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GEOTHERMAL EXPLORATION PROJECT
LAKES DISTRICT

Aluto Geothermal Field
Geophysical Exploration

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# Table of Content

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Abstract</td>
<td>11</td>
</tr>
<tr>
<td>Regional geology</td>
<td>1</td>
</tr>
<tr>
<td>Dipole Dipole Survey</td>
<td>4</td>
</tr>
<tr>
<td>Evaluation and Interpretation of Data</td>
<td>4</td>
</tr>
<tr>
<td>Schlum. Electrical-Resistivity Survey</td>
<td>6</td>
</tr>
<tr>
<td>Discussion</td>
<td>10</td>
</tr>
<tr>
<td>Self Potential Survey</td>
<td>10</td>
</tr>
<tr>
<td>Introduction</td>
<td>11</td>
</tr>
<tr>
<td>Field Procedure</td>
<td>11</td>
</tr>
<tr>
<td>Presentation and evaluation of results</td>
<td>12</td>
</tr>
<tr>
<td>Discussion of the results</td>
<td>12</td>
</tr>
<tr>
<td>Combined Head on Profiling</td>
<td>16</td>
</tr>
<tr>
<td>Method of data collection</td>
<td>16</td>
</tr>
<tr>
<td>Data presentation</td>
<td>17</td>
</tr>
<tr>
<td>Evaluation and interpretation of data</td>
<td>17</td>
</tr>
<tr>
<td>Thermal Method</td>
<td>21</td>
</tr>
<tr>
<td>Technical information</td>
<td>21</td>
</tr>
<tr>
<td>Results and discussion</td>
<td>22</td>
</tr>
<tr>
<td>Gravity Survey</td>
<td>23</td>
</tr>
<tr>
<td>Introduction</td>
<td>23</td>
</tr>
<tr>
<td>Data Reduction</td>
<td>24</td>
</tr>
<tr>
<td>Determination of anomalies</td>
<td>25</td>
</tr>
<tr>
<td>Evaluation and Interpretation of results</td>
<td>27</td>
</tr>
<tr>
<td>Conclusion</td>
<td>31</td>
</tr>
<tr>
<td>Recommendation</td>
<td>32</td>
</tr>
<tr>
<td>Acknowledgement</td>
<td>33</td>
</tr>
<tr>
<td>References</td>
<td>iii - iv</td>
</tr>
</tbody>
</table>
List of Figures

Fig.1 Location map of the Ethiopian Rift Valley and geothermal areas.

Fig.2 Geological sketch map of the Southern Ethiopia Rift Valley modified from Di paola 1972.

Fig.3-10 Lithostratigraphy, distribution of hydrothermal minerals, intensity of alteration, and VES interpretation of wells LA$_1$ - LA$_8$.

Fig.11 Dipole-Dipole resistivity map for N=3
Fig.12 Dipole-Dipole " " " N=5
Fig.13 Dipole-Dipole " " " N=6
Fig.14 Schlumberger apparent resistivity map for AB/2 = 500m.

Fig.15 Schlumberger apparent resistivity map for AB/2 = 1000m.

Fig.16 Schlumberger apparent resistivity map for AB/2 = 1470m

Fig.17 Schlumberger apparent resistivity map for AB/2 = 2150m.

Fig.18 Self potential anomaly map of Aluto-Langano geothermal field.

Fig.19 Combined Head-on profiling (profile 3N).
Fig.19a Combined Head-on profiling (profile 3N$_2$).

Fig.20 Combined Head-on profiling (profile 41).
Fig.21 Combined Head-on profiling (profile 42).
Fig.22 Combined Head-on profiling (profile 44).

Fig.23 Temperature Survey (Oitu-Bole graben)

Fig.25,25c Temperature Vrs depth, geothermal gradient in Aluto volcanic complex

Fig.26 Temperature distribution of Aluto geothermal field (NE - NW)

Fig.27 SW - NE temperature distribution

Fig.28 Bouguer anomaly profile across the central main Ethiopian rift.
Fig. 29  Regional Bouguer anomaly map of central main Ethiopian rift.

Fig. 30  2nd order Residual map of Langano geothermal prospect.

Fig. 31  Basement complex surface Isohypsals (after Dainelli, 1943)
Various geophysical methods were employed for the exploration of Aluto-Langano geothermal field and results are presented as electrical-resistivity, gravity, self potential and temperature gradient maps, sections and correlation of VES interpretation with geology of the deep exploratory wells (LA-1 to LA-8). Electrical-resistivity technique was the most frequently used but could not delineate boundary of the geothermal field. The shallow low resistivity distribution on the low lands around Aluto Volcano except the eastern side is related to clay rich pleistocene lake sediments and warm to hot geothermal fluid infiltration in the sediments. The resistivity picture of the volcano is masked by the high standing topography and coupling effects. There is a general trend of elongated low resistivity zone extending from Lake Ziway to Lake Shalla following the inferred west Langano fault zone that serves as a conduit for the migration of hot geothermal water from North to South.

Gravity maps and sections indicate the presence of local positive anomalies which could mean the existence of intrusive bodies with a contribution from densification of host rocks (deposition of denser hydrothermal minerals).

Hot wells LA-3 and LA-6 were drilled along the same fault zone (trending NNE) with bottom hole temperatures >300°C indicating that the field is structure controlled. There is no significant difference in the distribution of hydrothermal minerals among the production wells. Alteration minerals are abundant and permeability is poor in the Bofa Basalt and the bottom ignimbrite is more permeable with less occurrence of hydrothermal minerals.
INTRODUCTION

Aluto volcanic center is in the Main Ethiopian Rift (Fig.1) and is covered by Quaternary peralkaline rhyolites and pyroclastics where as the southern, western and northern foot-hills are covered by associated old lake sediments and pyroclastic deposits.

Aluto Langano geothermal field has been under exploration since 1969 with different geological, geochemical and geophysical methods.

geophysical techniques applied were:-

- dipole-dipole electrical-resistivity survey;
- Schlumberger electrical traversing and vertical sounding;
- Combined head on profiling;
- Thermal survey;
- Magnetic survey;
- Gravity survey.

Magnetic survey results are not dealt with in this report. The rest are treated in some detail where maps and sections are produced and correlated for sound interpretation.
REGIONAL GEOLOGY

It is worth presenting a summary of the regional geology of the Main Ethiopian Rift to upgrade the understanding of geophysical anomalies that has been done by different authors, namely: Mohr (1962), Macdonald and Gibson (1969), Dipaola (1971) and Kazmin (1975) as described in its chronological order.

Mesozoic rocks of Ethiopia, the major formations named as the Adigrat sandstone, the Antalo limestone and the upper sandstone are underlain by Precambrian (Basement rock of Ethiopia) rocks consisting of granites, schists and gneises. These two rock types are uplifted as a result of the Afro-Arabian swell during upper Eocene (Mohr, 1962) and effected as local thickness variation of mesozoic rocks due to pretrappean differential peneplanation mainly on the centers of maximum uplift (Central Ethiopia) shown in Fig.31 as elevation variation of basement rock surface. Generally, the thickness of mesozoic rocks increases to the south-east and covered most part of the survey area except Lake Abaya region. The thickness ranges upto 1000 mts. in the Arsi highlands of eastern rift shoulder.

The two formations, Precambrian rocks (150m thick) and Mesozoic rocks (≈200m thick) are exposed within the central part of the Ethiopian Rift close to the western rift margin on a Pre-trappean structure of Kella Horst of which the structural significance is ascribed to comparative argument of lithosphere-asthenosphere boundary depth between the west and the east sides of the rift, that it is shallower in eastern margin and implies greater extensional rate of crustal attenuation (Dipaola and Seife Michael Berhe 1981). Mesozoic rocks overlain by Trap Basalt erupted fissurally probably originated in the regions of maximum uplift along NNW-SSE
line of central Ethiopia (Fig.2) (Mohr, 1962). It covers almost all parts of the survey area and infact local thickness variations are due to pre-trapean land profile and its mobility. The maximum thickness ranges upto 3500m. in the simien mountains, about 2500m in the Arsi highlands and 220m. in Abbai-gorge (central Ethiopia). Thickness variations within the Ethiopian rift could not be known due to lack of exposures. This formation is not exposed on Kella Horst but on the sides 2km to the west and 4km to the south covered by Tertiary Ignimbrite which underlies the rift floor as a coherent formation. Its density is not determined yet. However, it is presumably less than that of Bofa basalt (2.6 gm/cm$^3$). Since it is relatively weathered and contains intercalations of tuffs, sediments and silicic differentiates though its petrography differs in different places.

Further fracturing of the lithosphere in Tertiary Quaternary times created the Ethiopian Rift system consisting of the major units (Mohr, 1962). The African rift system extending NNE from the Kenya border, the Gulf of Aden extending W.S.W and the Red Sea rift extending SE into Afar. It produced variable ranges of rocks from basic to silicic consisiting of Basalts, Trachytes, basic-silicic pyroclastics and rhyolitic lava flows with different levels of alkalinity between west and eastern rift rocks. More over, all rocks mainly to the eastern rift sides are differentiated products to the extent of peralkaline. These all rock types overly the pre-tertiary rocks in an alternate sequence. These rocks consist of local and regional rocks as the ones shown in all Langano geological logs of Deep Wells (Figs. 3,4,5,6,7,8,9,10).

Subsequent fragmentation of the rift created the Wonji fault belt divided into three sectors by two offsets named as: East Ziway and Corbetti-Shalla characterized by recent
basaltic fissural flows and cones (Lloyd, E.F. 1977). consisting of central type volcanoes at the middle of the two enechelon offsets (Aluto and Corbetti volcanos) (Fig.2). Rocks of these volcanos are the differentiated products of a parent melt that can possibly be situated or trapped within Tectonized Crust (Dipaola, 1981) and also possible to be responsible for the heat flux anomaly and the central type volcanos.

local hydrologic movement of the area under survey is from North to South and is possible to deduce from piezometric levels of Lake Ziway (1636m) to Lake Langano (1583m)(Hochstein, 1983) and also possible to Lake Abaya on a regional scale.

It is difficult to present a full description of the hydrology of the regions at this time, because of lack of data which is an important part for the assessment of subsurface geothermal energy since the magnitude of heat loss can imply the grade of subsurface energy. No detail local hydrological works were found. However, it is understood with local flow variations as described above lumped to the regional rift hydrologic movement from south to north. The main recharge is from the west and east plateaus, that can be deducted from its morphological contrast with the rift floor.

Dipole Dipole Survey

Data was obtained from geophysics department of EIGS collected in the middle and late 1970s.

Previous interpretation of the data includes MC Euen and Jihad Abakoyas 1976 and reinterpretation using finite difference method by H.P. Ross et al 1978.
Data in the present format is plotted for N=3, N=5 and N=6 as normal forms of dipole dipole resistivity maps. The dipole separation "a", was 500m for almost all of the survey area.

**Instrument Used**

Motor generator supplied by Geotronics consisted of a commercial VW engine that drives a 30 KVA 3-phase, 125 volt, 450 cycle generator with electronic regulator.

**Transmitter**

20 amp supplied by geotronics-time and frequency domain. Induced polarization (IP) transmitter. (Model FT-20A) 0.01 and 0.1 settings were used.

**Receiver**

Geomite Induced polarization receiver
Model R-401/R401S  
Imput impedance 10Mg ohm

**Evaluation and Interpretation of Data**

Maps produced (Figs. 11, 12,13) show that the geothermal fluid has invaded a vast area from Lake Ziway in the North to Lake Shalla in the south, and from Adami Tulu in the west extending to Bobesa fumaroles in the east. The impregnation of the silty Lake sediments with hot to warm geothermal water resulted in the low resistivity distributions in such a large area that one cannot use simple schlumberger resistivity traverses to delineate a boundary of the geothermal field as applied and proved in some geothermal fields of the world.
The distortion of the resistivity pattern on the Aluto Volcano is attributable to the topographic effect to which the dipole-dipole survey is more susceptible. Irrespective of some localized high resistivity anomalies the general trend is a stretch of low resistivity anomaly (10Ω-m) from Lake Ziway to Lake Shalla. Another fact to consider is that whether the presence of low resistivity distribution to the north of Aluto Volcano is because of the rising of hot geothermal water from Aluto volcano and flowing of its small component to the north because of local topography or that is related to the infiltration of the geothermal fluid from Lake Ziway (presence of hot springs on Tulu Gudo Island in Lake Ziway is an example) down south to Lake Langano and Lake Shalla.

Hydrologically, the gross ground water flow is from North to South in the area (Lake Ziway 1636m, Lake Langano 1585m and Lake Shalla 1570m)

There are 3 possible postulates to consider from the anomalies.

1. Hot water rises due to its less density from the Aluto system and a small component flows to the North guided by a local topography and impregnates in the formation that resulted in the low resistivity anomaly between Aluto volcano and Lake Ziway.

2. There is a separate system that is responsible for the thermal manifestations in Lake Ziway and in effect there is a hot water flow from North to South where by it joins the hot water from the Aluto system after travelling in the formation between Lake Ziway and Aluto volcano, consequently resulting in formation alteration including the lake sediments that produced resistivity low in the low-lands.
3. The system is one with two reservoirs, one in Lake Ziway and another under Aluto volcano and the flow is to the south with a common effect of the same system.

Traversing for $AB = 500\text{m}$ and $\frac{AB}{2} = 1000\text{m}$ and vertical electrical soundings (maximum $AB = 3160\text{m}$) were taken keeping the $MN$ spacings as $MN < \frac{AB}{5}$. Porous pots with concentrated copper sulphate solution for the potential electrodes and copper stakes, sheets, iron stakes, wire mesh, and aluminum sheets were used for current electrodes. Watering of electrodes was made to decrease the contact resistance. Reading accuracy was checked for many traversing stations using

$$\frac{V_{11}}{I_{11}} + \frac{V_{22}}{I_{22}} = \frac{V_{12}}{I_{12}} + \frac{V_{21}}{I_{21}} \quad \text{(Risk 1982)}$$

where $V =$ potential drop
$I =$ current
$11 =$ outer current electrode
$22 =$ inner current electrode

and the error was found to be < 3%. The error can arise from leakage and scale reading. Current and potential cables were laid parallel and far apart by 250m to overcome the coupling effect that arise from the proximity of current cables to the potential cables. Most sounding curves are H type and often show an up turn after $AB = 1470\text{m}$. The upturn could not be assumed as a formation or saturation change since permeability is relatively high as we go down; it is rather possible to consider the skin effect or two and three dimensional body effects.

**Discussion**

The maps show a uniform low resistivity distribution over a large area due to clay rich lake sediments with tongues of
very low resistivity structures (<5\(\Omega\)-m) that can be ascribed to the effect of warm to hot geothermal fluid impregnation.

Resistivity map for \(AB = 500\) m (Fig. 14) reflected the inhomogeneity of surface rocks with extensive low resistivity (<10\(\Omega\)-m) on the flat areas except to the east where we don't have lake sediments.

High resistivity anomalies (>100\(\Omega\)-m) coincide with topographic highs and rhyolitic lava flows. A relatively low resistivity closure (<50\(\Omega\)-m) coincides with fissures associated with weak steam and alteration grounds.

A map for \(AB = 1000\) m (Fig. 15) shows a relatively small variation and still the resistivity structure (>50\(\Omega\)-m) coincides with topographic highs, rhyolite lava flows and dry surface and near surface pyroclastics.

A better resistivity pattern is seen in relation to reservoir set up and productive wells. Productive wells located on the up flow zone (LA-3 and LA-6) are along the east Basuma fault and the low resistivity tongue (<10\(\Omega\)-m) extending towards Aluto and opening to Lake Ziwai is associated with this fault although with scarce data. The temperature increases to the north as confirmed by temperature distribution (Figs. 27 & 28). Reservoir characteristics are totally structure controlled. This system with dominant vertical permeability (Fig. 28) along LA-3 and LA-6 has resulted in alteration effect and saturation increment as a result of ascending hot geothermal fluid or steam that may condense at shallow depth. The low resistivity tongue North west of LA-8 is contrary to the temperature gradient structure (Fig. 15). However it is wise to check with deep drilling (about 500m) since the temperature gradient wells are shallow (50m) with respect to the depth of water table (about 300m). The high resistivity
separating the two low resistivity tongues is eliminated in the map for $\frac{AB}{2} = 1470\text{m}$ (Fig.16) and $\frac{AB}{2} = 2150\text{m}$ (Fig.17).

Geologic and Geo-electric correlation of deep exploratory wells.

Eight deep exploratory wells (Fig.3,4,5,6,7,8,9,10) were drilled in Aluto-Langano geothermal field with depths from cellar top and drilling time as indicated in table 2.

<table>
<thead>
<tr>
<th>Well No</th>
<th>Start of Drilling</th>
<th>Completion of Drilling</th>
<th>depth (m)</th>
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<tr>
<td>LA-1</td>
<td>7-11-81</td>
<td>11-6-82</td>
<td>1317</td>
</tr>
<tr>
<td>LA-2</td>
<td>6-7-82</td>
<td>15-11-82</td>
<td>1601.8</td>
</tr>
<tr>
<td>LA-3</td>
<td>21-1-83</td>
<td>13-6-83</td>
<td>2143.9</td>
</tr>
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<td>LA-4</td>
<td>6-7-83</td>
<td>23-10-83</td>
<td>2062.2</td>
</tr>
<tr>
<td>LA-5</td>
<td>15-11-83</td>
<td>11-3-84</td>
<td>1866.6</td>
</tr>
<tr>
<td>LA-6</td>
<td>24-3-84</td>
<td>2-7-84</td>
<td>2200.8</td>
</tr>
<tr>
<td>LA-7</td>
<td>11-7-84</td>
<td>17-10-84</td>
<td>2449.2</td>
</tr>
<tr>
<td>LA-8</td>
<td>28.10.84</td>
<td>8.3.85</td>
<td>2502</td>
</tr>
</tbody>
</table>

Schlumberger electrical-resistivity soundings of maximum $\frac{AB}{2} = 3160\text{m}$ were taken at each well site before the start of drilling. The VES interpretations were made and the interpreted true resistivity values were plotted along the geologic sections of each well that were used as calibrations of sounding data.

Measured temperatures of single (stable) run is plotted to indicate the condition of temperature gradient along the drilled depth except LA-1, LA-2 and LA-5 which are non productive.

Preliminary permeability information is derived from the circulation losses at each zone. For wells on Aluto volcano permeability is high in the above 300m thick Aluto-rhyolite formation and bottom tertiary ignimbrite. The Bofa basalt (about 1km thick) has got poor permeability but high temperature, may be permeability in this zone is reduced due to self
sealing where alteration intensity is high which is less in the bottom Tertiary ignimbrite.

For wells LA-1 and LA-2 the resistivity information is quite different from that of the other wells as the low resistivity values in the top layer is related to the saline old lake sediments and associated volcanic deposits that was enhanced by the infiltration of warm to hot geothermal fluid from Aluto volcano as they are located along the foot hills of the volcano.

For wells on top of Aluto volcano the resistivity distributions are related to different geologic layers in terms of permeability, saturation and thermal alteration. The top resistive layer is dry and unsaturated pumice and ash. The resistivity structure continues decreasing sequentially with depth with minor intermediates in the rhyolite lava and obsidian, lake sediments, breccias and highly altered thick (~1km) Bofa basalt. The resistivity values did not continue decreasing below some part of the basalt may be due to factors such as coupling effect, topographic effect, reflection of less altered Tertiary ignimbrite (resistive substratum) and inhomogeneity of Aluto volcanic complex.

SELF POTENTIAL SURVEY

INTRODUCTION

The survey was made on top and peripheries of Aluto volcano, before any deep exploratory well was started to be drilled on Aluto (Nov. – Dec. 1982). It was taken on six profiles with a total length of 72 kms radially arranged in an area of about 240km².
It is a new method to geothermal application, yet experimented in Aluto geothermal field with an objective that any possibility it could show as to the determination of up flow centers and sink of the geothermal fluid flow based on the consensus that mobility of mineralized (ionized) fluids set up an electric field (Hock, 1982). Accordingly positive self potential anomalies are associated with convergent flow and negative anomalies with divergent flows.

The survey was carried out under the supervision of prof. Hochstein (Auckland University, New Zealand). He recommended the method based on the pressure of time that site 3 had to be selected before site 2 was completed, and the problem of resistivity work result which was not able to determine and delineate the geothermal reservoir at that time.

**INSTRUMENT USED**

A time domain DC receiver (Scintrex) with an internal impedance of 3 megohm, non polarizing electrodes of copper rod in porous pots containing saturated CuSO₄ solution and a stranded copper cable.

**FIELD PROCEDURE**

Measurements were taken at 500 mt and 1000 mt interval using leap frog method. The readings of two successive 500 mt interval were checked against the readings of 1000 mt. Quite often, the sum of the two successive 500 mt reading is the same as the 1000 mt reading.

Technical care of the following was taken to overcome noise effects before any measurement was taken.
Porous pots with saturated copper sulphate solution were put in a plastic basin of water connected to each other at least for 2 hours. This helps to drop the difference of electrochemical potential of the porous pots. All electrodes were watered to improve electrical contact and grounded for at least one hour to overcome the noisy effect due to percolation of water that can result in electro kinetic potential (Corwin and Hoover 1979). Maximum care was taken not to ground porous pots near vegetation and not to expose it to a direct sun light.

The polarity of self potential was taken with respect to the convention i.e. positive nob of the instrument was always fixed to the progressive side of the profile and taking the sign of the reading that could bring a voltage indicator to zero position. The sign of the self potential is reversed when the polarity of the cable connection is reversed. Simultaneously, contact resistance measurements were taken for all separations and often it was between 30 - 40k. ohm.

PRESENTATION & EVALUATION OF RESULTS

Ideal potential is measured between two points, but all station readings were connected to a fixed reference point assuming a zero potential with respect to an infinite point located between Aluto volcano and Lake Ziway (Fig.1). The value of a station was determined by a series sum of all readings starting from the reference point, and is presented as a map (Fig.18).
DISCUSSION OF THE RESULTS

A long wave length (>10 km) of positive self potential anomalies with an amplitude of 100 - 500 mv. are observed associated with Aluto volcanic massif. A negative SP anomaly of maximum amplitude - 113 mv is associated with southwestern flanks of Aluto volcano and the flat terrain of Lake Langano. Large voltages upto 500 mv have been measured associated with high altitudes, high resistivity terrain (Rhyolite massif) and hydrothermal vents with fumaroles. These large range of values are also pronounced by the inhomogeneity effect of the Aluto massif. A smooth, long wave length is on flat terrains and on homogeneous formation (Lake Sediments). This can imply self potential anomaly is dominated by the surface effect.

It is difficult to give conclusive meaning of these anomalies. However, experimental works are being carried out in different parts of the geothermal fields in the world. The present stage and idea of this survey is just to see what kind of anomalies can be observed in relation to the other applied geophysical methods. It is a new technique; consistency of integration has not yet been arrived at as a conclusive result that can help to undertake quantitative analysis.

It has been understood that electro kinetic, Thermo-electric and to a minor extent electro chemical sources can arise a potential variation in geothermal fields. (Corwin and Hoover 1979, sill 1981, sill 1982 a,b,c). Secondary effects of noises that can reproduce measurements upto ± 10 mv are known as:

1. Topography
2. Electrode drift
3. Variation in soil moisture
4. Vegetation
5. Shallow moving ground water
6. Cultural effect

TOPOGRAPHY

The effect is due to the relief and movement of shallow ground water that can cause electro kinetic potential. Large negative potentials as large as $-6 \text{ mv/m}$ are sometimes correlated with an increase in elevation (Hoover, 1981).

Electrode drift

The effect is due to non-equilibrium of an electrode pair resulted from temperature difference, dilution or contamination by ground water of non polarizing electrodes.

Variation in soil moisture

Variation in soil moisture can result in self potential differences (Corwin and Hoover 1979). Watering of electrodes produces the same effect and it is pronounced by electro kinetic phenomena if it is not given time to stabilize.

Vegetation

Potentials are produced due to circulation of water in the roots and the soil.

Shallow moving ground water

It is purely the effect of electro kinetic potential created due to the movement of underground water.
Cultural noise

It is the effect of power lines, telephone lines and corrosion potential arising from pipelines, fences, and well casings.

The top of Aluto massif is dry and partly covered by vegetation and the depth of underground water table is in the order of 300mt. Local hydrologic movement is from Lake Ziway to Lake Langano i.e. from north to south. There are no power lines or telephone lines crossing the volcano or ground measured profiles. The large scale variation in SP readings on top of Aluto volcano can be attributed to the noisy effects of topography, relief, vegetation, soil moisture and areas of hydrothermal activity.

SP anomaly will be still large if the smooth mean anomaly is taken discarding all the large drastic variations. The smooth long wave length positive and negative anomalies are probably associated with streaming potential caused by local underground water movement. Local potential highs may sustain on top of Aluto volcano and qualitative assumption can be given for the cause as thermoelectric effect resulted from geothermal fluid movement. But nothing can be said about its application towards locating up flow zones of the geothermal reservoir. No distinct anomaly is observed around productive wells of Aluto Langano geothermal field (LA-3, LA-4, LA-6 LA-7, and LA-8).

Combined Head on Profiling

The work continued intermittently from 19/03/84 to 08/10/84 which overlapped with the resistivity survey at Corbetti geothermal prospect area, because of shortage of a resistivity unit.
In addition to the electrical soundings which were mainly on the sites of deep exploratory wells, for geologic and geoelectric layers correlation, it was anticipated that the combined head on resistivity profiling could lead to a zone of good permeability as the technique has proved itself in people's Republic of China, (Cheng 1980) and Iceland (Florenz 1983), in detecting near surface faults in low temperature geothermal fields.

For deep wells on Aluto volcano, permeability appeared to be not a satisfactory parameter and this technique was first tried if it could solve this immediate problem of the field by out lining a known (from surface expression and photo geological interpretation) the east Basuma fault zone.

The short coming of the start of this survey was that the electrode C, seemingly at infinity was not put greater than 2km because of the Lake Langano water on the south and the high standing flank of Aluto volcano in the north. Even then it appeared to show the trace of the fault at a relatively shallow depth and indistinctive manner. The work then continued on the top of Aluto Volcano and the array was used at large distances of C from the profile and similar cross overs for different separations on profiles 41,42 and 44 (Fig.20, 21,22) have shown up.

As the method used was to get conductive (fault) zones for different \( \frac{AB}{2} \) and OC, profiles 3M3F (fig.19,19a) were the first ones to be surveyed with this technique, where the station interval was 200m. The distances used for \( \frac{AB}{2} \) were 50, 100, 200 and 300m and the distances for OC were 0.5, 1,2 and 3 km respectively.
Instruments used

**Scintrex**

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Transmitter</td>
<td>15 Kw</td>
</tr>
<tr>
<td>Frequency</td>
<td>0.125 Hz, square pulse.</td>
</tr>
<tr>
<td>Receiver IPR</td>
<td>10 A with 3M-ohm internal impedance</td>
</tr>
</tbody>
</table>

**Method of Data Collection**

All of the lines except line 44 were oriented perpendicular to the trend of geological structures (faults) in the area. The spacing between neighboring stations was 200m. The current electrode at infinity was located in such a way that the line OC is perpendicular to the profile and parallel to the fault strike.

Measurements were taken for four different AB S (viz 200, 300, 680 and 850m) for OC. = 2, 3 and 5km along lines 41, 42 and 44.

The common procedure of the head-on data collection is to measure the resulting potential of the injected current through AC and BC.

It is also necessary to measure the resulting potential of the current injected through A or B. The apparent resistivity obtained by injecting current through A or B should be the mean of the apparent resistivities obtained by injecting current through AC and BC i.e. $\rho_{AB} = \frac{\rho_{AC} + \rho_{BC}}{2}$. This helps to check the accuracy of data collection in the field.
Data Presentation

It is a common practice to present the head-on data on a plot of $\rho_{aAC} - \rho_{aAB}$, $\rho_{aBC} - \rho_{aAB}$, $\rho_{aAC} - \rho_{aBC}$, $\rho_{aAC}$, $\rho_{aBC}$, and $\rho_{aAB}$ versus stations in km. But in the case of lines 3N and 3N$_2$, the data is presented for $\rho_{aAC}$, $\rho_{aBC}$ and $\rho_{aAB}$ versus stations in km. The $\rho_{aAB}$ was taken to check the field data collection. From lines on the top of Aluto volcano data is presented as plots of $\rho_{aAC} - \rho_{aAB}$, $\rho_{aBC} - \rho_{aAB}$, and $\rho_{aBC} - \rho_{aAC}$, $\rho_{aAC}$ and $\rho_{aBC}$ versus stations in km.

Evaluation and Interpretation of Data

As observed from the profiles there are some cross overs for the shallower penetrations (shorter AB and OSS) which account for the near surface inhomogeneities. But the ones because of conductive (fault) zones were continued for all or most of the AB, and OSS. The point of these cross overs is that the resistivity value just at the crossing point of the two curves $\rho_{aAC}$ and $\rho_{aBC}$ is a common value for both curves at the point; because when the array AMNB is approaching a conductive zone from left with B leading, $\rho_{aBC}$ decreases $\rho_{aBC} - \rho_{aAB}$ negative) since the potential array MN is not between B and the zone. When MN is between A and the conductive zone $\rho_{aAC}$ increases ($\rho_{aAC} - \rho_{aAB}$ becomes positive). But when MN crosses the zone, the condition becomes reversed. Just on the conductive zone $\rho_{aAC}$ and $\rho_{aBC}$ attain equal values i.e. the curves for $\rho_{aAC}$ and $\rho_{aBC}$, $\rho_{aAC} - \rho_{aAB}$ and $\rho_{aBC} - \rho_{aAB}$ cross each other and hence it is possible to find the strike of a conductive zone by mapping the cross over points on different lines.
The electrode separation along profiles 3N and 3N2 was limited because of the nearness of the Lake Langano water on the southern part and the Northern side is restricted by high standing flanks of Aluto Volcano. For these two profiles it was possible to get points of cross overs which were connected to trace the E.Basuma fault with an orientation of $36^\circ$E of N (Fig.19a).

The second stage was to detect the fault zone that passes through TG 25 with a N - S orientation from geological information. The work was started with $AB = 200$, 300, 680 and $850$ m and $OC = 2$, 3, 5, and $5 km$ respectively where the profile (line 41) is perpendicular to the fault strike and $OC$ parallel to it.

Profile 41 (Fig.20)

The work started with this profile on Aluto volcano from station -1.3 to 2.4 at station interval of 200m. Presence of conductive zones was detected as indicated by consistent intersections of the half space apparent resistivity profiles at stations 0, 1.05, 1.75 and 1.95.

There are indistinctive cross overs for $AB = 200$ m of $\frac{\rho_{BC}}{\rho_{AC}}$ and $\frac{\rho_{AC}}{\rho_{BC}}$ plot. The ones at 0.4 and 1.05 consistently persisted to exist from $AB = 850$ m i.e. for $AB = 200$, 300, 680 and $850$ m. The zone between these two cross overs is a low resistivity structure.

The cross over point at station 1.05 has shown the fault trace that passes through TG 25 where LA-7 was selected 150m south west of the fault trace as a better drill site. Unfortunately the temperature of this well at 1600m is $220^\circ$C (Fig.26) with decreasing temperature at bottom hole which could be because of the fact that all faults are not active
and it could be old which is sealed by deposition of hydrothermal minerals such that hot geothermal fluids cannot get access to pass through the fault zone and the deposited hydrothermal minerals are still conductive that the trace of the fault is identified. From the condition of LA-7 this technique can detect active and inactive (sealed and saturated in the case of geothermal fields) and it is difficult to differentiate the two by this method i.e the method invites other techniques like thermal method for confirmation.

A cross over point on the west of this profile is at picket 0.25 for $AB = 200\text{m}$ which continues at $-0.25$ for $\overline{AB} = 300\text{m}$ with an angle of $5^\circ$ down thrown to the west (or upthrown to the east). This cross over appears at station 0.25 for $\overline{AB} = 680\text{m}$ and at station 0.45 for $\overline{AB} = 850\text{m}$ with an angle of $12^\circ$ between the two separations (i.e. $AB = 680$ and $850\text{m}$, $\overline{OC} = 5\text{ km of}\overline{PA_{BC}}$ and $\overline{PA_{AC}}$ cross overs). LA-3 is at station 0.03 i.e. it is in this fault zone which is a major fault from geological information that passes through LA-6 which appears to be an active fault as shown by temperature gradients of wells LA-3 and LA-6 (Fig.25a)

Profile 42 (Fig.21)

This was the second profile to be surveyed on the volcano and two low resistivity cross overs are shown for $AB = 200\text{m}$ at stations 1.4 and 1.7 of $\overline{PA_{AC}}$ and $\overline{PA_{BC}}$ which are narrowed for $AB = 300\text{m}$ at pickets 1.5 and 1.7 and that finally turned out to be a single cross over at station 1.5 for both $AB = 680$ and $850\text{m}$ and $\overline{OC} = 5\text{ km of}\overline{PA_{AC}}$ and $\overline{PA_{BC}}$. This zone is shown as a structure of resistivity low by $\overline{PA_{BC}}$ - $\overline{PA_{AC}}$ profile which implies that it is a single conductive zone which may indicate the existence of a fracture containing hot fluid at depth.
Profile 44 (Fig.22)

This was the last profile for this technique on Aluto for drill site selection of LA-8 before the completion of LA-7, looking for a permeable zone to enhance production. Two low resistivity cross overs for stations 0.9 and 1.4 for $\frac{AB}{2} = 680$ are shown which did not show up in the case of $\frac{AB}{2} = 850$ m that could be due to presence of nearby conductive zones as shown by a neck of low resistivity structure which may be connected at depth as a single conductive zone. LA-8 is sited at station 0.9 for better production in a permeable zone.

Table 1 (Rodolfo Caceres Pers. comm)

<table>
<thead>
<tr>
<th>Well</th>
<th>Total mass flow rate (ton/hr)</th>
<th>Enthalpy (Kj/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA-3</td>
<td>38</td>
<td>1600</td>
</tr>
<tr>
<td>LA-4</td>
<td>100</td>
<td>1700</td>
</tr>
<tr>
<td>LA-6</td>
<td>40</td>
<td>1000</td>
</tr>
<tr>
<td>LA-7</td>
<td>75</td>
<td>835</td>
</tr>
<tr>
<td>LA-8</td>
<td>65</td>
<td>1150</td>
</tr>
</tbody>
</table>

Temperature gradients of LA-7 and LA-8 are lower than those of LA-3 and LA-6 (Fig. 25a) but the total mass out put of LA-7 and LA-8 are larger than that of LA-3 and LA-6 (Table 1). The sealing up of the fault zone of LA-7 and LA-8 is at depth and the feed zone is the fault zone along which LA-3 and LA-6 were drilled that serves as a feed zone for the eastern and western sides as shown by the results of LA-4, LA-7 and LA-8 (Table 1). South of LA-3 the subsurface temperature of this zone is decreasing as shown by LA-1 results and thermal maps (Fig. 26, 27).
From the lithostratigraphy of LA-3 and LA-7 a structure is evident where LA-7 shows a vertical displacement of 280m indicated by the elevation of a widely spread and thick (about 1km) Bofa basalt.

**Thermal method**

A thermal survey map of one meter depth in the area in 1974 (Fig. 23) didn't show a sound picture of anomalous zones, but rather showed diffused patches of indistinctive picture.

After the two deep strike exploratory wells of the southern (LA-1) and western (LA-2) foot hills of Aluto volcano, the problem was where to locate the next subsequent deep drill sites in the area of prospective geothermal potential. The existing geoscientific data available was not adequate to give proper indication of the sites. Few Schlumberger soundings taken on the top of Aluto were of a poor quality due to combined effects of near surface inhomogeneities and terrain (M.P. Hochstein, 1982). Hence thermal gradient wells were suggested to be drilled on selected locations for additional information. These shallow wells (Fig. 24) were located based on easy access and areal coverage.

**Technical Information**

**Drilling:** All the shallow wells were drilled with two inch galvanized steel pipes. The bottom sections were perforated to allow the influx of groundwater and steam. Aerated foam was used as a drilling fluid.
Instrument and Calibration: A triac resistance thermometer with a digital read out was used throughout the survey. Calibration of the thermometer with respect to a maximum thermometer, initially checked for accuracy in melting ice and boiling water was used for each set of measurements. The calibration was made by measuring hot water in a thermos flask with both Triac and the maximum thermometers at the same time. The absolute temperatures of the measurements were determined by adding the differences of the temperature measured by the two thermometers (i.e. Triac thermometer reading minus maximum thermometer reading) to the temperatures measured at different depths of the well by the Triac thermometer.

Data Collection: Measurements in all holes except in TG 21 were made in air, because these holes did not reach water table. Most of the holes were drilled in one day and measurements were made seven days after the completion of drilling. Repeated measurements have shown that the temperature measured after a couple of months were the same with those measured after seven days.

Results and Discussion

The main drawback of the thermal survey of the area was that all the wells except TG 21 didn't encounter water table and measurements were made in air. As a result temperature measurements took longer time to stabilize. A small movement of groundwater even across a strong thermal anomaly can carry away conductive heat flow, displacing surface temperature patterns and grossly distorting gradient measurements. The effect is more when groundwater is not reached.
The curves of the stable temperature (°C) versus depth (m) are given in Fig. 25. TG 11, 12, 13, 16 and 29 have constant temperature gradient. TG 15, 17, 20, 22, 24 and 25 show different temperature gradients at different depths. TG 18, 23, and 36 are convective showing the same temperature throughout their drilled depths, and also TG 27 and 28 show negative gradients (reversal). Temperature gradients of the conductive wells were used to indicate the up flow zone with the help of the results of other surveys. The highest temperature gradient is observed in the eastern and north eastern part of Aluto volcano (Fig. 25a).

Results from deep exploratory wells support the results of the temperature gradient wells as shown in temperature distribution cross-section of Aluto Langano geothermal field (Fig. 26 & 27). The highest temperature is observed around LA-6 and the thermal anomaly patterns and flow direction are shown in the same figure. Hence, it is possible to outline the heat flow direction of the survey area, from NE-SW cross section (Fig. 26). It is also seen that LA-6 is drilled in the highest thermal gradient anomaly zone in the field; although the iso-therms are open north wards due to lack of wells farther north east of LA-6. LA-3 and LA-6 are within the upflow zones, which are in the extension of east-Basuma fault zone.

GRAVITY SURVEY

Introduction

Previous works by Searle and McEuen 1972, Gouin (1974) McEuen and Jihad Abakoyas (1977) and Abera Alemu (MSc thesis, Addis Ababa University, 1983) couldn't show the actual regional gravity field of the Ethiopian Rift and the shoulders that could help to deduce the effect and the physical set up of the
anomalous mass in the crust. And also the accuracy of the stations’ altitude taken using paulin altimeters were uncertain, since a traverse that covers a wide area with no linear pressure change will have significant error. With this understanding, detailed gravity work under the Ethiopian Geothermal Exploration Project was carried out between 1982 to 1985 on Aluto volcanic mountain and its surroundings, using Lacoste and Romberg model G 303 gravimeter which is almost drift free with a reading accuracy of 0.01 mgals.

Elevations and coordinates of most stations were determined by tacheometric method with insignificant error whereas elevations and coordinates of stations over the east and west rift shoulders were determined using a paulin altimeter and 1:50,000 topographic maps. The accuracy of gravity anomaly is strongly controlled by the accuracy of altitudes of observation points. Significant error was assumed which could account for ±3 mgal with respect to elevation. All gravity stations were tied to the main gravity station at Bekele Mola Hotel (Langano, on the concrete cellar infront of room No. 15) determined by Gouin tying to the geophysical observatory main base station (AAU). Station interval was 1 to 5km using a vehicle and conditional foot traverses keeping the loop time less than 3 hours. In Langano area between Lake Ziway and Lake Awasa, 400 stations were occupied. Some of these were taken on bench marks and tacheometric locations.

DATA REDUCTION

All gravity data was reduced to sea level. The normal gravity formula adopted by the international union of Geophysics and Geodesy (1930), was used.
The following corrections were made to the observed gravity data.

1. Free air correction
2. Terrain "
3. Bouguer "
4. Latitude "

Free air reduction is purely the correction made due to a station elevation and the vertical gradient of gravity was assumed as 0.3086 mgal/m in the survey area.

Terrain corrections were made by the method of hammer (1939) for E to W zones. Inner zones (E to D) correction was estimated in the field during gravity measurements. The correction is often <3 mgals.

A mean crustal density of 2.67 gm/cm$^3$ was used for Bouger plate correction.

DETERMINATION OF ANOMALIES

The gross rift structures: Upper mantle plume (Grifiths, et al 1970), accumulations of low density younger volcanic products, rift in rift structures (faults, grabens etc.) and possible shallow intrusions resulted in gravity anomalies. Separations of the gravity effect of all the above factors need a reliable establishment of the regional gravity field and knowledge of the regional geology of the area covering the main Ethiopian rift and its shoulders. The areal coverage of the observation points is minimum as to the construction of the regional gravity field. However, observing the strong relative positive anomaly of the rift and based on the analysis of the works of previous authors and similar geologic structures namely McEwen (1970), FAIR HEAD, 1975, NDOMBIS.W. 1980, and Khan et al (1971), qualitative analysis of the gravity anomalies is given at this stage.
The Ethiopian rift is part of the African rift system that showed association of negative Bouguer anomaly greater than 1000 km wide, and a more localized 350km wide negative anomaly centred over the eastern rift (Girdler 1975). The same structure is observed over the Ethiopian rift system; i.e. there exists a broad regional negative gravity field (>400 km) with an amplitude of -260 mgals, over which a positive anomaly with a wavelength of 60 - 100 km is superimposed. This positive anomaly has an amplitude of about 50 mgals with respect to the -260 mgals reference line. This is assumed to be the effect of upper mantle pluming (Griffiths et al 1970) indicated as crustal anomaly in Fig.28 and local positive and negative gravity anomalies.

Separation of local anomalies with minimum data coverage of the area, had been tried considering the works of Gouin (1970). Two profiles about 150km long of new data across the main Ethiopian rift (passing through the foot-hills of Aluto and Corbetti volcanoes and two Gouin's profiles of the same orientation (Fig.29) were used for the determination of the regional gravity field. The same regional anomaly was transferred to the other three profiles (ABC) Fig.29 and the mean surface of the regional field was determined using a computer program (Auckland, University, New Zealand, 1985). Applying this technique a rough qualitative picture of the anomaly could be speculated i.e. a first order residual gravity anomaly with an amplitude of 60 mgals taking -270 mgals as a datum line was observed.

Separation of local positive and negative anomalies of an order 2 were made using the same technique of linear interpolation and a computer programme to determine the mean surface of crustal anomaly Fig.28. The amplitude of local positive anomaly was found to be +30 mgals and -20 mgals for the local negative gravity anomaly.
EVALUATION AND INTERPRETATION OF RESULTS

As described above, the Ethiopian rift is characterized by recent volcano-tectonic features: Central volcanoes (Aluto and Corbetti), craters, cones, faults and grabens with possible shallow intrusions. Petrogenetically mainly the eastern side of the main Ethiopian rift rocks are the differentiated products of parent magma situated at depth. All gravity anomalies are pictures of these complex rift geological features.

Two dimensional local positive anomaly situated between Lake Langano and Lake Ziway correspond to the Ziway sectors of the Wonji fault belt and has the trend of the main Ethiopian rift axis. This is assumed to be a shallow denser mass intrusion. It is a large intrusion about 35km wide with 30 mgals effect (Fig.30). The depth and the thickness of this intrusion cannot be assessed at this stage because of the problem of knowledge on the coherence of regional rocks and correlation of recent volcanic products. Moreover, absence of mesozoic rocks density, non construction of a reliable regional gravity field and uncertainty of the upper mantle depth pronounced the problem.

Separation of the gravity effect of the anomalous mass from the surrounding cannot be sought, because of non exposure of regional rocks nearer to the anomaly and existence of geological difference between east and west sides of Aluto volcano, so that it could be possible to see existence of anomalous mass within a shallow depth range (≈ 5km).

It is difficult to assume the intrusive body to be responsible for the local heat anomaly observed at Langano at present because of the above argument. Local negative gravity anomalies are also two dimensional and parallel to
the main trend of the Ethiopian rift axis. Gravity lows are observed north and south-west of Aluto volcano (Fig.29). It is related to a pre-existing large graben where later, Aluto volcano erupted. Lake Ziway and Lake Langano are situated within this graben.

The trace of Aluto caldera cannot be supported by gravity anomaly where it is ideal to get relative gravity low due to the effect of a low density material deposition. One of the following reasons can be presumed.

1. No density contrast between the inner and outer rocks of the caldera.
2. Modification by the intrusive body.
3. No caldera on Aluto volcanic complex, but only geomorphological contrast due to erosion, faults and craters.

Bouguer anomaly difference of 60 mgals is observed between the east and west rift shoulders of the main Ethiopian rift (Fig.28). The east is more negative. Concrete reasons cannot be given for the cause at this stage, because of absence of supplementary studies such as deep seismic survey, and detailed regional lithostratigraphic correlations of rift and plateau rocks. Rather possible speculations can be given based on the current geological information.

1. The effect of significant thickness variation of low density coherent formation in and outside the main Ethiopian rift, that is discussed in the general geology as thickness variation of Mesozoic rocks and surface elevation of Pre cambrian rocks (Fig.31). Formation thickness of Mesozoic rocks generally increases to the south-east direction in contrast to the surface elevation of Precambrian rocks. This can imply more general negative gravity in the same
direction, but the gravity coverage is within the central Ethiopian rift where we have maximum uplift. Therefore the gravity difference observed could be also due to local variation of mesozoic rocks affected by pre-trapean differential erosion and the thickness variation of Trap Basalt. The density of the trap basalt is not exactly known but presumably a bit less that that of Bo'fa Basalt (2.6 gm/cm³). No experimental results for the mesozoic rocks but it is assumed to be less than the mean crustal density (2.67 gm/cm³). In both cases the gravity effect is negative.

A maximum thickness of 2500m Trap Basalt is observed on Arsi high lands (Eastern rift shoulder) where as none on Kella Horst close to the western margin of the central Ethiopian rift (Di paola and Seife-Michael 1979). The same formation is observed around Kella Horst underlying the Tertiary-Ignimbrite. This can imply none uniformity of these rocks and the gravity difference is associated with this, though no regional comparative information was found between the east and the west rift shoulders.

2. More large deposits of low density quaternary - Tertiary volcanic products (Rhyolite lava flows and silicic pyroclastics) in the east rift margin and its shoulder.

3. Major crustal attenuation is to the east of the main Ethiopian rift that can result in up doming of lithospheric asthenospheric boundary, thus indicating low density partial melt (Girdler and Sowerbutt 1970). Geological support of this argument can be given from the works of G.M Dipaola and Seife 1981, i.e. the discovery of Kella Horst close to the western rift margin and a more peralkaline character of the rocks in the east implying comparatively shallower lithosphere - asthenosphere boundary.
Kella Horst was presented as a pre-Trapean uplift exposed as Precambrian and mesozoic rocks within the main central Ethiopian rift, and it implies a greater lithosphere thickness to the west of the rift.
CONCLUSION

Electrical resistivity survey could not delineate a boundary of the geothermal field but rather showed low resistivity distribution (<10 \( \Omega \cdot m \)) in the low lands associated with old clayey lake sediments and warm to hot geothermal fluid infiltration in the shallow formation.

Combined head on resistivity profiling indicated three fault zones that could serve as conduits for ascending geothermal fluids.

From the thermal anomaly the up flow zone appears to extend to the north east of LA-6 but no conclusive results are obtained from the self-potential survey results.

As revealed by the gravity survey results:

- Denser intrusive mass is assumed under Aluto volcano which may not be responsible for the local heat anomaly, but differentiated silicic melt is possible to exist under the volcano at a shallow depth the gravity effect of which is swamped by the effect of low density silicic products.

- Gravity difference between east and west rift shoulders (east more negative) is related to lithologic difference or extensional crust attenuation in the east.

- A deeper structural control is assumed to be a two dimensional nature of the intrusive body.

- A graben structure is revealed that joined Lake Langano and Lake Ziway depression prior to the growth of Aluto volcano.

In general

- Production of the field is fault controlled.
- The field seems to be promising to the north of LA-3.
Recommendation

For locating subsequent drill sites:

Four TG wells between LA-6 and Lake Ziway (Fig. 24) are recommended to be drilled at least up to local groundwater level to understand the pattern of the thermal anomaly.

Combined head-on profiling survey along two profiles (Fig. 24) has to be conducted to trace the East Basuma fault zone extension up to lake Ziway which appears to be the most active fault zone in the area for geothermal energy production.
ACKNOWLEDGEMENT

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The geothermal project staff are thanked for their genuine co-operation and particularly the project Geologists deserve gratitude for their co-operation during the preparation of geological logs of the deep wells and for their valuable discussions.

W/t Ejigayehu Mamo and W/o Amelework G/Medhin are acknowledged for typing the report.
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14 Befekadu Oluma, Abiy Hunegnaw and Daniel Ayana-Langano-Aluto geophysical geoelectrical exploration III, Unpublished project report, ETH/78/007 October 1983
Fig 1. Location map of the Ethiopian Rift valley and Geothermal areas.
FIG. 2 Geology sketch map of the southern Ethiopian rift valley modified from DI poola (1972).
Fig 3 Lithostratigraphy, distribution of hydrothermal minerals, intensity of hydrothermal alteration, deduced pre-completion permeability and VES interpretation of LA-1.

Symbols & abbreviations for FIG-1 & FIG-2:
- Sediments interbeded with pyroclastics
- A-A Younger silicic tuffs and breccias
- 777 Kuchenai rhyolite
- 11111 Wenshe danto basalt
- Older lake sediments
- Older silicic tuffs and breccias
- Bofa basalt
- Igneinbrite
- Undifferentiated basic lavas
- Low
- Moderate
- High
- Differentiation

Abbreviations:
- Ab-abrite
- Ad-adaloria
- Ch-chlorite
- Cl-clays
- Co-clintonite
- Ca-cristabolite
- Cl-calcite
- Cz-clinozoisite
- Dc-dolomite
- Ep-epidote
- G-garnet
- He-heulandite
- Hm-hematite
- Total depth 1311.6m
- Cellar top coord E74047 N53808.

Geology from Solomon Kebede
Fig. 4. Lithostratigraphy, distribution of hydrothermal alteration minerals, intensity of hydrothermal alteration, deduced pre-completion permeability and VES interpretation of LA-2.

Symbols & abbreviations for FIG.1 & FIG.2:
- O O O: Sediments interbedded with pyroclastics
- R R R: Bola basalt
- △ △ △: Aluto rhyolite lavas
- △ + △: Younger silicic tuffs and breccias
- △△: Older lake sediments
- △△△: Older silicic tuffs and breccias

Geology from Solomon Kebede

ABBREVIATIONS:
- Ab: albite
- Ad: adularia
- Ch: chlorite
- Cr: clays
- Lx: leucoxene
- Py: pyrite
- Cp: clinoptilite
- Cr: cristobalite
- Cz: calcite
- Do: dolomite
- Ep: epidote
- Fr: feldspar
- He: hematite
- Sm: smectite
- Id: iddingsite
- Ze: zeolite
- Sph: sphene
- Chab: chabazite
- Trid: tridymite
- Qtz: quartz
- Heu: heulandite
- Heu: heulandite
- Low: Low
- Moderate: Moderate
- High: High
- Total depth: 1596.3m
- Elevation: 1724.02m
- Cellar top coord E69949; N61501
Fig. 5 Lithostratigraphy, distribution of hydrothermal minerals, intensity of hydrothermal alteration, VES interpretation and measured temperature of LA-3.

SYMBOLS

- Pumice, ash, breccia, obsidians
- Ailto rhyolite
- Tuff, ash flow weakly welded
- Lake sediments
- Basalt
- Tertiary ignimbrite
- Rhyolite lava

ABBRIVATIONS

- SiO₂: Chalcedony, epidote, crysotoblite
- Ab: Albite
- Ad: Adularia
- Co: Calcite
- Do: Dolomite
- Ch: Chlorine
- IMa: Ilite, montmorillonite

Geology from Molla Belaineh

T = 15
10/7/85 Date after 9 days of heating

Intensity of Alteration:

- None
- Low
- Moderate
- High

Depth (m):

- 0
- 300
- 600
- 900
- 1200
- 1500
- 1800
- 2100
Lithostratigraphy, distribution of hydrothermal minerals, and VES interpretation of LA-5

FIG. 7

LEGEND


C, Calcite; CH, Chlorite, Q, Quartz; Cl, Clay; A, Andalusite; E, Epidote; Al, Albite; Fe, Iron oxide; S, Sulphide.

Geology from Solomon Kebede
Fig. 8. Lithostratigraphy, distribution of hydrothermal minerals, intensity of hydrothermal alteration, VES interpretation. B: complete loss zones of drilling fluid of LA-6.

Key to symbols and abbreviations for Fig 5

SYMBOLS

Recent Alato pyroclastics

Upper pleistocene - recent Alato rhyolite lavas and interbedding pyroclastics

Late pleistocene silicic tuffs and breccias

Pleistocene lake sediments

Pleistocene volcanic ash

Pliocene - Pleistocene basalts

Miocene - Pliocene ignimbrite

ABBREVIATIONS

Major

Minor

Trace

None

Low

Moderate

High

Trace by

Complete loss zones of the drilling fluid Ametaneg Hale

Geology from Solomon Kebade

After 36 days of heating
Fig. 9: Lithostratigraphy, distribution of hydrothermal minerals, intensity of hydrothermal minerals, intensity of hydrothermal alteration, VES interpretation and measured temperature of LA-7.

Geology from Tsegaye Abebe.

**SYMBOLES**

1. Abundance of alteration minerals
   - Trace
   - Low
   - Medium
   - High

2. Lithologic units
   - Pumiceous breccia
   - Crystalline rhyolite and obsidian
   - Lithic/crystal tuff and ashes
   - Lithic breccia, basic/acidic
   - Wensho darget basalt
   - Sediments
   - Bafa basalt
   - Crystalline ignimbrite
LEGEND

@ Hot Spring
@ Deep exploratory well
@ Fumarole
=== Motorable road

Langano Geothermal Field

FIG. 11 Dipole-dipole resistivity map for N=3
Langano Aluto Geothermal Field

Fig 14: Schumacher apparent resistivity map for \( AB = 500 \text{ m} \)

- Fumaroles
- Hot springs
- Deep Exploration well
- Borehole and traverse stations
- 1000m – Topographic contour (m)
- 10 - Resistivity contour (in ohm-m)
LEGEND

* Reference point

~1600~ Topographic contour (m)

100 Self potential contour (mv)

Region with negative self potential

* Observation point

○ Deep exploratory well in order

→ Hot spring

* Fumarole

Fig. 16. Self potential anomaly (mv) map of Aluto-Langano Geothermal field.
Fig 19: PROFILE 3N

Geothermal Exploration Project
(Emerald Lakes District Field)
Langano Geothermal Field
Geophysical Exploration
Profile 3N
Combined Geologist & Geologist
Orientation of 3D was made approximately II
to the inferred Benuna fault (N20°E)

Traced By: Tseming Bogale
3/19/94
Geothermal Exploration Project
(Ethiopian Lakes District Rift)
Langano Geothermal Field
Geophysical Exploration
Profile 3N2

Combined field on profiling
Orientation of CO was made approximately 110°
the inferred E Basuma fault (N20°E)

Fig. 19a Profile 3N2
[1 km north of profile 3N and parallel to it]
Combined head on profiling

FIG 20 Profile 41

Geothermal Exploration Project
(Anchorage Lakes District Rift)
Lakana Geothermal Field
Geophysical Exploration

Station (Km)
Geothermal Exploration Project
(Ethiopian Lakes District Rift)
Langano Geothermal Field
Geophysical Exploration

Combined head on profiling

Fig 21 Profile 42
Geothermal Exploration Project
(Ethiopian Lakes District Rift)
Langano Geothermal Field

Combined head on profiling

Fig 21a
Fig. 23

TEMPERATURE SURVEY

Gite'Boile Graben

LEGEND

20 Temperature reading in °C

Not signifies

Contour interval = 10°C

Drill hole size

Scale 1:150,000

After Berhenu Melaku et al.
August 1974

NORTHERN BAY OF
LAKE LANGANO

GERBER ISLAND
Fig 25 Change of temperature with depth for (TG-11 to TG-29 and TG-36)

Aluto-Langano Geothermal Field.
Fig 26  Temperature Distribution of Aliu Geothermal field.
Geothermal Exploration Project
(Ethiopian Lakes District Rift)
Langano Geothermal Field
Geophysical Exploration

Fig 27 Temperature Distribution
Fig 28 Bouguer anomaly profile across the central main Ethiopian rift

--- Observed gravity across the southern foot of Aluto volcano (E-W)
Fig 29: Regional Bouguer anomaly map of central meta-Ethiopian rift.
Fig 31  Basement complex surface isohypsals (after Dainelli, 1943)