Integrated Analysis of Geological, Geochemical & Geophysical Data from Alalobeda Geothermal Field, Northern Afar Region - Ethiopia

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The Tendaho Graben, Northern Afar Region (Ethiopia), hosts some well-studied exploitable geothermal systems. Previous investigations in Dubti and Ayrobera, including deep exploratory drilling, proved the existence of an exploitable, shallow geothermal reservoir, whereas a deeper reservoir, albeit characterized by suitable thermal conditions, exhibits rather low permeability (Aquater, 1995; Battistelli et al., 2002)

A further step towards the development of the geothermal resources in the Ethiopia was the exploration of the Alalobeda geothermal field, located in the western sector of the Tendaho Graben

From the morphological viewpoint, the Alalobeda geothermal prospect can be divided into two main sectors: one extending along the western shoulder of the Tendaho Graben, where basalts of the Afar Stratoid Series (ASS) extensively outcrop and the other corresponding to the collapsed sector filled by a thick sedimentary sequence. The latter is composed mainly by siltstone and subordinate sandstone possibly with intercalations of thin basaltic levels

The graben shoulder is characterized by a very rugged morphology, defined by sharp ridges usually elongated in a NW-SE direction, which follow the main graben structure and rise some 200-300 m over the surrounding land with side slopes of as much as 60 %
The stratigraphy of the Alalobeda prospect is characterized by the predominance of basaltic rocks belonging to the ASS of Upper Pliocene to Lower Pleistocene age, covered in the NE part of the prospect by alluvial, colluvial, aeolian and lacustrine deposits with local intercalations of basaltic levels, which tend to become thicker moving to the NE (Abbate et al., 1995; Acoccella et al., 2008)

The products of the Afar Stratoid Series have an estimate thickness of 1,500 m and are underlain by the Dahla Basalts Fm. (basalts with rare intercalation of ignimbrite & sediments): in the Alalobeda project the contact between Afar Stratoid Series and Dahla Basalts in deemed to occur at an approximate elevation of -1,000 m a.s.l. in the ridge region and to deepen progressively moving into the Tendaho Graben
The structural pattern is dominated by the presence of two main systems of faults associated with regional trends, namely: i) the NW-SE (Red Sea) system, responsible for the formation of the Tendaho Graben and of a sequence of horst and graben within the graben itself and ii) the NNE-SSW system (Main Ethiopian Rift - MER), clearly recognized in the ridge portion of the prospect. A WSW-ENE system, identified by the remote sensing study and with possible strike-slip component, is probably related to conjugate fracturing accompanying the faulting of the Tendaho Graben.
The investigations performed during the exploration of the Alalobeda prospect include Surface Geology and Remote Sensing Surveys, Geochemical Analyses and a Geophysical Campaign. On the base of the investigation results, the GEOTHERMAL MODEL of the Alalobeda prospect can be reconstructed and a scheme of the geothermal fluid circulation proposed.

For a better understanding of the overall setting of the Alalobeda prospect, in terms of interrelation between stratigraphy, structure and hydrothermal alteration, the results of the MT survey were examined through a detailed analysis of the blocky 1D inversion of all the soundings.
MT 1D model analysis was focused on the interpreted depth of the resistive basement and consequent identification of lateral geoelectrical discontinuities. Moreover, the configuration of the shallow and deep conductive units was studied and the presence of a very deep conductive unit was recognized.

The investigated area was accordingly subdivided into three distinct sectors: A, B and C; characterized by different geoelectrical structures.
The geoelectrical interpretation has been combined with the technical information derived from all the other geophysical investigations performed in the Alalobeda prospect. The most interesting findings of such combined interpretation are mentioned hereafter:

✓ The gravimetric survey clearly shows that the structure of the area is mostly controlled by the Red Sea, NW-SE trending system. Transversal elements, either NNE-SSW or WSW-ENE, affect marginally the overall structural pattern.

✓ The major structures identified through both gravimetry and MT are almost perfectly coincident with the contacts between Sectors A and B and Sectors B and C. Similarly, the positive gravimetric anomaly along the shoulder of the Tendaho Graben follows Sector B in its southern portion.

✓ It is reminded that the gravimetric anomaly is interpreted as being related to an intermediate depth source, possibly due to hydrothermal alteration (propylitization) of the basalts causing a density increase.
The WSW-ENE structures recognized through the geoelectrical and gravimetric surveys may be interpreted as associated with sinistral strike-slip faults conjugate with the formation of the Tendaho Graben.

The micro-seismic survey highlighted a zone of maximum density of the events (green area). This anomaly occurs in the northern portion of Sector B, just south of the WSW-ENE structure which displaces the SW boundary of this sector.

This area is also characterized by the shallowest depth of the hypocenters, which does not exceed 5 km and presumably reflects the boundary between brittle and ductile zones.

A good consistency of the favourable factors pointing to the potential existence of a geothermal system can be recognized. These factors tend to single out a preferential zone centered around the main hydrothermal manifestations of Alalobeda and are utilized for inferring the extent of the reservoir.
The CONCEPTUAL MODEL accordingly describes the essential features of the Alalobeda geothermal system, merging both qualitative and quantitative information.

**Heat Source:** The heat source of the Alalobeda geothermal system is related to the magmatic chamber/s responsible for the emission of basalts and subordinate rhyolites of the Upper Extrusive Complex (<1 Ma).

Two situations can be identified as preferential ones for the emplacement of a magmatic chamber, namely: i) Along the axis of the Tendaho Graben, ii) At the intersection of faults of the Red Sea system, trending NW-SE, with faults of the Main Ethiopian Rift system, trending NNE-SSW. These zones are expected to be under higher extensional regime and thus to constitute preferential structures for magma uprising.

The configuration of the magmatic chamber was investigated by means of magnetotelluric surveys. The 1D inversion model showed the presence of a deep conductive unit (1-6 Ohm m), possibly attributable to partial melt related to an active magmatic chamber. Such unit is found at an average depth of 9-11 km, with a tendency to rise to about 8 km.
**Cap-rock and Reservoir Configuration:** In the peculiar geological setting of the Alalobeda prospect, the basalts of the *Afar Stratoid Series* are expected to play both roles of cap-rock and reservoir formation, while the underlying *Dahla Fm.* would play exclusively the role of reservoir.

Obviously, the different roles to be played by the basalt assume the development of well distinct histories which modified the original conditions of the basalt.

The definition of the geometry of the cap-rock and reservoir formations, in terms of lateral extension and depth, has been essentially based on the findings of the MT survey, combined with the indications derived from the geological, gravimetric and micro-seismic surveys.

Two clear boundaries were recognized, namely: (i) to the NE, the contact between Sectors B and C; (ii) to the SE the zone where a marked resistivity increase of the potential cap-rock unit is observed. In the remaining area investigated by the MT survey encompassing both Sectors A and B, a continuous horizon of low resistivity, possibly associated with the cap-rock of the system, could be recognized. This area can be classified as zone of potential geothermal interest (~40/45 km²).

Within the zone of potential geothermal interest, a **FIRST PRIORITY ZONE** can be singled out.
Cap-rock and Reservoir Configuration: The zone thus delimited includes the main hydrothermal manifestations and covers a surface of about 8 km², being associated with the following elements:

- Structural viewpoint: the zone is essentially controlled by the NNW-SSE trending faults of the Red Sea system, it occurs at the intersection with the NNE-SSW faults of the MER system (represent a favorable indication with respect to the deep permeability)

- The hot springs and numerous fumaroles are located almost in the centre of the zone

- The following electrostratigraphic sequence has been encountered: (1) upper conductive unit, with resistivity of 1-4 Ohm m and average thickness of 200 m; (2) moderately conductive unit, with resistivity of 3-6 Ohm m and thickness of 800 m; (3) resistive unit, with resistivity of ~100 Ohm m, intersected at a depth of about 1,000 m

- The lowest portion of the moderately conductive unit may be associated with the cap-rock of the system

- The resistivity value of the basement (~100 Ohm m) is always subject to a high degree of indeterminateness

- The positive Bouguer anomaly, possibly reflecting phenomena of hydrothermal alteration of high temperature

- A coincidence is observed between first priority zone and zone of maximum density of seismic events
Thermodynamic and Chemical Characteristics of the Reservoir: The thermodynamic and chemical characteristics of the Alalobeda prospect have been inferred on the base of the nature and composition of the thermal manifestations (hot springs and fumaroles) of the area in the form of liquid or gaseous emissions.

The application of the geothermometric functions to the water samples of the Alalobeda hot springs indicates consistently a temperature of 200-220 °C. These values are in substantial agreement with those provided by the associated steam discharges (200-210 °C).

Both temperatures and the isotopic composition, concur in suggesting the water-dominated nature of the geothermal system.

The chemical composition of the reservoir was reconstructed from the chemistry of the Alalobeda hot springs. Geothermal fluids have a Na-Cl composition, with relatively high content of SO$_4$ and SiO$_2$ and TDS of approximately 1,400 mg/kg (slightly lower than the TDS registered at Dubti).

Reservoir pH is about 5.9; a substantial pH decrease to 5.0 at 100 °C is foreseen upon conductive cooling, whereas a considerable increase to 7.7-7.8 at 100 °C is predicted upon adiabatic cooling.
**Scheme of the Hydrothermal Circulation:** The isotopic composition (tritium content) of the geothermal fluids, as inferred from the chemical analysis of the Alalobeda hot springs compared with the isotopic values of the Ethiopian rainwaters, suggests that the reservoir hosts paleowaters.

Independently from the age of the fluids, it may be assumed that *meteoric water infiltrating deeply into the ground, upon getting in proximity of an active heat source* (approximate depth of about 8-10 km), tends to heat up and to upflow in correspondence of sectors characterized by intense fracturing and hence by good permeability as well as by thinning or termination of the cap-rock.

These fluids rise up to a depth of a few kilometres, where their temperature is presumably slightly in excess of 200°C.

The uprising of the heated fluids is restricted by the presence of impervious formations (cap-rock).

Fluids tend therefore to expand laterally through fractured basalt flows and to install convective cycles, typical of geothermal systems. Due to their temperature, different hydrothermal alteration processes develop in the convection zone with formation of secondary minerals.

The outflow of the system is supposed to take place mostly along the main faults intersecting the geothermal system, as expressed by the distribution of the thermal manifestations, which consist with one exception of fumaroles and steaming ground.

Based on the gas composition, vapors of the fumaroles appear to have separated at T, P close to 100 °C, 1 bar.

The lack of the manifestations to the East of the graben plain not necessarily means that no outflow is taking place, since it may be related to the presence of impervious sedimentary products on surface, hindering the emergence of geothermal fluids from depth.
Thank you for your kind attention

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