3$ , but a better fit was obtained from multiple stacked sills at depth of 3 to 4.5 Km (Fig. 6). The final steps of differentiation therefore apparently occurred at shallow depth in small size bodies, such as stacked sills or closely spaced dykes, located at in a magma storage system that has maintained a stable geometry over the past few thousand years. Therefore, huge ( $400 \text{ Km}^2$ ) and powerful shallow magmatic heat source characterize the area.

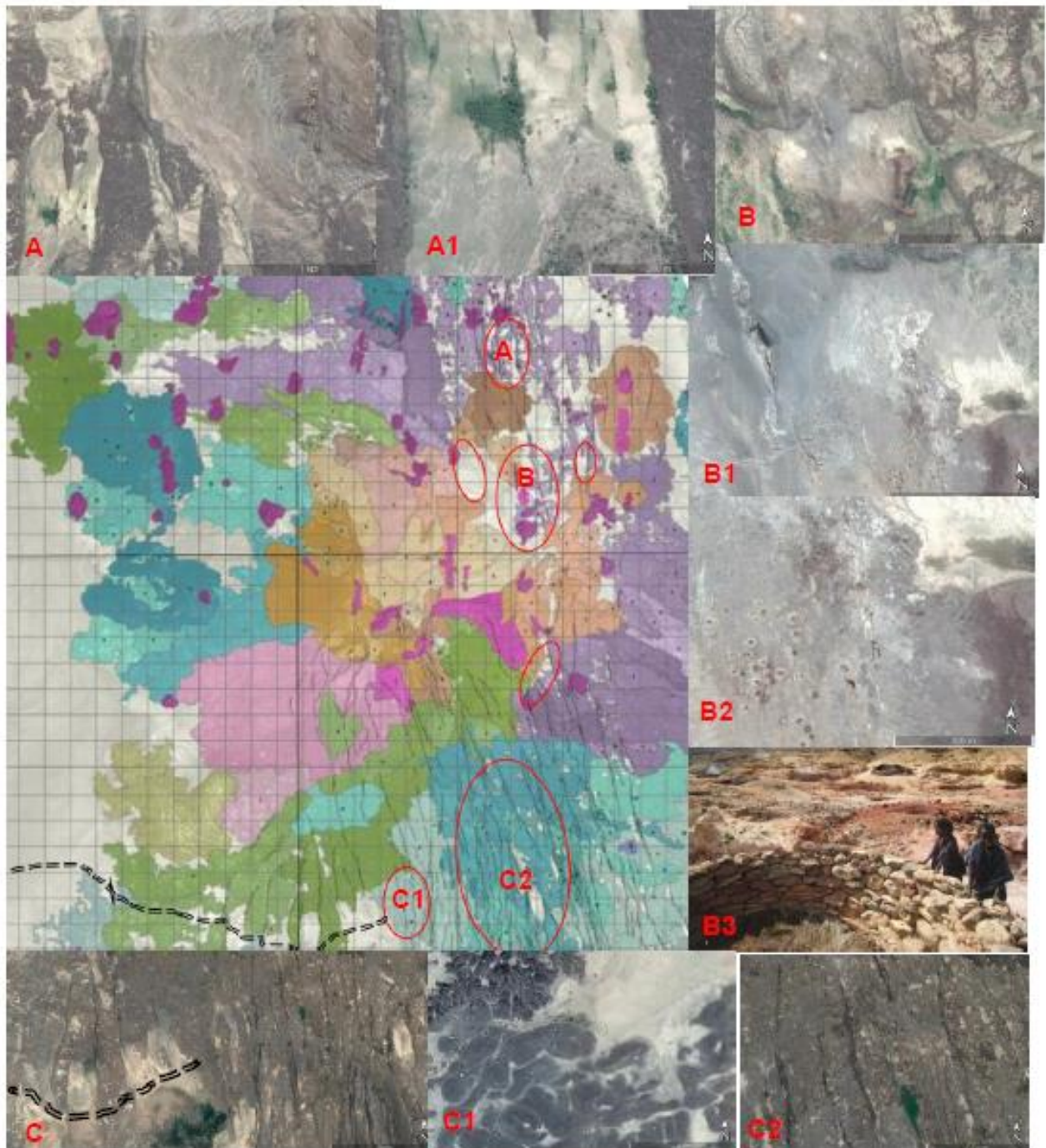


**Fig. 6:** Schematic model of magmatic plumbing showing the presence of a shallow magma chamber at Dabbahu and the 70 Km long diking event (2005-2010) of Manda Harraro further south (from Wright et al., 2012).

Dabbahu (also known as “Boina” for this reason, Barberi et al. 1975) is also the site of intense hydrothermal manifestations, with innumerable steam bents, fumaroles, hot-springs and silica deposits, notably on the E and S flanks. On the eastern plateau, at least 5 areas are observed, and are even visible on satellite imagery with fumaroles and steaming grounds aligned along N-S fissures and faults, covering a surface of over  $100 \text{ Km}^2$ . This plateau, at an average altitude of 700 to 800m, allows a local population to live there, benefitting from a scarce vegetation also developed along the steam leaking faults.

To the south, two wide areas totalizing another  $100 \text{ Km}^2$  are observed. The westernmost is accessible by track from Teru township and is the site of numerous condensing devices engineered by families using the grazing lands in the small grabens at the foot of the volcanic massif. The southernmost correspond with the northern extremity of the Manda Harraro range where numerous N-S trending faults are leaking steam feeding a rather abundant vegetation developed along the fault planes (Fig.7).

The environment East and South of Dabbahu is so dry that the solution of reference for the population is to condensate the naturally steaming grounds for liquid water production and other uses (washing, boiling food and tea...). The technique is to improve the steaming of the fissures and faults by some diggings and to install devices for channelling and condensing the steam, then allowing to collect the water in basins made of the red clay resulting from the hydrothermal alteration of the volcanic rocks found on site through diggings (Fig.8).



**Fig. 7: Geological map of Dabbahu (Field et al., 2013) showing the location of the main hydrothermal zones (red ellipses) to the East and South of the pantelleritic domes and flows (in beige and yellow) of the main centre. Some of the hot grounds and steam vents are visible on satellite images, as shown on a few examples. A1 is a detailed view of open leaking fissures in a graben north seen in A. The black circles in B2 are engineered steam condensation wells SE of the 2005 pumice eruptive fissure. Photo of one of them in B3 (from Field). Satellite image C is covering the southern emissive fissure zone, engineered in C1 (white dots with black circles) and favouring the development of vegetation along steaming fissures in C2.**





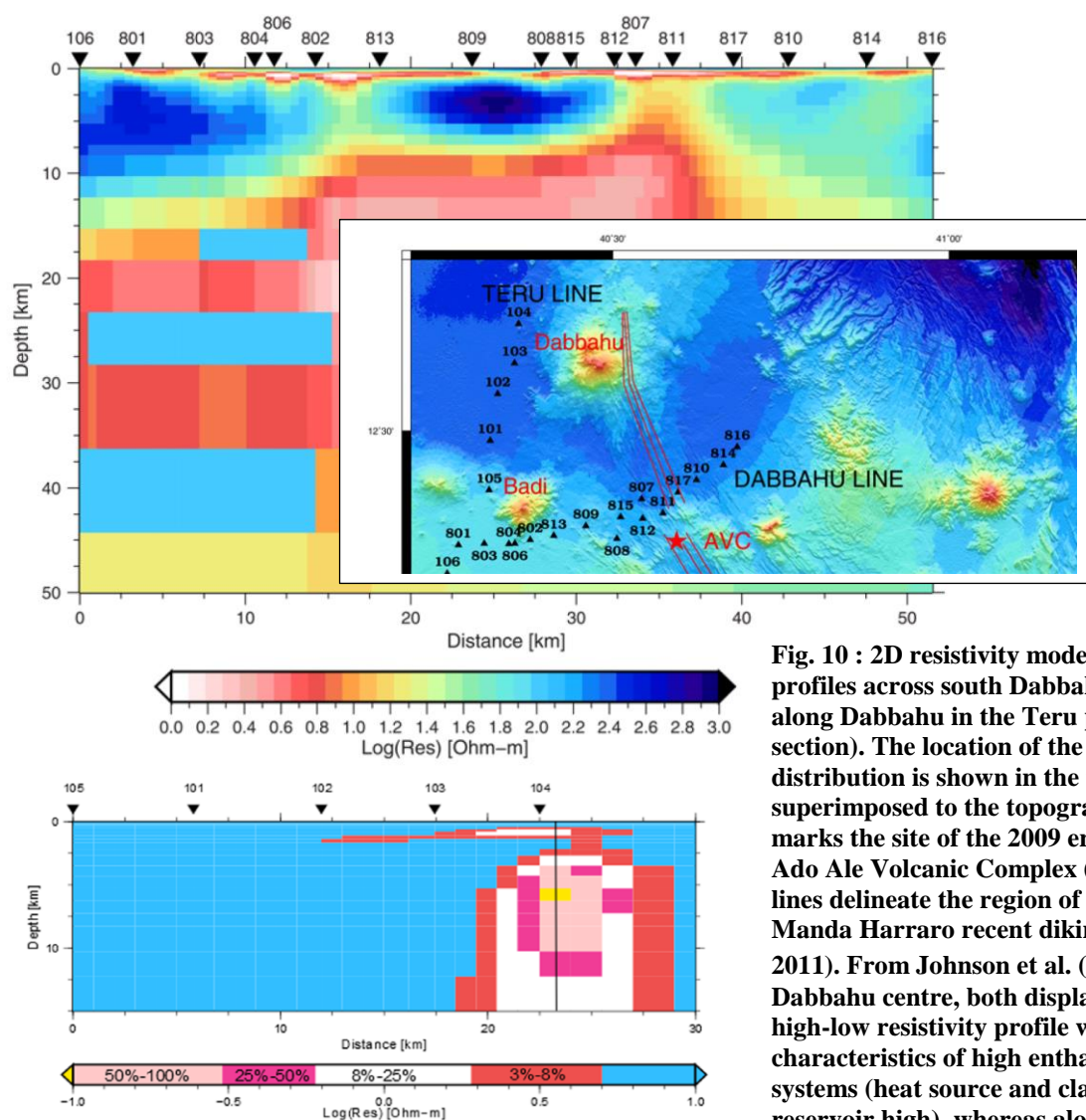
**Fig. 8: Traditional device for water condensation from fumaroles (“Boina”) using branches on a well dug along an emitting fault (SE Teru, Afar, area C1 in Fig.7). Observe the geothermal grass (“Fiale”) growing around the site in this otherwise arid plateau (Photo: J.Varet, 2016).**

This is done in a very artisanal way by digging with hand instruments through the rocks and clay infilling of the steam vent along narrow (centimetric opening in width) faults zones (the hot steam progressively transform the volcanic rock into clay with time) in order to increase the steam discharge, and install branches fixed with stones (a circular dry-stone wall is built) in order to condense the steam into liquid water. Water drops falling from the branches on the clay carpeted floor are driven along channels drawn in a clay towards the modelled basin. Such devices are observed all around Dabbahu volcanic centre (Fig.8) and allow for the Afar pastoralist population to benefit from water for herds and humans whereas grazing lands also developed in the surroundings thanks to widespread steaming grounds (Fig.9).

Two MT profiles (Fig. 10) were undertaken in the Dabbahu massif by Johnson et al. (2016). The results indicate the characteristic resistivity profiles that are expected in a geothermal system, with a very low superficial resistivity zone that can be interpreted as the clay cap of the geothermal reservoir, displaying high resistivities, whereas a deeper (8 to 3 Km deep) low resistivity zone indicate the magma chamber. Note that these characteristics extends over a width of 20 Km across the active rift axis. The Teru line exhibits this structure over a width of 10 Km only, but this line is located on the western side of Dabbahu, and not on the eastern side where a much wider area of hydrothermal activity is observed, and will show a much larger extension (at least 20 and up to 40 Km).



**Fig. 9:** Steam condensing devices used to provide spaces for cooking, cleaning and water production for the cattle at W Dabbahu, site B2 in Fig. 7. Photo: Wright et al.)



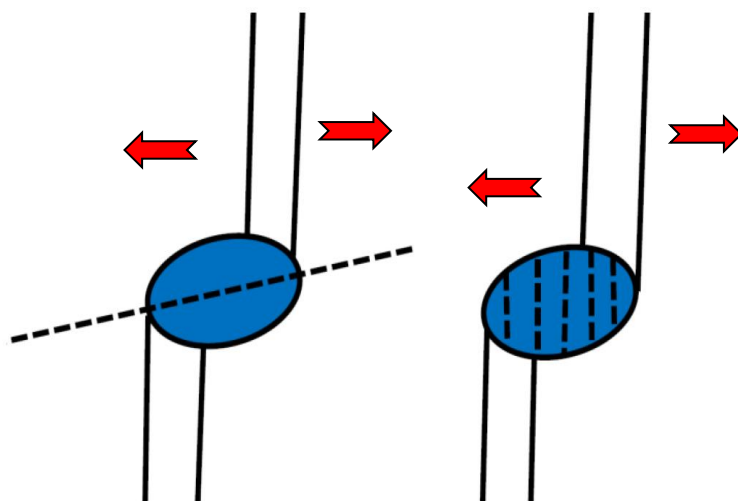
**Fig. 10 :** 2D resistivity models along two MT profiles across south Dabbahu (upper section) along Dabbahu in the Teru pain (lower section). The location of the MT sites distribution is shown in the upper right insert superimposed to the topography. The star marks the site of the 2009 eruption within the Ado Ale Volcanic Complex (AVC). The thin lines delineate the region of the Dabbahu and Manda Harraro recent diking episode (2005-2011). From Johnson et al. (2016). Near the Dabbahu centre, both display the typical low-high-low resistivity profile with depth characteristics of high enthalpy geothermal systems (heat source and clay cap low, steam reservoir high), whereas along the active spreading segment (site 807 & 811), the resistivity is continuously low showing active magmatic an hydrothermal upwelling.



As a whole, with :

- an exceptionally large magmatic heat source,
- abundant water recharge,
- active complex fracturation along the leaky transform fault induced by the fracture zone displacing the two en-échelon spreading segments,
- determining high permeability for the geothermal reservoir (Fig. 11),

Dabbahu geothermal site appear as potentially one of the world “Giant” (over 2.000 MWe).



**Fig. 11: Development of large geothermal sites in the East African Rift Valley and Afar, at the favour of leaky transform faults and fracture zones linking two spreading segments, allowing for the development of magma chamber providing a caldera or a set of domes, or both. A feature characterizing the site of Tulu Moye, Olkaria and Dabbahu (see Birba & Varet this volume).**

### 3. Proposed developments

A large area (over 50 Km<sup>2</sup> in surface) where numerous steam manifestations occur along N-S faults limiting grabens, easily accessible by track from Teru, was identified as a first target in the South-East flank of the Dabbahu volcanic complex during a geological exploration undertaken by Géo2D for AGAP in 2015. These faults and open fissures result from the interference of the NE-SW fracture zone (reactivated in 2005 in the Teru plain) with the main NNW-SSE trend of spreading.

Confirmed by MT results as an area showing the characteristic resistivity profiles of a geothermal steam reservoir, this first target is interpreted as a “leaking” of the main geothermal reservoir located in the Dabbahu volcanic centre. This “outflow” is however large enough to constitute an interesting target for the first small-size geothermal project AGAP is looking for.

The relatively easy access to the area by an existing dirt road allow for reduced civil works. A first unit of up to 5MWe fed by shallow geothermal wells (500m to 1,000m depth to be precised by further MT/TEM survey) should answer the socio-economic needs of the population in Teru, implying the development of a local grid. This should help for local agro-industrial development (eg. food processing abattoirs, milk industry) and exports which would create additional incomes for the target Afar community.



Note that, contrasting with the conditions encountered in the central geothermal zone of the Eastern Dabbahu plateau - where the only sources of water are these steam condensing devices - the Teru region is exceptionally green in Afar (comparing only with the Awash basin). It is an area of strong agricultural development (mainly cattle breeding), with a relatively large population (more than 80,000 inhabitants), spread in numerous villages, in addition to the small Teru Township. The area therefore demonstrates important development perspectives.

This S Dabbahu site can be further developed but should be considered as a first step before much larger development are engaged further north and west in the central part of the geothermal system. That will necessitate the construction of an access road across the southern slope of Dabbahu to contour the summit and reach the eastern plateau. This option will allow for the development of the whole geothermal site, demonstrating the presence here of one of the world Giants, exceeding 2.000 MWe.

This will necessitate to undertake a High Voltage connection to the Federal electric grid which will result as a major contribution to the Ethiopian economy, as base load production is lacking in this north-eastern part of the country. Of course, this target falls above AGAP's capabilities, and appropriate partner(s) will be searched for, whether private or public.

AGAP already engaged the procedure for the obtention of the lease from the Ethiopian Energy Authority and is presently looking for a development partner. The first part of the project will be engaged in 3 phases:

1. Prefeasibility study: complementary surface geology, fluid geochemistry with gas sampling and analysis, and complementary geophysical (MT-TEM) survey allowing to precise the extension and characteristics of the reservoir and establish a comprehensive geothermal model of the SW part of the field.
2. Feasibility: exploration-production drilling at a depth of 500 to 1000m aiming to reach a superficial steam reservoir and characterize the initial geothermal development of the SW part of the field.
3. Production: the construction of the first power plant (5 MWe with binary ORC technology) and corresponding local networks, will allow for a production serving the needs of the Teru Woreda.

Once the feasibility of the first unit will be confirmed, the surface survey will be extended further North and allowing for a complete conceptual model of the giant geothermal field. This will be based on the exploitation of the deep reservoir implying the construction of access road and electrical power line.

Given the importance of the project for the country, the necessary concertation will be developed with the Regional Government and concerned Federal Authorities. AGAP will not be in the capacity to remain the sole operator of the project but will keep an active part in providing the guarantee for the local population to be engaged and supportive of the further developments to be carried by public national and/or private partners.

## 7. CONCLUSION

Although initially consider for answering the needs of the local Afar population in the area and in the nearby more densely populated and fertile Teru plain (with a first target of circa 5 MWe answering the needs of 100.000 people), the present investigations engaged by AGAP with the support of Go2D allowed to show that the Dabbahu geothermal site appears as one of the world “Giant” and certainly as a major target in order to answer the growing need for base-load power for the Federal electrical network This particularly in the NE part of the country (including eventually in the future the connection with Eritrea).

AGAP – the community based geothermal development company - is therefore looking for financial and technical partners to develop this site in the following steps:

1. Complete the prefeasibility study with supplementary surface studies: gas-geochemistry and TEM-MT survey in the SW part of the lease;
2. Engage the feasibility of the first 5 MWe plant based on the shallow drilling (600 to 1000 metres deep) reaching the fractured steam reservoir on the SW side of the lease.
3. Build and operate the first 5 MWe binary plant and the networks serving the needs of the local population on site and in the nearby Teru area.
4. In the meantime, extend the survey to the whole lease area and elaborate a quantitative conceptual model of the whole Giant geothermal field.
5. Engage the feasibility study implying deep drillings for the whole geothermal field (2.000 MWe) and power line; create the access road to the Eastern side of the area.
6. Develop in successive steps the Dabbahu Giant up to 2.000MWe or eventually more. These with appropriate partners to be identified.

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