Proceedings, 6th African Rift Geothermal Conference
Addis Ababa, Ethiopia, 2nd – 4th November 2016

INTEGRATED ANALYSIS OF GEOCHEMICAL AND GEOPHYSICAL DATA FROM ALALOBEDA GEOTHERMAL FIELD NORTHERN AFAR REGION

Claudio Pasqua[1,2], Egidio Armadillo[2], Daniele Rizzello[3], Massimo Verdoya[2], Paolo Chiozzi[2], Solomon Kebede[4]

[1]ELC-Electroconsult, Via Marostica, 1, 20146 Milano,[2]Dipartimento di Scienze della Terra, dell'Ambiente e della Vita - DISTAV, University of Genova, Italy, [3]Tellus sas, Via Pozzetto, 2, Sassello, Italy, [4] Geological Survey of Ethiopia, P.O. Box 2032, Addis Abeba, Ethiopia

e-mail: claudio.pasqua@elc-electroconsult.com

ABSTRACT

This paper illustrates the first results of the geological, geochemical and geophysical investigations in the Alalobeda geothermal field located in the Tendaho Graben, Northern Afar Region (Ethiopia). The tectonic pattern of the Alalobeda field is characterized by the superposition of three regional rift zones: the Red Sea (NW-SE), the Main Ethiopian Rift (NNE-SSW) and, to a lesser extent, the Gulf of Aden (ENE-WSW). Gravity anomalies highlight the graben bedrock and the main fault systems which in turn well correspond to magnetic anomalies recorded by the basalts of the Afar Stratoid Series. Geochemical analyses of water samples collected from hot springs indicate reservoir temperatures of 200-220°C. Such temperatures are substantially consistent with those (on average 185-225°C) inferred from fumaroles gases. The geothermal field is characterized by a quite continuous seismic activity of low-energy, consistently with the regional pattern, mostly exhibiting shallow earthquakes with magnitude <4.0. The seismicity cutoff-depth, which can represent a rheological, temperature-dependent boundary, occurs at 3.5-5 km depth. A possible increase of temperature gradient in correspondence of the major surface manifestations of the geothermal system could be indicated by the decrease of focal depths. The results of a magnetotelluric survey give a picture of the possible extension of the cap-rock and reservoir formations. The surveyed area unexpectedly shows extremely low resistivity values for the basaltic rocks forming the bedrock, due to intense argillification phenomena. Below the high-conductivity cap-rock, the more resistive basement can act as the reservoir formation, although its resistivity is somewhat higher than that commonly recorded in other geothermal fields.

1. INTRODUCTION

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). As a further step towards the development of the geothermal resources in the Ethiopia, the exploration of the Alalobeda geothermal field, located in the western sector of the Tendaho Graben, was recently started through a series of geological, geochemical and geophysical surveys. This paper illustrates the results of such investigations and presents a conceptual model of the geothermal field.
From the morphological viewpoint, the Alalobeda geothermal prospect can be divided into two main sectors (Fig. 1): 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 of fluvial, lacustrine and aeolian origin. The latter is composed

mainly by siltstone and subordinate sandstone possibly with intercalations of thin basaltic levels, and has an average elevation of 400 m a.s.l.

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 elevation of these landforms is about 600 m a.s.l., reaching the maximum value of 726 m a.s.l. in the central portion of the study area. The individual ridges are separated by narrow valleys up to 1,000 m wide.

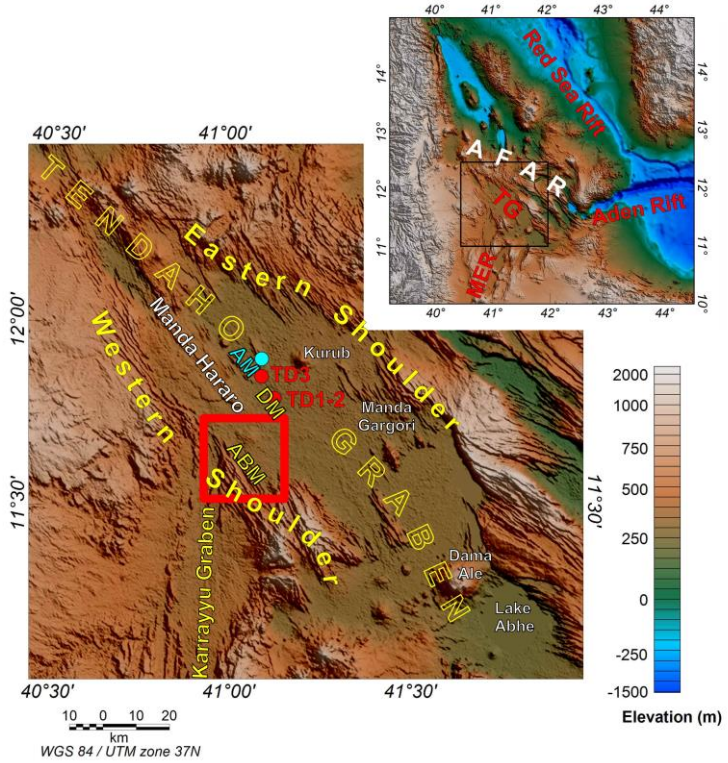

Figure 1: The Alalobeda prospect area in the Tendaho Graben (TG). ABM, AM, DM: Alalobeda, Ayrobera and Dubti manifestations respectively. TD1-TD3: deep exploratory wells in the Dubti area.

2. GENERAL SETTING

The stratigraphy of the Alalobeda prospect is characterized by the predominance of basaltic rocks belonging to the Afar Stratoid Series 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; Acocella 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 Formation, consisting of basalts with rare intercalation of ignimbrite and 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), 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.

3. INTERPRETATION OF THE ELECTRICAL RESISTIVITY DISTRIBUTION

The investigations performed during the exploration of the Alalobeda prospect include surface geology and remote sensing surveys, geochemical analyses and a geophysical campaign (see Rizzello et al., this volume). 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 (Rizzello et al., this volume) were examined through a detailed analysis of the blocky 1D inversion of all the soundings. Such 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. On the whole, with a few exceptions, a good consistency among adjoining soundings was observed, allowing a reasonable correlation along performed transversal profiles, subject obviously to the inaccuracies which are implicit in geoelectrical interpretation. The investigated area was accordingly subdivided into three distinct sectors, as described here after (Figure 2).

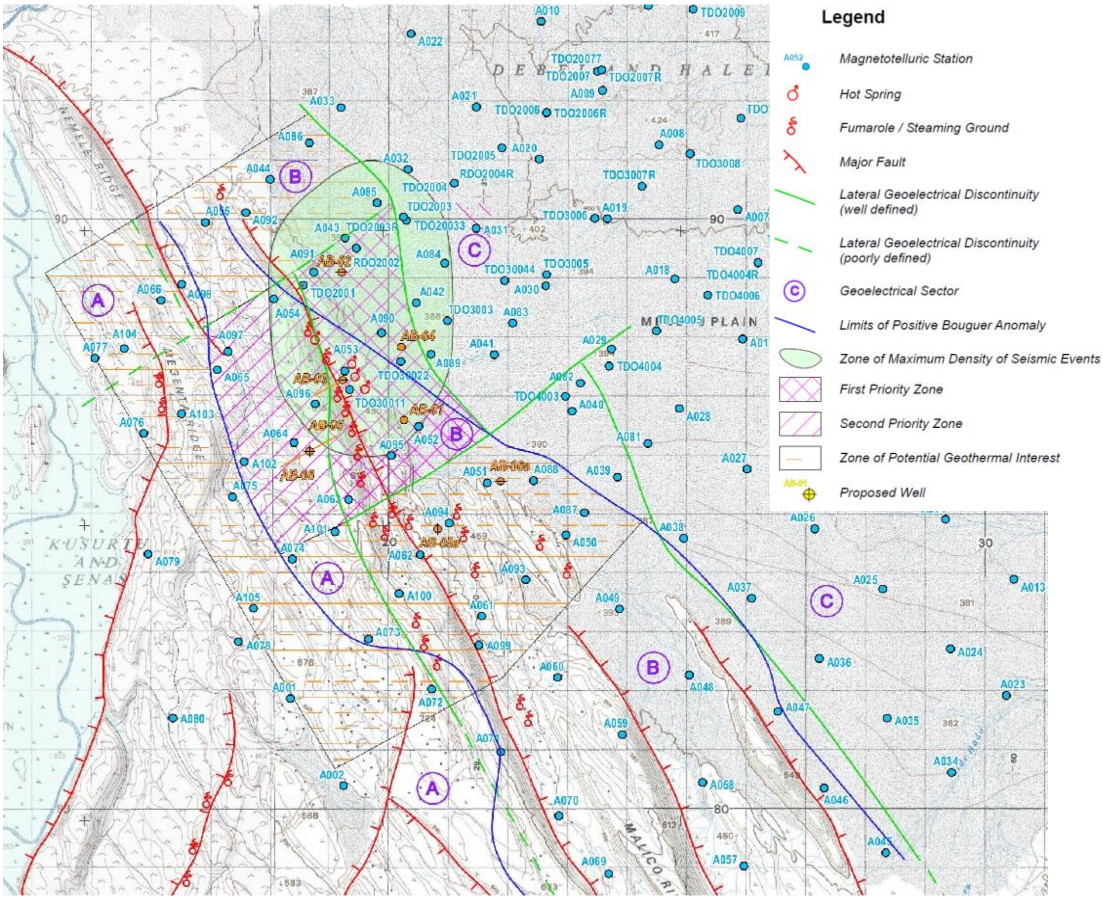

Figure 2 Zonation of Alalobeda prospect based on 1D blocky inversion

3.2. Sector A

Geographic Distribution: It extends in the SW portion of the investigated area, following the ridge where basalts of the Afar Stratoid Series outcrop. In the NW portion of this sector, the contact with Sector B approximately coincides with the limit of the ridge, which is with the shoulder of the Tendaho Graben. Moving SE, such contact tends to diverge more and more from this limit.

Geoelectrical Configuration: Geoelectrical configuration is rather regular, consisting of the following 5 units: (1) shallow unit, usually with medium resistivity (10-20 Ohm m), locally rising to as much as 100 Ohm m; (2) upper conductive unit, at an average depth of 50 m and approximate thickness of 50 m, with a resistivity value of 0.5-1.5 Ohm m; (3) intermediate unit, characterized by an extremely variable value of resistivity, generally ranging between 5 and 50 Ohm m; (4) lower conductive unit, found at an average depth of 300 m, with a thickness of 400-600 m and a resistivity of 1-3 Ohm m; (5) resistive basement, detected at an elevation of -500 m a.s.l. in the northern part of the sector, where resistivity usually exceeds 100 Ohm m, and rising to -200 m a.s.l. in its southern part, where resistivity is 30-60 Ohm m.

Geological Interpretation: The whole geological sequence investigated through the MT/TEM survey surely corresponds to basalts with very minor intercalations of pyroclastics: therefore, the resistivity variations must be mostly attributed to phenomena of secondary alteration rather than to primary lithological factors. Under this reasoning, the above mentioned units (4) and (5) are deemed to correspond to strongly argillified basalts and to basalts either unaltered or affected by propylitic alteration, respectively. Units (1) and (3) exhibit resistivity values rather variable and on the whole lower than expected, but can be interpreted as basalts locally moderately weathered or altered. The main doubt refers to the geological nature of unit (2), characterized by an extremely low resistivity accompanied by a very regular configuration. These resistivity values can be explained by a pyroclastic intercalation of clay composition, by a thick horizon of paleosoil or by a level affected by very pronounced argillification phenomena or by their combination. No one of these situations was recognized in the course of the geological mapping, wherefore the doubts on the actual nature of this level remain unsolved, although it should be added that these doubts are due to affect only marginally the overall geothermal interpretation and the definition of the first priority zone.

3.3. Sector B

Geographic Distribution: It forms a 5 km wide band delimited by Sectors A and C, extending along the SW shoulder of the Tendaho Graben. Northwards the sector becomes narrower, as its contact with Sector C is translated about 2 km to the SW and its contact with Sector A becomes less clearly defined. A similar SW translation, affecting the contact between sectors A and B, has been hypothesized in the extreme northern part of the investigated area.

Geoelectrical Configuration: The sector is characterized by the relatively larger depth of the resistive basement, which is found at an average elevation of -600 m a.s.l. in the northern part, where its resistivity is >100 Ohm m, dropping to -700/-800 m a.s.l. in the southern one, where its resistivity tends to become slightly lower (50-80 Ohm m). The sequence overlying the resistive basement can be subdivided into two units: (1) The upper unit has a thickness of 100-200 m and a resistivity of 1-2 Ohm m; (2) the lower unit, with an average thickness of 800 m, exhibits a resistivity of 3-7 Ohm m in the northern part, with a tendency to increase up to 10-25 Ohm m moving southwards.

Geological Interpretation: The upper unit classified above as (1) is deemed to correspond, at least partly, to the thin level of sediments overlying basalts at the margins of the Tendaho Graben. Unit (2) on its side surely belongs to the Afar Stratoid Series and its fairly low resistivity values can be only explained by processes of alteration. The registered values of 3-7 Ohm m are somewhat higher than expected for a formation affected by very intense argillification and due to represent the potential cap-rock of the geothermal system. However, the possibility should be considered that these values actually represent an “average” of the whole unit and that deeper highly conductive and relatively thin horizons can be masked by the above formations and hardly recognized through the MT method due to resolution limitations. The resistive basement corresponds to basalts either fresh or affected by propylitic alteration.

3.4. Sector C

Geographic Distribution: It occupies the NE part of the Alalobeda prospect in the plain sector, being separated from Sector B by a very well defined lateral discontinuity, which runs in a NW-SE direction and, in correspondence of the Mederu Plain, appears to be displaced some 2 km to the SW by a WSW-ENE trending structure.

Geoelectrical Configuration: It exhibits a very regular geoelectrical configuration, consisting of an upper conductive unit with a thickness of 300-600 m, overlying a resistive basement with resistivity decreasing proceeding to the SE (from 50 to >100 Ohm m in the NW to 40-50 Ohm m in the SE). The basement is usually found at a depth of 0 ÷ -200 m a.s.l. with a tendency to deepen to the NE. The conductive unit can be on its turn subdivided into three levels: (1) the upper portion, constituting on the average one third of the total thickness, has a resistivity of 1-3 Ohm m; (2) in the lower portion resistivity drops to 0.5-1.0 Ohm m; (3) a rise of resistivity to 2-3 Ohm m is observed in the south-western portion of the sector. In this same portion the maximum thickness of the conductive unit is registered, with a tendency to taper off on both sides.

Geological Interpretation: The conductive unit is interpreted as corresponding to the sedimentary sequence and the relevant differences of resistivity may reflect lithological variations in terms of grain size, from clay to sand. The resistive basement corresponds to the basalts of the Afar Stratoid Series: their high resistivity values reflect the absence of argillification, wherefore the contact between Sectors B and C is deemed to constitute a clear boundary of the potential extent of the geothermal reservoir.

3.5. Integrated Interpretation

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 (see Figure 2):

- ✓ The gravimetric survey (Rizzello et al., this volume) 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 gravimetry 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 exactly 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 in Fig. 2). 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.

In general, a good consistency of the favorable 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.

4. CONCEPTUAL MODEL OF THE FIELD

The conceptual model (see Figure 3) accordingly describes the essential features of the Alalobeda geothermal system, merging both qualitative and quantitative information , and includes: general setting of the prospect from the geothermal point of view; inferred heat source(s); cap-rock and reservoir geometry; hydrodynamic and chemical characteristics of the geothermal system; scheme of the hydrothermal circulation. These features are described in the following paragraphs.

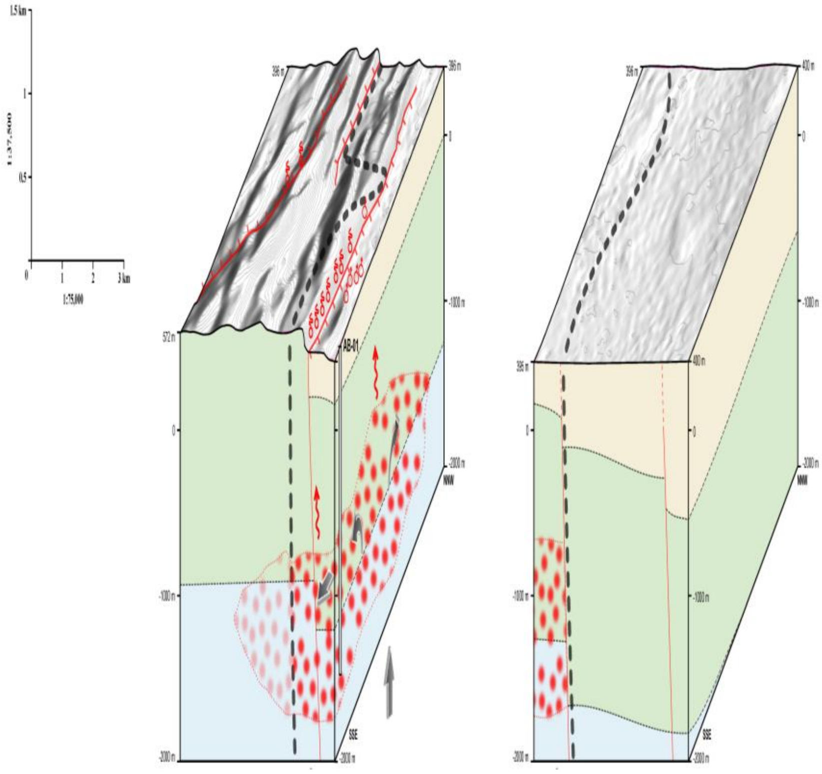

Figure 3 The proposed Alalobeda conceptual model

4.1. 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, dated at <1 Ma. These products are found in the form of small central volcanoes or of lava flows of fissural origin intercalated within the fluvio-lacustrine sediments of the Tendaho Graben.

In the Alalobeda area these recent volcanics are not outcropping and therefore any inference on the location of their source can only be indirect. In the specific geodynamic context of the area, in principle, two situations can be identified as preferential ones for the emplacement of a magmatic chamber, namely: i) Along the axis of the Tendaho Graben, as proved by the occurrence of central volcanoes along the axis itself and from the relative abundance of lavic intercalations within the sedimentary sequence in the deep wells drilled in the Dubti and Ayrobera zones. 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 latter situation can be actually recognized in the Alalobeda area and more specifically in correspondence of the junction between the south-western border of the Tendaho Graben and the major NNE-SSW faults which encompass the hot springs zone. The configuration of the magmatic chamber was investigated by means of magnetotelluric surveys in the Dubti-Ayrobera areas in 2014 (Stimac et al., 2014) and in the Alalobeda area in 2015 (Rizzello et al., this volume). In the former case, the 2D inversion model identified a low-resistivity body at a depth >5 km, with a width of 15 km, interpreted as partial melt within the Afar Stratoid Series. The conductive unit extends to a depth of 15-18 km, being underlain by a moderately resistive unit. Additional MT soundings carried out in the same year and interpreted through 3D inversion (Didana et al., 2015) confirmed the presence of an upper crustal conductor at a depth of 10 km, which spans the whole survey area, from Dubti to Ayrobera, but failed to identify the underlying moderately resistive unit. This structure indicates the occurrence of a large intrusive magmatic body fed by deep mantle sources.

A similar situation was recognized in the Alalobeda area from the MT soundings conducted in the framework of the present project. In fact, 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 in the north-eastern part of the investigated area and in the central portion of the basaltic ridge. The deep conductive is underlain by a resistive unit, whose top is found at depth usually included between 15 and 30 km. A further confirmation about the likelihood of the existence of an active chamber is provided by the observation that the chloride contained in the reservoir fluids is probably contributed almost entirely by magmatic HCl entering the roots of the system with other magmatic gases (i.e., CO_2 and He, as indicated by $\delta^{13}C$ values of CO_2 and $^3He/^4He$ ratios).

The exact geometric configuration of the chamber(s) cannot be inferred just from surface evidences, but, based on structural and resistivity considerations, an extension between the main thermal manifestation and the Debel and Halebayre “dome” may be assumed, at a depth presumably in the order of 10 km.

4.2. 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 formation would play exclusively the role of reservoir. In fact, the sedimentary sequence, with a thickness nowhere exceeding a few hundred meters, is not adequate by itself to restrict the escape of the geothermal fluids.

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: i) The basalt associated with the cap-rock formation underwent intense phenomena of argillification at temperatures lower than 200 °C, which determined conditions of imperviousness. Resistivity of the cap-rock formation is expected not to exceed 5 Ohm m. ii) The basalt associated with the reservoir formation underwent phenomena of high temperature hydrothermal alteration (propylitization), which enhanced the brittle nature of the rock: such brittle nature on its side allowed, in presence of neo-tectonic activity, the formation of widespread fracturing and hence the increase of permeability. Resistivity of the reservoir formation is expected, by analogy with other geothermal fields in the world, to be in the order of 20-50 Ohm m.
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. The geographical distribution of fumaroles has not been considered because owing to the low vapor/liquid separation temperatures (close to 100°C), fumaroles might be related to liquids that have experienced substantial lateral migration. The integrated interpretation of these investigations leads to the following main conclusions:

- Two different causes may be called for to explain the low resistivity units registered through the MT survey. In fact, such low resistivity can derive either from the primary lithology of the rocks or from intense argillification phenomena. Making reference to the subdivision into three sectors of the area, it is assumed that the conductive units of Sector C correspond to fine grained sediments, while those of Sectors A and B consist of strongly altered basalts.

- In Sector A, disregarding the very shallow and narrow conductive unit, of hard interpretation and of negligible bearing over the potential geothermal system, the conductive unit is quite constant in terms of both thickness and resistivity, covering a surface of at least 30 km^2 .
- In Sector B the very thick horizon of low-medium conductivity can be at least partly attributed to the cap-rock formation. The average value of 5 Ohm m of this horizon rises to 8-10 Ohm m proceeding southwards.
- The whole resistive basement of Sectors A and B can in principle play the role of reservoir formation, although the interpreted values of resistivity (often in excess of 100 Ohm m) are somewhat higher than the ones normally recorded in other geothermal fields. However, it should be noted that the absolute resistivity value of the basement interpreted in the 1-D inversion is normally subject to wide margins of uncertainty.
- An important drawback identified in the previous Dubti and Ayrobera deep exploration programs referred to the fact that the potential basaltic formation was characterized by an overall limited permeability, in spite of the existence of intense neotectonic activity: such situation was the main reason for the general disappointing results of the deep wells. It is therefore essential to identify those sectors presumably associated with more widespread fracturing, based on the structural setting as interpreted from the remote sensing study and the geological mapping, as well as on the results of the geoelectrical and micro-seismic surveys. From the point of view of structural setting, the priority sector can be referred to the intersection between the shoulder of the Tendaho Graben and the major faults, which belong to the Main Ethiopian Rift system, trending NNE-SSW and well developed in the south-western portion of the prospect. The Alalobeda main manifestations are situated in correspondence of such intersection.
- From the point of view of micro-seismic activity, it is observed that the main anomaly in terms of density of events is centered around the main manifestations.

The combined analysis of these observations can be used to carry out a zonation of the prospect based on the probability of existence of a geothermal system and to infer the geometric configuration of the reservoir. 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 magnetotelluric 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. Such zone extends over a surface of some 60 km^2 (in acceptable agreement with the areal extension of 41-49 km^2 estimated on the base of tritium and flow rate of Alalobeda hot springs), out of which about 80% fall over the basaltic ridge, that is in an environment characterized by very hard accessibility. The bottom of the conductive unit, which may indicate the top of the reservoir, occurs at a depth of 800-1,000 m bgl.

Within the zone of potential geothermal interest, a first priority zone can be singled out, delimited on two sides by NNW-SSE trending geoelectrical discontinuities between A and B and between B and C sectors and on the other two sides by two transversal discontinuities trending WSW-ENE. The zone thus delimited includes the main hydrothermal manifestations and covers a surface of about 8 km^2, being associated with the following elements:

- Approximately two thirds of the zone extend in the Tendaho plain at an average elevation of 390 m a.s.l., whereas the remaining one third is found in the ridge, characterized by rough morphology and elevation locally exceeding 600 m a.s.l.
- The whole zone is underlain by basalts of the Afar Stratoid Series, covered in the north-eastern portion by a layer of sediments, with a thickness presumably not exceeding 200 m.
- From the structural viewpoint, although 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 Main Ethiopian Rift system, well developed south of the zone; as mentioned above, such condition may represent a favorable indication with respect to the deep permeability.
- The hot springs are located almost in the center of the zone. Numerous fumaroles and steaming ground manifestations are found within the zone and in its immediacies, being controlled by NNW-SSE faults of the Red Sea system and, moving southwards, by NNE-SSW faults of the Main Ethiopian Rift system.
- 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 resistivity value of the moderately conductive unit could actually derive from the average of different units, which can be hardly discriminated through the MT method due to resolution limitations. The lowest portion of this unit may be associated with the cap-rock of the system.
- The resistivity value of the basement (>100 Ohm m) is higher than the values normally registered in geothermal reservoirs (20-50 Ohm m), although it should be reminded that the values calculated from the MT curves are always subject to a high degree of indeterminateness.
- The positive Bouguer anomaly, possibly reflecting phenomena of hydrothermal alteration of high temperature, only partly encompasses the zone.
- On the other side, an almost perfect coincidence is observed between first priority zone and zone of maximum density of seismic events. The depth of these events reaches its minimum in this zone, reflecting the uprising of the contact between brittle and ductile zones.

It should be reminded that the actual lateral extent of the first priority zone is associated with a very high degree of uncertainty. In fact, only the eastern boundary is well defined, while the other boundaries are based on somewhat flimsy evidences. At any rate, it is stressed that the identification of the first priority zone serves mainly the purpose of selecting drilling targets rather than of estimating the potential of the reservoir.

For this purpose, in view of the definition of the drilling program, a second priority zone has been identified. Such zone is located over the shoulders of the Tendaho Graben to the west of the first priority zone, occupying an area of about 7 km^2 and extending within the positive gravimetric anomaly, but at the margin of the micro-seismic anomaly. From the geoelectrical point of view, the zone is characterized by the presence of a thick conductive unit, underlain by a resistive basement: the contact between the two units, assumed to reflect the top of the reservoir, occurs at an average elevation of -400 m a.s.l., that is some 200 m higher than the elevation registered in the first priority zone.

4.3 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 of the area in the form of liquid or gaseous emissions. These manifestations consist of hot springs, mostly concentrated in the Alalobeda proper sector within a 700x350 m wide zone, and fumaroles, which tend to occur along or at the intersection between NNE-SSW and NNW-SSE trending faults. 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 the estimated temperatures and the isotopic composition, which exhibits a relatively low oxygen isotope shift, 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, which is 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.
Fluids composition appears to be fairly benign, although some scaling phenomena may in principle take place. In particular:

(i) Calcite precipitation is expected upon boiling, between temperatures of 210 and 140 °C approximately. Its deposition is chiefly predicted downstream of the flashing zone, especially at short distance from it. No calcite precipitation is foreseen upon conductive cooling.
(ii) Anhydrite precipitation is expected at high temperatures only, above 185 °C and 189 °C for adiabatic cooling and conductive cooling, respectively.
(iii) No amorphous silica precipitation is foreseen above 100°C. However silica precipitation may take place either (i) below 90°C, for adiabatic cooling from 220 to 100 °C followed by conductive cooling, or (ii) below 75 °C, for conductive cooling from 220 °C.

On the base of the estimated pH values, no corrosion phenomena are expected.

4.4. Cap Scheme of the Hydrothermal Circulation

The isotopic composition 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, which infiltrated into it during one or more previous pluvial periods. Such indication seems to be confirmed by the fact that tritium content in the water points to a residence time included between 500 and 3,000 years. It should be added that, during the possible future exploitation of the field, a hydraulic gradient could be created such as to recall fluids from peripheral regions, which are going to recharge the system.

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 represented by a magmatic intrusion, 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. In the specific case of Alalobeda, it is deemed that the heat source occurs at an approximate depth of about 10 km and that the sector of enhanced permeability is found at the intersection of the major tectonic systems, namely the Red Sea and Main Ethiopian Rift ones.

These fluids rise up to a depth of a few kilometres, where their temperature is presumably slightly in excess of 200 °C. They are of a sodium-chloride type: the Cl-B and Cl-Li relationships suggest that Cl is probably contributed almost entirely by magmatic HCl entering the roots of the geothermal system with other magmatic gases (i.e., CO_2 and He, as indicated by $\delta^{13}C$ values of CO_2 and $^3He/^4He$ ratios).
The uprising of the heated fluids is restricted by the presence of impervious formations (cap-rock), which formed in the past as a result of argillification processes at temperature lower than 200 °C. 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 minerals such as epidote, quartz, albite, adularia e chlorite, as well as of clay in the form of illite.

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. In fact, it is observed that these manifestations are located, in the surroundings of the inferred reservoir, along NNW-SSE trending faults, whereas, moving further away to the south, they tend to align along NNE-SSW structures. Based on the gas composition, vapors of the fumaroles appear to have separated at T, P close to 100 °C, 1 bar. The only hot spring situated outside of the main manifestations, approximately 700 m to the NNW, consists on its side of natural steam condensate, possibly affected by mixing with local rain waters.

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. The chemical composition of the geothermal fluids suggests that the Alalobeda system has no connection with the Dubti system investigated through deep drilling. The distance itself between these systems, in the order of 20 km, points to the extreme unlikeness of Alalobeda being a lateral outflow of the Dubti reservoir.

Finally, it is worth reminding that no evidence of the existence of a shallow geothermal aquifer (similar to that present at Dubti) has been recognized, neither from geological nor from geoelectrical observations, although here again the impervious nature of the superficial formations might at least partly explain the absence of these evidences.

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