



COUNTRY UPDATE ON GEOTHERMAL EXPLORATION AND DEVELOPMENT IN ETHIOPIA

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ABSTRACT

Ethiopia is located in the Horn of Africa between 3.5° and 14°N and 33° and 48°E. Access to energy is among the key elements for the economic and social developments of Ethiopia. The energy sector in Ethiopia can be generally categorized in to two major components: (i) traditional (biomass), and (ii) modern (such as electricity and petroleum). As more than 80 % of the country's population is engaged in the small-scale agricultural sector and live in rural areas, traditional energy sources represent the principal sources of energy in Ethiopia. The current total installed electrical capacity in Ethiopia has reached 2414 MW. The medium and long term electrical generation development plan consists mainly of hydro projects. Generation from wind and geothermal power plants are foreseen to compliment the hydro.

The government's Energy Policy is an integral part of its overall development policy. It aims to facilitate the development of energy resources for economical supply to consumers. It seeks to achieve the accelerated development of indigenous energy resources and the promotion of private investment in the production and supply of energy.

Ethiopia started long-term geothermal exploration in 1969. About 120 localities within the rift system are believed to have independent heating and circulation systems. From these localities about two dozen are judged to have potential for high enthalpy resource development, including for electricity generation. Only two prospect areas have been subjected to exploration drilling to date. Currently geothermal exploration and resource assessment is being carried out in strategically selected prospect areas in the Ethiopian Rift Valley. Electrical geothermal potential is estimated at over 10, 000 MW.

A total of 675 MW geothermal power is planned to be developed from six selected prospects by 2020 and 2500 MW by 2030. In order to achieve the countries medium term plan in geothermal development both the public and the private sector participation is envisaged. Financial resources are secured or are on the process of being secured for the planned development under the public/private sector.

1. INTRODUCTION

1.1 Location and economy

Ethiopia is located in the horn of Africa between 3.5° and 14°N and 33° and 48°E (Figure 1). The country has an area of 1.14 million km² and a population of over 90 million. The Ethiopian economy, which is non- oil-driven economy, has grown on average 10.2% for the last 5 consecutive years. The growth and transformation plan GTP envisions a major leap in terms of not only economic structure and income levels but also the level of social indicators.

1.2 Energy and electricity sector

The energy sector in Ethiopia can be generally categorized into two major components: (i) traditional (biomass), and (ii) modern (such as electricity and petroleum). As more than 80 % of the country's population is engaged in the small-scale agricultural sector and live in rural areas, traditional energy sources represent the principal sources of energy in Ethiopia.

The continuous economic growth has undoubtedly influenced the growth of energy demand. The current total installed electricity generation capacity has reached over 2,414 MW. The delivery of an adequate electricity service is essential. To fulfill the high growth rate of electricity demand which is 32%/ yr, it is planned to increase the generation capacity to over 25,000 MW by 2030. The aim is to address both domestic demands while exporting surplus power to neighboring countries and beyond. The need to expand the transmission and distribution system is also emphasized in order to deliver the energy generated to the consumer in an efficient and reliable manner. The GTP further envisages increasing the customer base of the power utility from the current level of 2 million to 4 million and the universal electricity access rate from 45% to 75%.

The government policy direction is to generate virtually all of our electricity from clean and renewable sources centered on hydropower, geothermal, wind, solar and other renewable energy resources.

Hydropower generates more than 90% of electricity in Ethiopia. However, as the rainfall in Ethiopia varies considerably from year to year, the need to diversify the country's energy sources to ensure a stable supply is desired. It also implies that overdependence on hydropower makes energy supply unstable, resulting in heavy strains on the pace of growth in every sector and the whole economy by extension.

At the transmission front, the Ethiopia-Kenya, the proposed 500KV AC/600KV HVDC line between Ethiopia-Sudan and Egypt, and the proposed 230KV line between Ethiopia-Republic of South Sudan, are the major ones to be noted as their completion signifies the complete integration of Eastern Africa power market, taking into considerations the ongoing development of interconnection projects in the Nile equatorial lakes region, including the proposed 400kv line between Kenya and Tanzania.



FIGURE 1: Location map of Ethiopia

1.2.2 Energy policy

The government's Energy policy is an integral part of its overall development policy. It aims to facilitate the development of energy resources for economical supply to consumers. It seeks to achieve the accelerated development of indigenous energy resources and the promotion of private investment in the production and supply of energy. Electricity supply, as an element of the development infrastructure is being advanced in two fronts: (a) the building up of the grid based supply system to reach all administrative and market towns, and (b) rural electrification based on independent, privately owned supply systems in areas where the grid has not reached.

An independent power producer (IPP) may engage in power development for selling the generated electricity to the public utility, known as the single buyer model. The single buyer model does not exclude captive geothermal power generation, i.e. generation for own use in primary economic production or service industries owned by the developer. EPC turnkey contracts could be negotiated and signed between a private companies and the public utility, in which the private sector would have the role of not just as a project developer but also as a critical stakeholder that can bring financing to the table under the right circumstances.

2. GEOTHERMAL EXPLORATIONS AND DEVELOPMENT IN ETHIOPIA

Ethiopia started long-term geothermal exploration in 1969. Over the years, an inventory of the possible resource areas within the Ethiopian sector of the East African Rift system, as reflected in surface hydrothermal manifestations has been built up. The inventory work in the highland regions of the country is not complete but the rift system has been well covered. Of the about 120 localities within the rift system that are believed to have independent heating and circulation systems, about two dozen are judged to have potential for high enthalpy resource development, including for electricity generation. A much larger number are capable of being developed for non-electricity generation applications such as in horticulture, animal breeding, aquaculture, agro-industry, health and recreation, mineral water bottling, mineral extraction, space cooling and heating, etc. (UNDP, 1973).

Since the late 1970's, geoscientific surveys mostly comprising geology, geochemistry, and geophysics, were carried out at, from south to north, the Abaya, Corbetti, Aluto-Langano, Tulu Moye and Tendaho prospects (Teklemariam and Beyene, 2005). In addition, a reconnaissance survey of ten sites in the central and southern Afar has been carried out, some of these being followed up by more detailed surface investigation. The prospects and fields discussed here are shown in Figure 2.

Due to various factors that determined where the first geothermal power plant would best be located, detailed exploration work was decided to commence in the Lakes area of the rift system during the 1970's. The ICS was already being extended into this region of load growth. The best prospect areas from the technical point of view were located in the Afar which had then been poorly endowed with essential infrastructure and local load demand to support power development. The present circumstances however favor resource development also in the Afar region.

Exploration work peaked during the early to mid 1980's when exploration drilling was carried out at Aluto. Eight exploratory wells were drilled with five of these proving productive. During 1993-98, exploration drilling was also carried out at Tendaho. Three deep and three shallow wells were drilled and geothermal fluids were encountered in the 200-600m-depth range.

Resource utilization was delayed until 1999. A 7.2 MWe net capacity pilot plant installed at Aluto has faced operational difficulties that are essentially due to the lack of the appropriate field and plant management and operation skills. In 2007 activities related to problem identification and putting the plant back into operation have been carried out at the Aluto-Langano geothermal field. The plant is

partially rehabilitated and has been put back into an operation of about 4 MWe but currently it is not operational again.

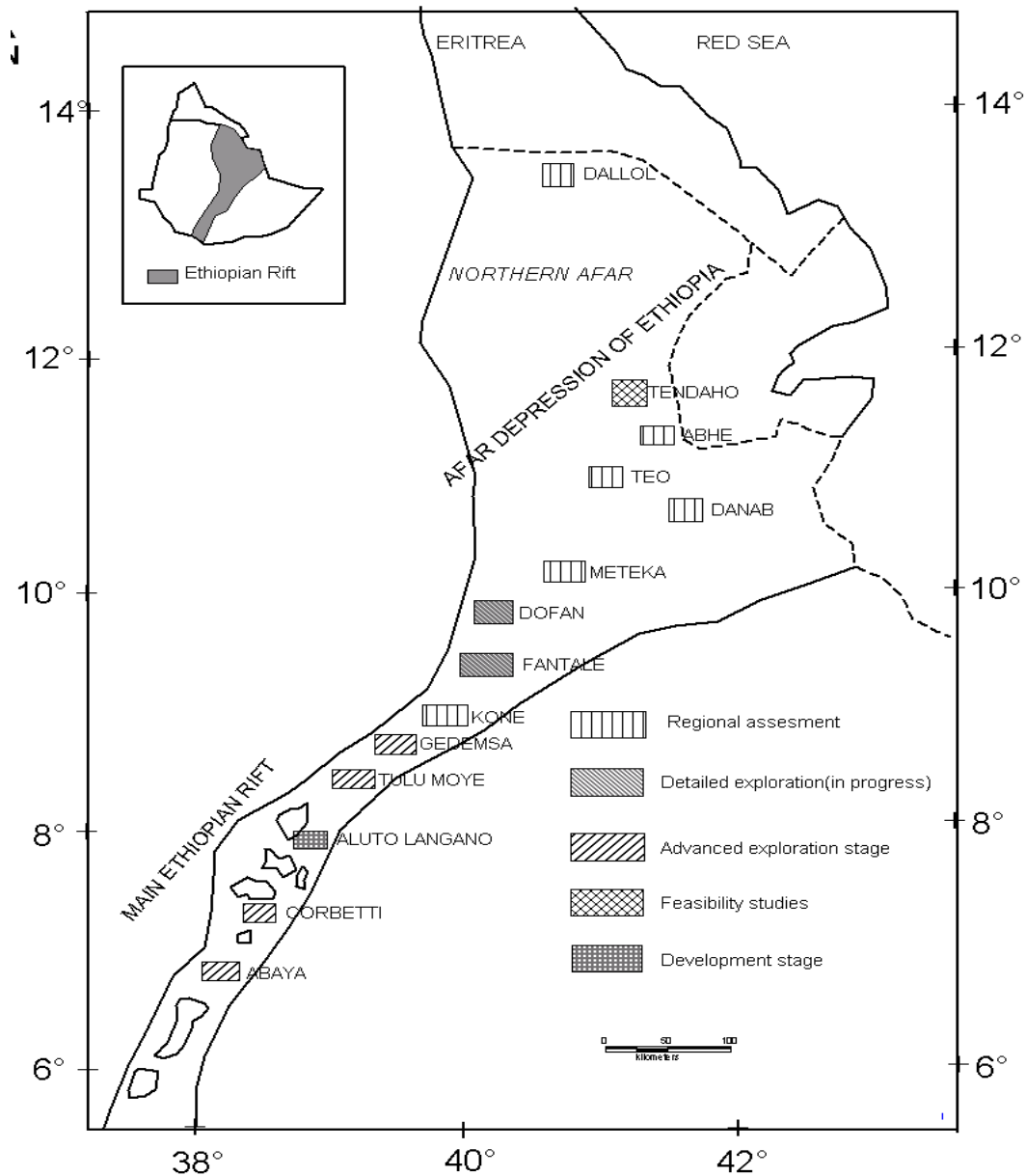


FIGURE 2: Location of geothermal prospects in Ethiopia

During the three decades that geothermal resource exploration work was carried out in Ethiopia, a good information base and a good degree of exploration capacity, in human, institutional and infrastructure terms, has accumulated, ensuring that selected prospects can be advanced to the resource development phase much more rapidly than before.

The exploration work to date has been carried out by the Geological Survey of Ethiopia (GSE) but has benefited from a number of technical cooperation programs. The most consistent over the long term had been support by UNDP, which also helped in creating other technical capacities of the GSE. The European Development Fund financed the overseas cost of the exploration-drilling project that resulted in the discovery of the Alutu resource. The development cooperation program of the Italian Ministry of Foreign Affairs provided the funding for the offshore costs of the surface and drilling exploration of the Tendaho prospect. The reconnaissance survey of the Afar was spawned by the Petroleum Exploration

Promotion project financed by IDA during the 1980's. The IAEA is assisting the GSE in the isotope geochemical study of hydrothermal fluids and in the process is providing training and experience in the application of the technique in geothermal investigations. IAEA also provided technical advice and equipment. The German Geological Survey (BGR) assisted in geophysical investigations (MT) of the Tendaho deep geothermal reservoir during 2006-07. The specialized geothermal science and technology training programs in Japan, Italy, New Zealand, Iceland and Kenya (in cooperation with United Nations University- Geothermal Training Programme of Iceland) contributed in human resource training and development.

The explored prospects in the country are at various stages of exploration and include: (i) more advanced prospects where exploration drilling has been conducted (Aluto Langano and Tendaho), (ii) prospects where surface exploration is relatively at higher level (Abaya, Corbetti, Tulu Moye and Fentale and Dofan), and (iii) prospects where surface exploration is at lower level and warrant further exploration in the future (Kone, Meteka, Teo, Danab, L. Abe and Dallol).

2.2 The more advanced prospects

2.2.1 The Aluto-Langano geothermal field

Detailed geological, geochemical and geophysical surveys were carried out in the Langano area during the late 1970's and early 1980's. Results showed the existence of an underground fluid at high temperature with evidence of long time residence in zones occupied by high temperature rocks (ELC, 1986). The objective then was to locate an economically exploitable geothermal reservoir.

Two wells (LA3 and LA6) drilled on the Aluto volcano produced 36 and 45 t.p.h. geothermal fluid at greater than 300°C along a fault zone oriented in the NNE-SSW direction. Two wells drilled as offsets to the west (LA4) and east (LA8) of this zone respectively produced 100 and 50 t.p.h. fluid with a lower temperature. LA5, drilled in the far SE of the earlier two wells was abandoned at 1,867m depth due to a fishing problem but however later showed a rise in temperature over an extended period of time. LA7 was drilled in the SW but could discharge only under stimulation, being subject to cold-water inflow at shallow depth. The earliest wells drilled in the prospect were drilled outside the present limits of the reservoir area, to the south (LA1) and west (LA2) of the area drilled later.

A 7.2 MWe pilot geothermal plant was installed in 1999 utilizing the production from the above exploration wells. The plant has not been fully operational due to reasons that have to do with the lack of operational experience. But since 2007 the plant has been partially rehabilitated and put back into an operation of about 4 MWe but currently not operational again.

Ethiopia and Japan signed a memorandum of understanding in June 2009 to generate geoscientific and reservoir engineering data that can be used for expansion and further development of the Aluto Langano geothermal field. Under this framework, the main activities conducted in August 2009 are magneto telluric (MT) and Audio magneto telluric (AMT) survey on 40 selected stations. During this survey, while experts from Phoenix Company of Canada conducted the MT study under contract for West Jec consultants of Japan, Ethiopian geophysicists took part in the field survey with the aim of obtaining hands-on experience in MT data generation and processing.

From the various resistivity maps produced, the area around the central and southern portions of the resistivity discontinuity R1 and the central portion of the resistivity discontinuity R2 especially in the uplifted relatively high resistivity zone detected at depths between 1,000 m and 2,000 m, can be recommended as promising zones for future drilling targets for production wells (Figure 3).

The study outlined subsequent two phases for the expansion and power development, which include: (i) the drilling of four appraisal wells and resource assessment in the next phase, and (ii) the drilling of production wells and step by step installation of 2x 35MW units in the final phase.

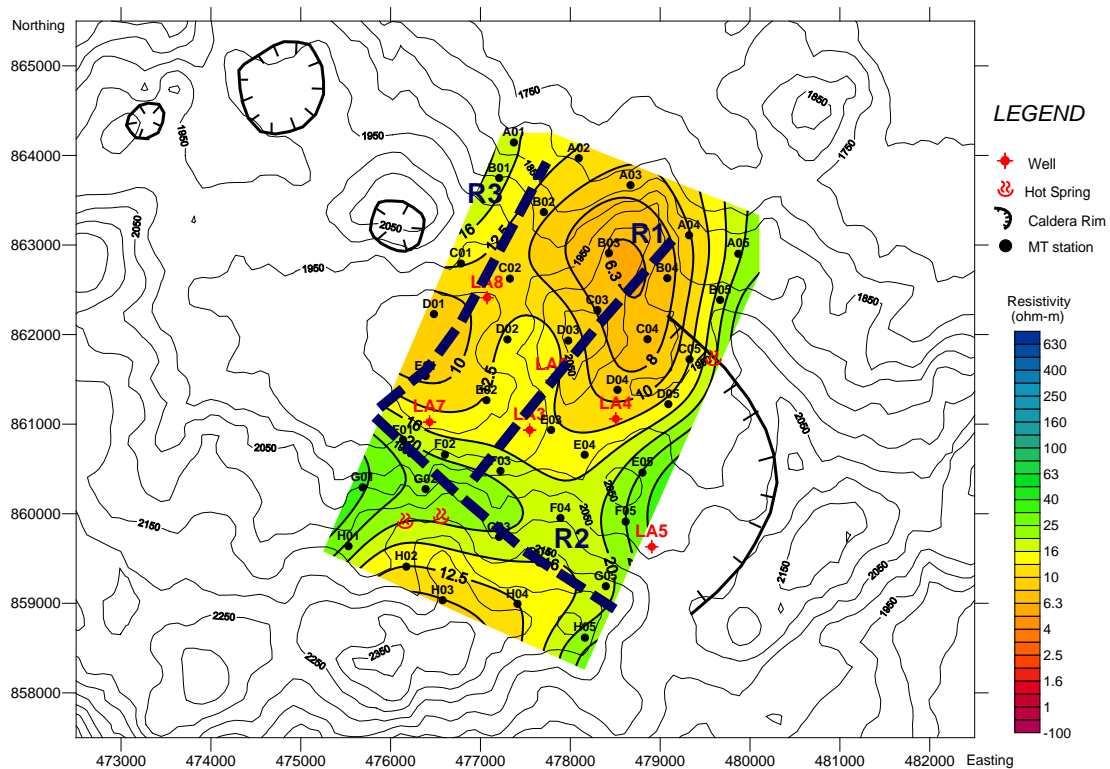


FIGURE 3: Resistivity map at a depth of 2,500 m at Aluto (3-D inversion results; West Jec, 2010)

In 2011, additional magnetic and gravity surveys were carried out with the objective of identifying and locating subsurface faults, caldera structures that may host another reservoir if it exists. Thus the surveys were conducted to cover most Aluto volcanic complex including its surroundings.

From the various maps, a caldera within a caldera structures have been recognized with various vents and craters (Figure 4). Lineaments in NNE, NE, and NW are features identified and located as fault structures. Several ring fractures and domes were also located. The horizontal derivative and analytical signal maps based on high values plotting are found to be, specially, useful in identifying and locating these structures. Fault depth varies between 80 and 2100 meters (Bekele, 2012).

The NNE faults found within Aluto geothermal field are active sites of the present day extensions, continuously generating fractures to counteract the sealing effect of hydrothermal activity. This fault system divides the inner caldera, and most of the Aluto geothermal wells are found at and around this fault system. The open magnetotelluric resistivity anomaly found east of these structures could be the expression the second reservoir, probably deeper than the productive reservoir found in the central area.

2.2.2 The Tendaho geothermal field

Geothermal exploration was carried out in the Tendaho area with economic and technical support from Italy between 1979 and 1980. Between 1993 and 1998, three deep (about 2,100m) and three shallow exploratory wells (about 500m) were drilled and yielded a temperature of over 250°C. The Italian and Ethiopian governments jointly financed the drilling operation in the geothermal field. A preliminary production test and techno-economic study indicated that the drilled shallow productive wells could supply enough steam to operate a pilot power plant of about 5 MWe, and the potential of the deep reservoir was estimated to be about 20 MWe. But recent estimations put a much larger potential.

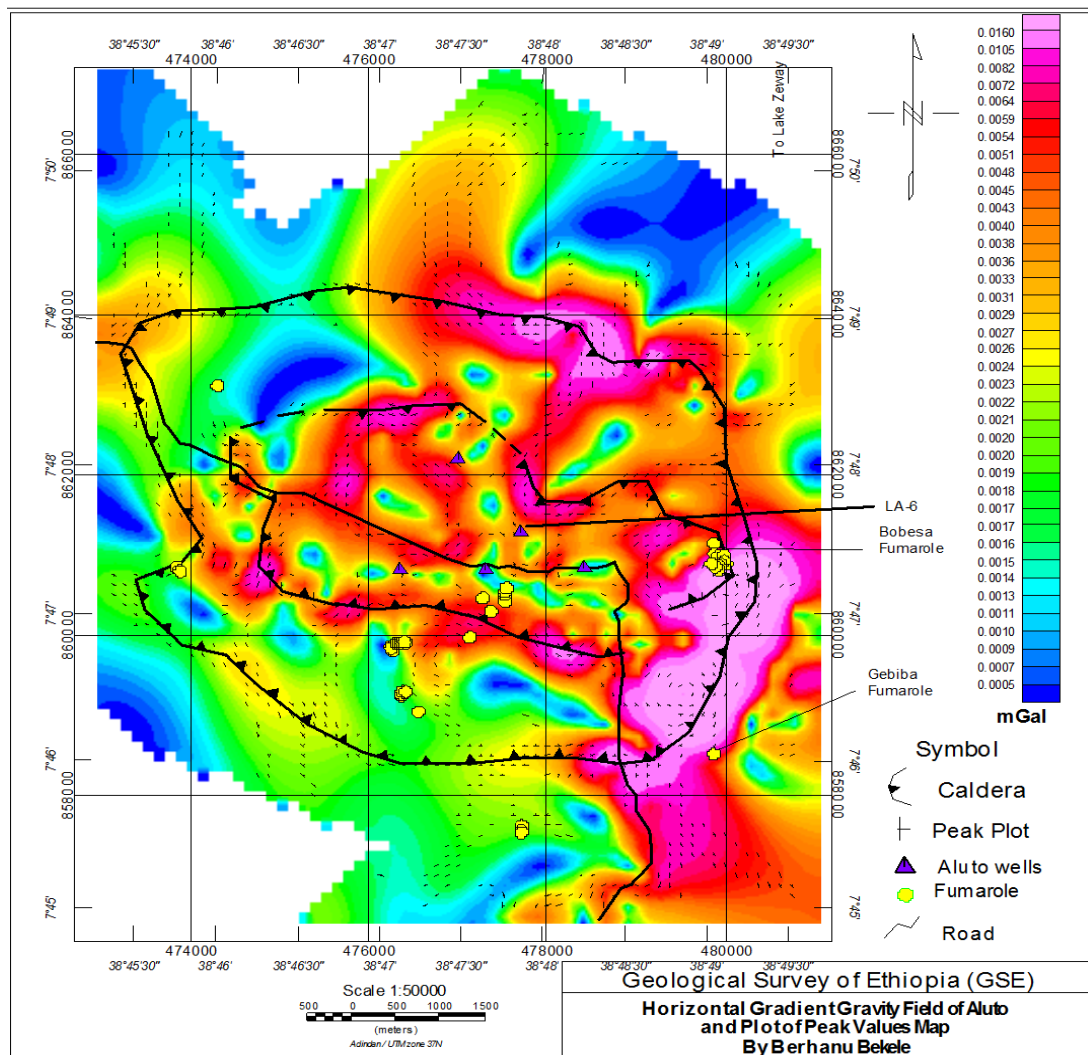


FIGURE 4: Map of horizontal gravity gradient field of Aluto

Based on this and further studies, the Geological survey of Ethiopia and the Ethiopian Electric Power are currently working on Tendaho for progressing it towards development.

In the framework of the BGR GEOTHERM programme in 2007 to 2009, Magnetotelluric (MT) and Transient Electromagnetic (TEM) field surveys were conducted at the Tendaho prospect in Afar region of Ethiopia. The surveys covered Dubti and Ayobera areas, both north of the Awash River. Concurrent to the MT & TEM surveys, geochemical survey consisting of fluid (gas & water) sampling from wells, hot springs and rivers was carried out to check if there interference between wells. Processing, interpretation and analysis of MT data provided useful subsurface information and the results obtained from such endeavour are summarized here below.

The magnetotelluric soundings show in their 2-dimensional inverted resistivity sections regions with resistivity's as low as 2 Ohm-m, especially in near surface layers as well as at greater depth (below 7 km). Based on the inverted resistivity, we get a good overview of the lateral resistivity structure as presented in Figure 5 (a, b, c) for selected elevations.

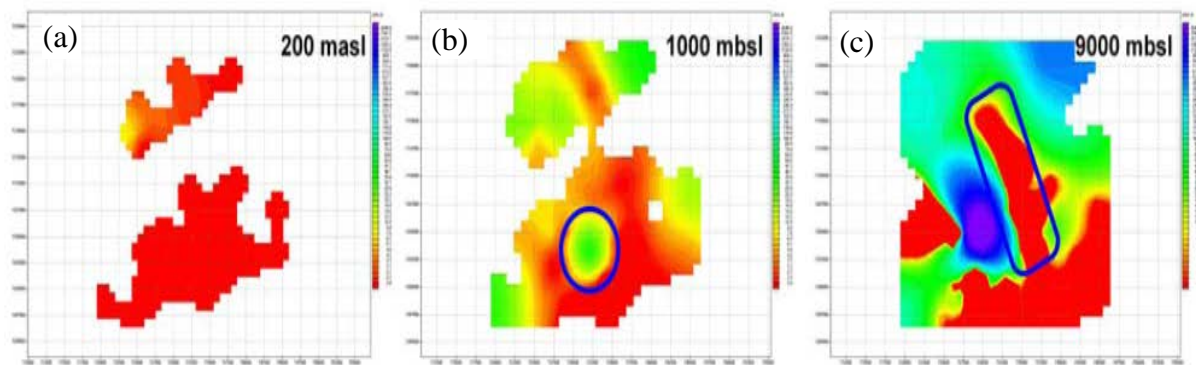


FIGURE 5: Lateral resistivity variation in selected profiles for various elevations

In Figure 5, Left: at 200 masl (150 m below surface). Shallow low resistive layer is (red) due to sedimentary infill. The sediments are up to 1 km thick. Centre: at 1000 mbsl (1350 m below surface). Slight increase of resistivity ($> 10 \Omega\text{-m}$) possibly due to mixed layer clays and advancement towards deeper reservoir (blue circle). Right: at 9000 mbsl (9350 m below surface). Resistivity value that drops below $2\Omega\text{-m}$ is along NW-SE trending feature (partly molten magma dyke?). This may form the deep heat source feeding the shallow geothermal reservoir.

A review and reinterpretation of geophysical data collected at Tendaho was performed in 2011 with the objectives of improving the understanding of the subsurface of Tendaho geothermal fields, delineate geothermal reservoirs, and locate exploration drilling sites. After correcting for the magnetic and gravity field variations that are unrelated to the earth's crust, several filters were applied to the reduced data, so that anomalies of interest can be enhanced and displayed in a more interpretable manner.

Three high residual gravity ridges separated by gravity lows are reflection of subsurface rift configurations imprinted on Afar stratoid basalts. Computation of horizontal gravity gradients enabled to map the contact between masses of different densities. With such edge enhancement fault/contacts, calderas, craters, domes and vents are outlined. The magnetic method defined the axial region of the Tendaho rift which coincides with the central high gravity ridge. Estimates of vertical and horizontal positions have been made using Euler 3D deconvolution for fault, and sill/dyke models. Such models enabled to construct faults blocks constituting two half grabens separated by hinged high blocks with central depression (Bekele,2012). Geologically mapped thermal manifestations and craters bear positional correlations with the geophysical interpreted faults, ring fractures, calderas, craters, and vents. Both gravity and magnetic data show that the Tendaho graben is severely affected by fault systems, trending NW, NE, EW, and NS

Based on the obtained results, it is highly recommended to drill a deep well at Ayrobera, where faults and ring fractures intersect and coincide with steaming grounds. Other highly recommended drilling site is at southeast position of the mud pools. But this has to be done after conducting high resolution MT survey at the recommended sites. Other recommended geothermal studies are Heat flow survey to estimate the resource and micro seismicity to locate fractures and monitor drilling activities.

A total of 129 MT sites were acquired from Tendaho high temperature field in 2011-2012. The main objective of the survey is to understand the deep geothermal reservoir of Tendaho. Geothermal Field using closely spaced MT stations and 1D and 2D inversions of MT data along ten profiles were performed. The 1D and 2D inversion of MT data from Tendaho high temperature field revealed three main resistivity structures down to a depth of 15 km: low resistivity surface layer underlain by a resistive layer followed by good conducting structure (Lemma et al, 2012).

The low resistivity surface layer shows areas with either sediments, lateral flow of geothermal fluids or Zeolite-clay alteration zone. Below the conductive layer is a high resistivity zone that can be correlated

to Afar stratoid basalts or epidote alteration zone. The high resistivity structure can also be associated with the deep reservoir of the geothermal system. The deep good conductive body is associated with a probable heat source of the geothermal system.

The possible fracture zone inferred in the Afar stratoid basalts may give high temperature and high permeability. The 2D resistivity elevation slices showed possible up flow zone south east of the exploratory wells drilled in Dubti area. The high resistivity structure at depth of 2-3 km b.s.l and inferred fracture zones at this depth are possible targets for drilling at Dubti and Ayrobera area.

2.3 Prospects where surface exploration is at higher level

Over the years, a number of prospects have been subjected to surface investigation: geology, geochemistry and geophysics and the shallow subsurface has been investigated by drilling at a few of the prospects. They are mostly located in the MER, especially in its most recent zones of tectonic and magmatic activity, the different sectors of the discontinuous WFB. These prospects from south to north are: Abaya, Corbetti, Tulu Moye, Fentale and Dofan.

2.3.1 The Abaya geothermal prospect area

Abaya is located on the northwest shore of Lake Abaya, about 400 km south by road from Addis Ababa. The Abaya prospect exhibits a widespread thermal activity mainly characterized by hot springs, fumaroles and altered ground. Spring temperatures are as high as 96 °C with a high flow rate. Integrated geoscientific studies (geology, geochemistry, and geophysics) have identified the existence of a potential geothermal reservoir with temperature in excess of 260°C (Ayele et al., 2002). Further geophysical studies including drilling of shallow temperature gradient wells were recommended.

The 132 KV transmission line to Arba Minch to the south starts at the Wolayta Soddo substation located about 40 km distance to the NNW of the prospect. This raises the prospect for development of the resource, once it is adequately explored, including by drilling.

2.3.2 The Corbetti geothermal prospect area

The Corbetti geothermal prospect area is located about 250 km south of Addis Ababa. Corbetti is a silicic volcano system within a 12 km wide caldera that contains widespread thermal activity such as fumaroles and steam vents. Detailed geological, geochemical and geophysical investigations conducted in the Corbetti area indicate the presence of potential geothermal reservoirs with temperatures exceeding 250°C. Six temperature gradient wells have been drilled to depths ranging from 93-178m (Kebede, 1986). A maximum temperature of 94°C was recorded. The data shows the probable existence of an economically exploitable deep geothermal reservoir.

A 132 KV power transmission line passes within 15 kms of the prospect and is the main trunk line to southern Ethiopia, to towns along the two branches of the highway to Kenya.

The Corbetti prospect has been given in concession for an Iceland based private company (Reykjavik Geothermal). In 2011-2012 the Compny has conducted MT/TEM surveys with supplementary other geoscientific studies and the results indicated the Corbetti the geothermal reservoir lateral extent and depth and a potential up to 1000 MW has been estimated, RG (2012).

2.3.3 The Tulu Moye geothermal prospect area

The area is characterized by volcanism dating from Recent (0.8 –0.08 Ma) to historical times. Volcanism involved the extrusion of per alkaline felsic lava associated with young tensional and transverse tectonic features dating from 0.1 to 1.2 Ma, with abundant silicic per alkaline volcanic products (Di Paola, 1976) . This suggests the existence of a deep seated magma chamber with a long

residence time. The area is highly affected by hydrothermal activity with the main hydrothermal manifestation being weak fumaroles, active steaming (60-80°C) and altered ground. The absence of hot springs is related to the relatively high altitude of the prospect area and the considerable depth to the ground water table. During 1998-2000, integrated geological, geochemical and geophysical studies including shallow temperature gradient surveys (150-200m), confirmed the existence of potential geothermal reservoirs with a temperature of about 200°C (Ayele et al., 2002) and delineated target areas for further deep exploration wells.

2.3.4 The Fentale geothermal prospect area

The Fentale geothermal prospect is characterized by a recent summit caldera collapse, felsic lava extrusions in the caldera floor and widespread fumaroles, suggesting the existence of a shallow magma chamber. Active tensional tectonics form fissures up to 2m wide near the volcanic complex. Ground water discharge to the system is assured by the proximity of the area to the western escarpment. The results of an integrated interpretation of previous data suggest that the area is potentially prospective for future detailed geothermal resource investigations. Therefore, due to the presence of an impervious cap rock, the western part of the prospect particularly deserves to be investigated during a more detailed geothermal exploration programme. In this view, the Geological Survey of Ethiopia has carried out detailed geological, geochemical and geophysical investigations in order to delineate and select target areas for deep exploration wells.

Semi-detail/semi-regional magnetic and gravity studies were conducted around the north-eastern periphery of Fantale volcanic mountain in 2011-2012. The survey was made along six NW-SE oriented profiles confined within an area of about 268 km² around the Filwoha hot springs.

The objectives of the study were to locate local/regional structures that could be associated with the circulation of thermal fluid, locate possible heat sources and alleviate the understanding of the geothermal field in the north-eastern portion of Fantale geothermal prospect area.

As a result, the gravity and magnetic data revealed both local and regional structural and lithological units in the north-eastern Fantale volcanic mountain in great detail. E-W and NW-SE local structures and NNE-SSW, NE-SW and N-S lineaments related to traces of regional structures. The north-east south-west massive intrusion intersected by north-west south-east dyke is delineated in the vertical integral map of the gravity field. The heat source in the area could be the high velocity structure interpreted as mafic intrusion and/or the prevailing regional heat anomaly existing under the rift.

2.3.5 The Dofan geothermal prospect area

Geological, geochemical, and geophysical investigations in the Dofan geothermal prospect show that the area is characterized by a complex volcanic edifice that erupted a considerable volume of pantelleritic lava from numerous eruptive centers between 0.5-0.2 Ma (Cherinet and Gebreegziabhier, 1983). The presence of several hydrothermal manifestations (fumaroles and hot springs) within the graben, together with an impervious cap, needs to be regarded with high priority for further detail exploration and development (Teclu, 2002/2003).

The area is located about 40 km from the high voltage substation in the Awash town.

2.4 Prospects where surface exploration is at lower level

During the 1980's, reconnaissance geological, geochemical and geophysical investigations have been conducted at Dallol, Kone, Meteka, Teo, Danab and L. Abe, areas that are found in a zone extending between the southern and northern Afar geological provinces. Meteka and Teo hold promise for the discovery of economically exploitable geothermal resources at high temperature and warrant detailed surface investigation, to be followed by exploration drilling. The Lake Abe area warrants further

investigation in a wider exploration context that encompasses areas in the eastern part of Tendaho graben and the Lake Abe prospect in Djibouti.

The prospects that have been dealt with low exploration stage are located to the north of 12° N latitude and comprise terrain that is at the most advanced stage of rift evolution in the eastern Africa region and holds a much greater potential for geothermal resources than any other region of equivalent size. This region should be considered as a prime target area for future exploration and development. With the improving availability of the economic development infrastructure in the region, the power-supply system in the load growth areas of northern Ethiopia would benefit from geothermal power generating facilities located in this part of the country.

From these long-term points of view, reconnaissance and preliminary surface evaluation works should commence in the not too distant future in the regions of southern and central Afar, North of 12° N latitude, in order to raise the available level of knowledge regarding the resource areas and to provide the necessary information that is required for long-term planning.

3. CURRENT GEOTHERMAL EXPLORATION AND DEVELOPMENT ACTIVITIES

Currently the following geothermal activities are being carried out in Ethiopia:

3.1 Aluto Langano geothermal field

3.1.1 Deep drilling

The drilling of two appraisal wells for testing, reservoir modeling and subsequent selection of production wells has been carried out. The wells (LA-9D and LA-10D) have been drilled to depth of 1920 m and 1951 m respectively. Both wells are productive with bottom hole temperatures of over 300° C. Currently testing is being carried out to determine the output of each well in MWs.

3.1.2 Surface exploration

Geo scientific surface investigations including, Geology, geochemistry, MT/TEM, gravity and microseismics are being carried out with the assistance of Iceida. Initial results have indicated that the Aluto geothermal anomaly occurs not only along a fault zone located at the current productive wells but also has extension both to the east, west and north. Accordingly, a third well to be drilled soon (LA-11D) is sited north of the current production wells and preparatory work to begin the drilling of the third well has began.

3.2 Tendaho geothermal prospect

3.2.1 Surface exploration at Doubti and Ayrobera

Surface exploration in two target areas of Tendaho (Doubt and Ayrobera) has been finalized under the framework of ARGeo project. The purpose of the survey is to develop a conceptual model and site deep wells in target areas. A review of all the available geoscientific data for the Tendaho area, development of a new 3D model of temperature in the area, and definition of areas of interest for further exploration and development have been made. The new conceptual model developed for the Dubti area is largely consistent with previous assessments, but leverages data into a new reference frame that will facilitate further assessment of the geothermal potential of the area. A more detailed conceptual model of the Ayrobera area is provided, but there is still more uncertainty for this area than Dubti.

Geologic and geophysical data and interpreted geo-referenced images were imported to Leapfrog Geothermal Software, and integrated to develop a temperature model of the entire region. This model

relies on available well temperature data and interprets “updoming” of the bottom of a widespread shallow conductive layer as indicating conversion of low-temperature smectite clay to higher temperature minerals in areas of known thermal manifestations. Example wells were defined that would test and validate the new model for both Dubti and Ayrobera.

The main product of this study is the 3D model, but written reports are also provided as background to the model. This report summarizes the geologic basis for the 3D model and provides discussion of the conceptual models interpreted for the prospect areas.

3.2.2 Surface exploration at Alalobeda

Surface exploration in Allalobeda target area of Tendaho prospect has also been completed with iceida assistance. The exploration work included geophysical exploration (MT, Gravity and Microseismics) and subordinates other geo scientific methods. The purpose is to have a conceptual model of the geothermal system and subsequent well locations. The conceptual model of the field is currently being finalized.

3.2.3 Feasibility study at Doubti

Feasibility study for shallow resource development at Doubti has been conducted with French development agency assistance. The purpose of the study is to assess the feasibility of development and exploitation of Tendaho geothermal resources on the basis of the various studies conducted in the project area, including the drilling of six exploratory wells. Among the different scenarios, the immediate exploitation of the proven resource pertaining to the shallow reservoir, through a power plant of installed capacity up to 12 MWe, has been recommended. The technical, economic and financial viability for the development and exploitation of that resource is analyzed. As to the drilling of production wells for the development of a 12 MWe project, different possible options are analyzed (elc, 2014). Cuurently a geothermal consultant and a drilling service company are being hired for implementation of the project.

3.3 Geothermal Master Plan study

The master plan study has started with JICA assistance two years ago and currently is finalized. The project has been scheduled to conduct geo scientific, social and economic surveys in 22 prospects inorder to have potential estimation and to prioritize them. The results of the study has showed that a minimum geothermal potential of 4200 MWe and a maximum of 10,800 MWe. Ranking of the prospects for development is made on the bases of geothermal knowledge and potential, project economics and site specific factors (gse and jica, 2015).

3.4 New geothermal law and institutional set-up

Current project in geothermal law and institutional set up has focused: (i) assessing portfolio development options with a particular emphasis on advantages and disadvantages of alternative models for stakeholders in both the public- and private sectors, (ii) estimating investment requirements and economic benefits from alternatives (iii) identifying at a high-level organizational capacity requirements, (iv) support needed by private sector firms and (v) potential gaps in/modifications needed to the regulatory/legal framework.

So far, the new geothermal law for operation of geothermal activities in both the public and private sector has been drafted. A geothermal development model in which the public sector mainly engages in exploration, up to test drilling and the private sector enters after the the resource is proven is proposed. A draft document for the establishment of a new geothermal entity has been proposed.

3.5 Private sector participation

Regarding the private sector participation, hot and detailed power purchase agreement for Corbetti geothermal development has been signed with the government. The agreement considers development of the Corbetti prospect to 500 MWe with estimated investment cost of 2 billion US\$. Currently mobilization works are being conducted by Corbetti geothermal company to commence test drilling.

British based company called, Cluff geothermal has also started exploration work at Fentale geothermal prospect.

4. FUTURE GEOTHERMAL DEVELOPMENT PLANS

4.1 Work plan

Since recent times, the country has shifted its policy of relying in a single source of electric power (hydro) to secure energy in the country and thus geothermal sector development is receiving support. As a result a medium term and long term geothermal development plan has been established. According to the medium term plan, a total of 675 MW geothermal power is to be developed from six selected prospects by 2018 (Table 1) and in the long term 2500 MW will be developed by 2030.

TABLE 1: Medium term geothermal development plan

Prospect	Initial output (MW)	Commissioning
Aluto Langano	75	2018
Tendaho	100	2020
Corbetti	300	2020
Abaya	100	2020
Tulu Moye	40	2020
Dofan Fantale	60	2020
Total	675	

4.2 Financial plan

One of the major challenges in Ethiopia's geothermal sector development program is financing. In order to achieve the countries medium term plan in geothermal development both the public, development partners and the private sector participations are envisaged.

The following financial resources are secured under the public sector: (i) for the expansion of the Aluto Langano Geothermal field to 75MW, about 150 million US\$, (ii) The development of the Tendaho geothermal resources at various sites within Tendaho is scheduled with financing of the French Development Agency, the world bank and Ethio-Iceland bilateral cooperation.

Apart from Aluto and Tendaho, the remaining four prospects of the six selected areas are expected to be developed by both the public and the private sector financial involvement.

5. CONCLUSIONS

Despite the long history of geothermal exploration in Ethiopia and an estimated 5000 MW potential, so far only a very little fraction of the total potential is harnessed. In order to avert possible shortfalls and also due to their added advantage in complementing the hydro generation during unfavorable periods of severe droughts, geothermal development in Ethiopia has been given more attention, since recent years.

Currently geothermal is: (i) integrated in the National Energy Development Plan, (ii) participation of international financial institutions, bilateral donors and development agencies to assist geothermal development projects has grown, and (iii) the private sector is being encouraged to participate in geothermal development projects and as a result activities in selected prospects by the private sector have started.

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