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A REVIEW OF GEOLOGICAL AND GEOPHYSICAL EXPLORATION OF CORBETTI GEOTHERMAL PROSPECT, ETHIOPIA

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ABSTRACT

Corbetti geothermal prospect is in the main Ethiopian rift with extensive surface thermal manifestations. Hydrothermal activity took place in a setting of alternating hydrological changes, denudation, sedimentations and periodic volcanism within the caldera floor. Hydrothermal features are controlled by volcanological and tectonic structures such as caldera rim fractures, fissures, faults and eruption centers. The main surface alteration minerals are clays.

Caldera and post caldera lavas are peralkaline rhyolite (pantelleritic rhyolite) as confirmed by petrochemistry. There is a change in chemistry between post caldera and caldera rocks. The movement of sub-surface hot geothermal fluid is from Corbetti caldera to Lake Shalla which is supported by local hydrological gradient and electrical resistivity results where an elongated low resistivity structure along the Wonji fault belt is opening to Lake Shalla from the caldera. The low resistivity anomaly is associated with northern caldera rim structure and craters. The eastern component is related to inferred caldera rim and E-W fissures with hydrothermal features. Southern half of the caldera is characterized by high resistivity property that may not mean the absence of geothermal reservoir underneath but could be the effect of topography, coupling effect and inhomogeneity of the caldera complex.

Two dimensional denser intrusive body is assumed due to the presence of >10 mgals that could not be compensated by topographic effect between Lake Shalla and Lake Awassa.

The inferred caldera rim is supported by the Bouguer anomaly map of the prospect area and geological evidence.

INTRODUCTION

Corbetti geothermal prospect is located in the central part of the main Ethiopian Rift (lakes district rift Fig. 1) which is part of the African Rift System that is a major tectonic structure resulted from diverging lithospheric plate movements during Tertiary times. Structurally this system is a broader graben trending in a NNE - SSW direction. Most of the system is characterized by recent tectonic, volcanic and hydrothermal activities.

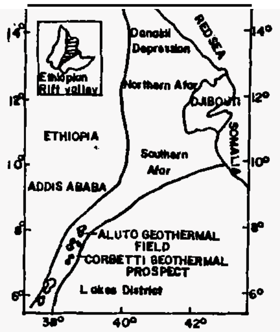


Fig.1 Location map of the Ethiopian rift valley and geothermal areas.

Corbetti caldera is covered by Quaternary pantelleritic volcanics (rhyolites and basalts) and recent sediments. The petrogenesis of these peralkaline rhyolites is inferred to be the crystal fractionation of parent basic magma.

Based on geothermal considerations for power production, Corbetti caldera (Fig.2) is a promising geothermal prospect

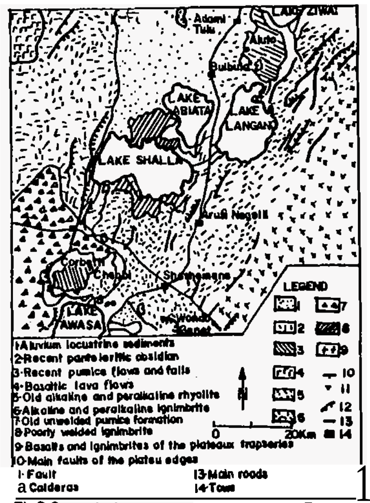


Fig2 Geological sketch map of the southern Ethiopian rift valley modified from Di Paola (1972)

Corbetti caldera is resulted from the eruption of large amount of peralkaline rhyolite, ignimbrite and pumice that produced regional colapse during Quaternary times. The caldera is elliptical in shape and the diameter is about 10 km. N-S and 18 km. E-W. The rim of the caldera has a variable height, it is less than 80m in the north and about 200m of the west.

The area is covered by extensive lake sediments and Quaternary volcanics such as Quaternary rhyolites and pyroclastics including pumice, ignimbrite and ash. Besides these recent obsidian lava flows, hyaloclastite and recent fissural basaltic eruptions also occur. In general the geology of the area comprises both basic and silicic products, the basics are basalts and hyaloclastites probably direct product of the mantle. The silicics are results of crystal fractionation from basic magma, based upon petrochemistry data.

The prospect area has been under exploration since 1970 with the following work conducted.

(a) Detailed geological mapping, XRD analysis of surface hydrothermal minerals.

(b) Petrography and Petrochemistry.

(c) Geochemical investigation

(d) Geophysical surveys, mainly:
  i) Dipole - dipole resistivity
  ii) Schlumberger electrical resistivity traversing and sounding.
  iii) Gravity

STRUCTIRAL GEOLOGY

The dominant structures visible on the surface are the NNE trending Wonji fault belt faults such as Corbetti - Shalla sector (Fig.4), and the associated Wonji group volcanism such as basaltic and peralkaline rhyolite centres. The two clearly visible important faults outside the caldera are Fende and Weransa faults. Fende fault trends NNE from Aje area towards south-west of Shalla (Fig. 4) and Weransa fault trends NW-SE and downthrown about 160m near Cheleleka and dies out just at the main road (Shashamene-Awassa road).

Both Chebbi and Urji volcanoes, are controlled by E-W and N-S structures (faults). Besides these, other structures are fissures trending in an East-West direction. Dykes and joints are associated with caldera rim. Cross structures are also evident on Urji volcano (Fig. 3). Most volcanological structures and features are associated with hydrothermal manifestations.

Volcanological structures such as eruption centres, craters and caldera are easly visible in the area. The Corbetti caldera rim is manteled by recent lava towards the eastern side. However, it is traced by using the following evidence from field and laboratory studies.

Evidence from Field Observations

1. Most volcanological features, such as eruption centres, faults, craters and cones are possibly associated with caldera rim fractures (Fig.3).

2. Hydrothermal manifestations are reference for the inferred caldera rim. The hydrothermal features follow mostly circular (elliptical) patterns as one expects the growth to be controlled by the inner of the caldera rim fractures.

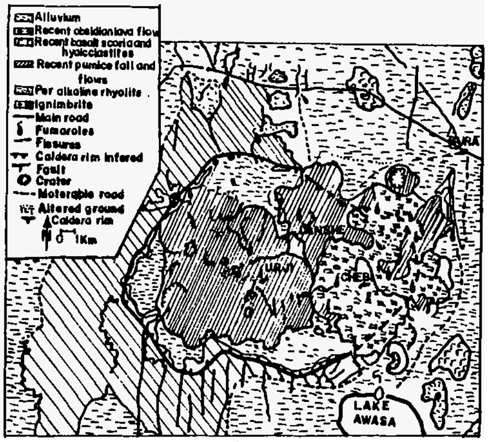


Fig.3 Geological sketch map of Corbetti Geothermal prospect

3. Lithological similarity

4. Morphological expression (evidence of visible caldera structures).

Evidence from petrography and chemical analysis of rocks.

Surface Alteration: Mineralogy

This section summarizes the result of surface hydrothermal mineralogy of selected clay fractions and non-oriented powder specimens collected from several places of Corbetti area. The result of reconnaissance work reflects five types of alterations:

  i) Kaoline type
  ii) Montmorillonite (smectite)
  iii) Sinters and silica
  iv) Weak clay and
  v) Interstratified minerals.

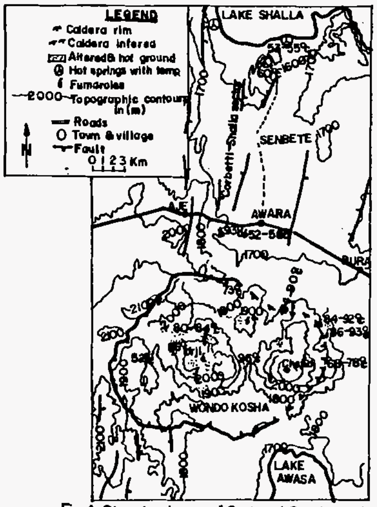


Fig.4 Structural map of Corbetti Geothermal prospect and location of thermal features with temprature(°c)

i) Kaolin type (acid water): This type of alteration is mostly associated with hot and steaming ground. Most of the rocks are altered to halloysite (meta-halloysite formed by alteration of vitric pyroclastics) disseminated hematite possibly of hydrothermal origin, secondary quartz and ± K - feldspar assemblages. Example of hydrothermal reactions which can produce the above mineral assemblage:-

$2Fe_3O_4 + 1/2O_2 = 3Fe_2O_3$ Oxidation
Magnetite Hematite

H_4SiO_4 (aq) $= SiO_2 + H_2O$ **Silicification**
Secondary Quartz

Kaolin type of alteration is characteristic of shallow zone acid sulphate steam condensate in which H_2S, boiled from deeper chloride water has been oxidised to H_2SO_4. Furthermore, Oxidation of H_2S in near surface environment produces acid water which reacts rapidly with host rock to give argilic alteration assemblage like kaolinite. Acid water can be derived also by condensation of volcanic gases in meteoric water.

Argillic alterations derived from acid water and rock interaction are important for exploration as they can occur directly on the margins or areas of upflow of geothermal field.

ii) Montmorillonite (smectite) Type: This type of alteration encountered out side Corbetti caldera. The presence of montmorillonite implies the altering fluid was probably less acidic.

iii) Sinters and Silica:

a) Sinters: The sinters are related to the past hydrology and hydrothermal activity. Sinter chips are widely distributed in most places of thermal features and are very useful in interpreting past hydrothermal environments. In general sinters are drived from near neutral alkali-chloride water and they are resistant to weathering.

b) Silica: (secondary quartz): This is the result of present activity which can be related to strongly acid conditions. Silica is closely associated with fumaroles in most places. The possible origin can be due to silicification, $H_4SiO_4\ (g) = SiO_2 + H_2O$ (Ellis 1977). In most places pumice is cemented by silica and the vesicles and cavities are filled with silica which causes rock porosity to decrease and their hardness to increase with increased silicification.

iv) Weak clay (partly altered) this is low rank alteration.

v) Interstratified minerals: Their mode of occurrence is generally very complex. The mode of occurrence of surface interstratified minerals at Corbetti caldera area is probably due to the following reasons.

i) Surfacial condition or weathering and rain effect (PH=8),

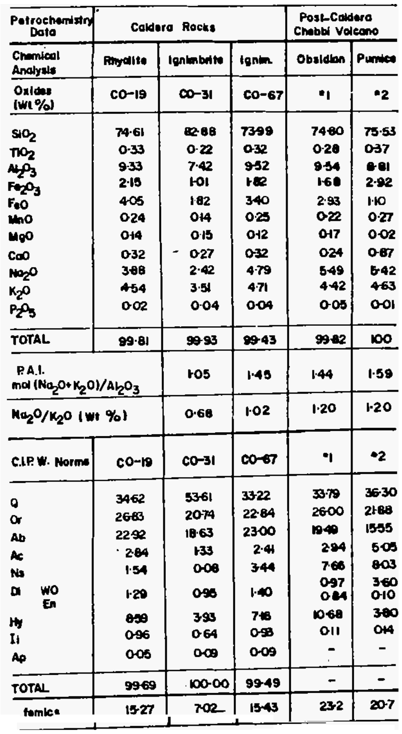
ii) Nature of soil (high alkaline tropical soil), iii) Nature of rock (peralkaline rocks). iv) The past hydrology and hydrothermal activity to some extent.

Petrochemistry of Peralkaline Rocks

The main objectives of the chemical analyses are (i) to classify the lavas (ii) to compare and contrast changes in chemistry between post and caldera lavas (iii) to help (prove) the existence of the proposed caldera rim (iv) to provide chemical data for future work, that is to characterize the present fresh (unaltered caldera lavas) rocks with altered subsurface (drilled) rocks, that may be recovered in the future and/or to compare the chemical changes caused by hydrothermal fluid rock interaction in particular.

Peralkaline rocks have a molecular excess of (Na_2O) over Al_2O_3 and defined by the presence of normative AC (acmite). Furthermore, the most obvious indication of peralkalinity is the presence of certain index minerals or alkali minerals of which alkali - pyroxene, alkali-amphiboles and aenigmatite (cossyrite) are the most common. Most of these minerals are found in all Corbetti specimens.

Petrographically the caldera rocks are characterized by phenocrystic sanidine, anorthoclase acmite, fayalite, aegirine ± aenigmatite. This minerals association is typical of peralkaline rocks and all chemical analysis of lavas confirm that they are sodic and peralkaline.



Petrochemistry Data	Caldera Rocks			Post-Caldera Chebbi Volcano	
Chemical Analysis	Rhyolite	Ignimbrite	Ignim.	Obsidian	Pumice
Oxides (Wt %)	CO-19	CO-31	CO-67	*1	*2
SiO_2	74·61	82·88	73·99	74·60	75·53
TiO_2	0·33	0·22	0·32	0·28	0·37
Al_2O_3	9·33	7·42	9·52	9·54	8·81
Fe_2O_3	2·15	1·01	1·82	1·68	2·92
FeO	4·05	1·82	3·40	2·93	1·10
MnO	0·24	0·14	0·25	0·22	0·27
MgO	0·14	0·15	0·12	0·17	0·02
CaO	0·32	0·27	0·32	0·24	0·87
Na_2O	3·88	2·42	4·79	5·49	5·42
K_2O	4·54	3·51	4·71	4·42	4·63
P_2O_5	0·02	0·04	0·04	0·05	0·01
TOTAL	99·81	99·93	99·43	99·82	100
P.A.I. mol $(Na_2O+K_2O)/Al_2O_3$		1·05	1·45	1·44	1·59
Na_2O/K_2O (Wt %)		0·68	1·02	1·20	1·20
C.I.P.W. Norms	CO-19	CO-31	CO-67	*1	*2
Q	34·62	53·61	33·22	33·79	36·30
Or	26·83	20·74	22·84	26·00	21·88
Ab	22·92	18·63	23·00	19·49	15·55
Ac	2·84	1·33	2·41	2·94	5·05
Ns	1·54	0·08	3·44	7·66	8·03
Di WO	1·29	0·96	1·40	0·97	3·60
En				0·84	0·10
Hy	8·59	3·93	7·18	10·68	3·80
Il	0·96	0·64	0·93	0·11	0·14
Ap	0·05	0·09	0·09	-	-
TOTAL	99·69	100·00	99·49	-	-
femics	15·27	7·02	15·43	23·2	20·7

Toblel. Chemical analysis and Norms of peralkaline rhyolites from Corbetti Caldera area.

Based on the chemical data, Corbetti caldera area silicic rocks are peralkaline rhyolite (pantellerites) as confirmed by the new classification scheme (Fig. 6). The glassy nature of the post caldera lavas (obsidian and pumice) are a result of some factors such as the water content of the magma, an accident of eruptive process or physical and chemical properties of the magma.

The results obtained from the chemical analysis of caldera rocks, support the infered caldera rim, Both post and caldera rocks are peralkaline rhyolite (pantellerites) as said earlier, but there is a change in chemistry between post and caldera lavas. It was shown that: (a) There is evidence of increasing Na_2O and depletion of Al_2O_3 as seen in young lavas (post caldera rock Table 1) & Fig.5. (b) There is evidence of increasing sum of normative femics (table 1) possibly due to increasing crystal fraction as suggested by Ewart etal (1968) for case (a) and (b). Generally the post caldera lavas exhibit an enrichment particularly in some elements such as sodium. This indicates at least a change in type of compostion of the chemical phase responsible for fractionation process.

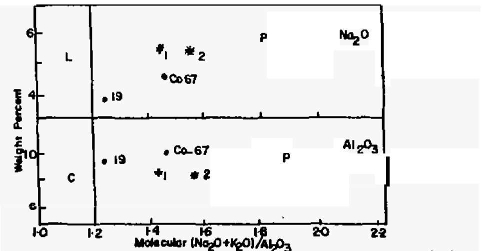


Fig5 Variation diagrams for Na_2O & Al_2O_3 weight percent versus agpaic index (A·I) The boundary line is arbitrary and plotted according to the data colleted by Macdonald and Bailey (1973) from different peralkaline provinces for comendite (C) and pantellerite (P)

* Refers post caldera lavas
• Refers caldera rocks

As shown on variation diagram (Fig. 5) the observed enrichment of sodium in the youngest lavas of chebbi can only occur during fractionation though quartz and alkali feldspar separate from the magma (Ewart etal 1968).

Based on the present chemical data the lavas can be correlated with Macdonald (1974) and Ewart etal (1968) views. Crystal fractionation of alkali basaltic magma was possibly the dominant genetic process in the production of peralkaline rhyolite (pantellerites) of Corbetti areas.

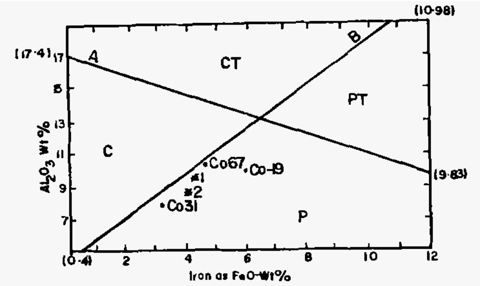


Fig.6 New classification scheme for peralkaline, quartz normative extrusive rocks based on Al_2O_3 and iron as FeO contents. The boudary line drawn to separate trachites from rhyolite (A) and comendite from pantelleritic rocks (B) symbols refer to rock names, C=Comendite; CT=comendite trachytes; P=pantellerites and PT=pantelleritic trachytes, from Macdonald (1974)

Geophysics

The geophysical methods applied were:

- Dipole-dipole resistivity survey (1972-1979)
- Schlumberger traversing ($AB/_2$ =500m and 1000m) and soundings of larger separation (max $AB/_2$ =3160m).
- Gravity

Instrument used for Electrical Methods

Motor Generator supplied by geotronics which consisted of a commercial VW engine that drives a 30 KVA 3-phase, 125 Volt 400 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 10 Meg ohms.
  From 1983 on wards.

Scintrex

2.5 KW and 15 KW transmitter
IPR-10 and IPR-10A receivers
f = 0.125 HZ
Pulse: +On, Off,-On, Off each 2 seconds.

Schlumberger traversing and soundings were done between 1972-1979 in the first phase along with the dipole-dipole survey on the flat land between Corbetti caldera and Lake Shalla.

The second phase waspurely sounding work within and around the peripheries of Corbetti caldera with the gravity survey in the prospect area.

The third phase continued from 1984 to 1985 which covered the caldera with additional gravity work.

Dipole-dipole survey was done with a = 500m and n= 1 to 6. The work was mainly on the flat area between Corbetti caldera and Lake Shalla. Maps produced for n=3 and n=5 defined a low resistivity zone extending from Corbetti caldera to Lake Shalla.

Results of schlumberger electrical soundings are presented as pseudo resistivity maps for $AB/_2$ = 1000m, $AB/_2$ = 2150m and the lowest interpreted resistivity soundings vs corresponding elevations at which they first occur.

All of these maps show similar. trends of resistivity structure.

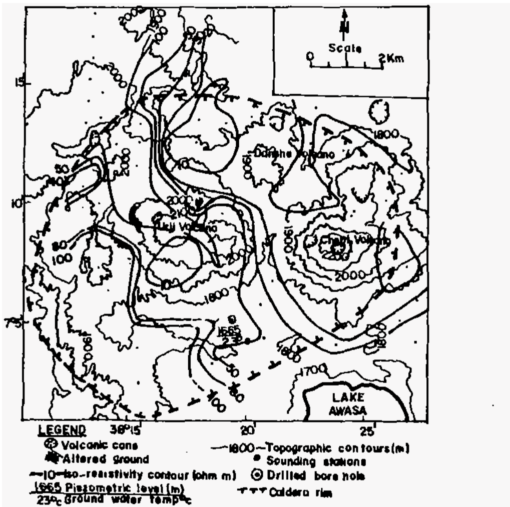


Fig 7 Schlumberger apparent resistivity (Ω-m) map for AB/2=1000m

Three closures of 10 ohm-m resistivity zones are revealed for AB/ = 1000m (Fig.7) north and south of Urji an8 east of Chebbi. The ones south of Urji and east of Chebbi show local topographic effects where small shallow components of hot fluid in the respective directions are different from the general outflow trend (from south to north) of the area. These anomalies are with a better picture for $AB/_2$ = 2150m (Fig.8) where resistivity contours from 50 ohm-m in the south of 10 ohm-m in the north are revealed showing a sequential resistivity anomaly value decrease from south to north.

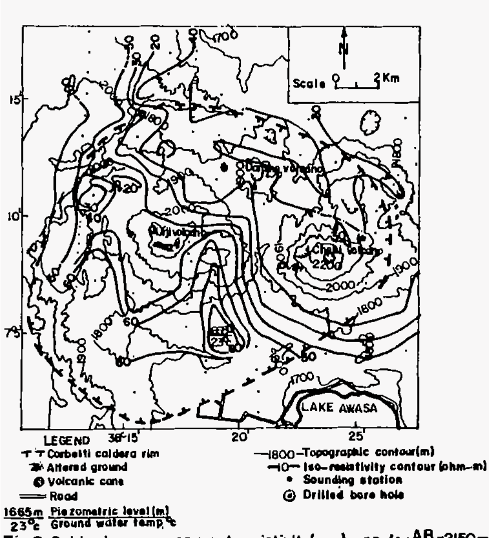


Fig.8 Schlumberger apparent resistivity(Ω.m) map for $\frac{AB}{2}$=2150m

Similar picture is shown by the interpreted resistivity map (Fig. 9). The flow of geothermal fluid from Corbetti caldera to Shalla (25 km) is shown by two wells on oppsite sides of the caldera (Figs. 7-9) with different piezometric levels and tempratures which indicate higher ground water temperature and deeper water table in the north and shallow ground water table and ambient ground water temperature in the south.

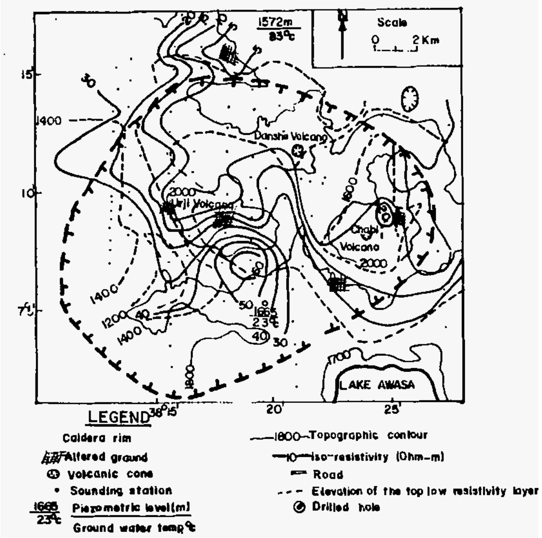


Fig.9 Map of lowest interpreted resistivity(Ohm) sounding Vs its corresponding elevation(m) of which it 1st occurs

Lake Awassa is also at a higher elevation (1680m.a.s.l.) than Lake Shalla (1570 metres) that shows the local hydrological situation such that the gound water flow is from south to north and the presence of hot springs on the southern shores of Lake Chitu and Lake Shalla could mean a contribution from Corbetti caldera to the Shalla system of the hot fluid, and absence of the thermal features south of Corbetti caldera is'a clue to predict the hot water migration from the caldera to Lake Shalla.

Gravity Survey

The work was started in March 1983 with Lacoste and Romberg G 303 gravity meter and 346 stations were occupied in an area of 1440 km². The instrument has a reading accuracy of 0.01 mgals and negligible drift.

Absolute Bouguer map of the area is produced (Fig. 11) and shows the following features.

(a) Local positive anomaly to north of the caldera associated with Wonji faultbelt;

(b) Negative local anomalies on Chebi and Urji volcanoes as reflections of topographic contours; regardless of the topographic expression the general Corbetti caldera is within a positive gravity anomaly;

(c) A Graben structure seems to extend to the caldera from the south west as a thick infill of alluvial and lake sediments.

(d) An outline of the caldera rim is traced along sharp gradients of the anomaly.

Two profiles 1 and 3 were made to cross the west and east rift margins to be able to construct a reliable regional field. The data coverage is small; however, including Gouins profiles (A,B, and C) Fig.10 the mean surface of the regional field was constructed using a polynomial fit method based on linear interpolation of the field on profile 1 and transferred to other profiles.

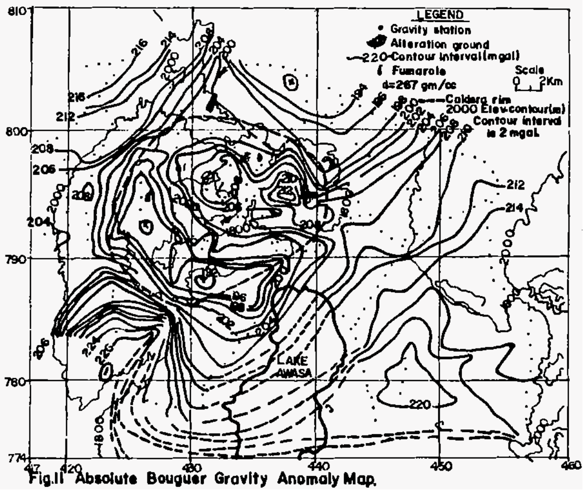


Fig.11 Absolute Bouguer Gravity Anomaly Map.

A large negative wave length about-260 mgals (Fig. 13) is related to the upcoming of lithosphere-asthenosphere boundary that can induce partial melt (Girdler and Sowerbutts 1970).

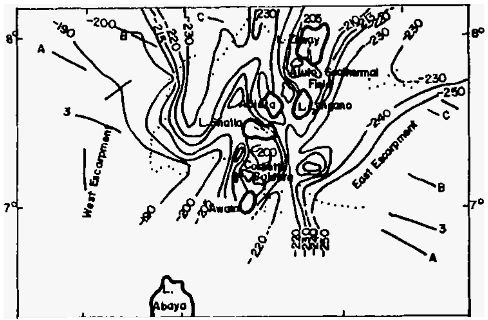


Fig.10 Regional Bouguer anomaly map of central main Ethiopian

Positive wave length (>100km) is observed in the rift with an amplitude of 50 mgals considering -260 mgals as a datum line. It is named as a crustal anomaly (Fig. 13) and related to upper mantle pluming (Griffiths etal 1970). The values are apparent since it totally depends on the reliability of the regional field.

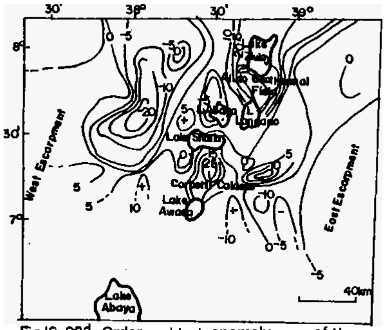


Fig.12 2nd Order residual anomaly map of the main central Ethiopian rift.

Different order of anomalies were separated by reducing the effect of the regional field and crustal anomaly.

Local positive and negative anomalies are observed in the 2nd order residual map (Fig. 12) accumulation in the tectonic troughs (grabens). It is clearly shown by two gravity profiles, one across the flat area south of Shalla and north of Corbetti caldera (with long wave length) (Fig. 13). Corbetti caldera is in the gravity high with slight modifications by the products of Urji and Chebi volcanoes, silicic lava flows and pyroclastic deposits with additional continental deposits and alluvium within the caldera (Fig. 11).

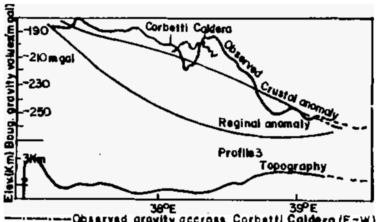


Fig.13 Bouguer anomaly profile accross the centml main Ethiopian rift.

A geological structure (graben) is assumed for the case of a local gravity low north of Corbetti caldera as a thick infill of lake sediments and alluvium. The positive anomaly is large and extends from Lake Shalla to Awassa and lies in association with the volcanoes and the Shalla sector of Wonji fault belt with common fissural silicic and basaltic lava flows which is the result of recent fragmentation of the rift floor close to the eastern rift margin.

Three postulates can be put forward regarding the local heat anomaly in relation to the intrusive body.

1. The intrusive mass is a heat source.
2. The large denser mass intrusion is at a greater depth and a melt is derived from this mass and emplaced at a shallow depth as a heat source.
3. The larger denser mass intrusion is cold and secondary intrusion occurs to the level of shallow depth.

Discussion and conclusion

The post caldera volcanoes Danshe, Urji and Chebbi are related to a series of highly explosive pantelleritic erruptions of volatile rich magma. At the end of the activity a degassed magma errupted to give the pantelleritic obsidian of Chebbi (Dipaola, 1972). The growth of Chebbi, Urji and Danshe volcanoes represent a post caldera activity.

Most of the surface alteration is controlled by volcanological and structural features. Based on surface alteration mineralogy it was possible to classify five surface alteration types. Furthermore, the result of surface mineralogy helps to develop the preliminary model of the geological history of the area.

Corbetti geothermal prospect was characterized by periodic volcanism and two stages of hydrothermal activity. The early activity was near neutral fluid under shallow water table that deposited silica sinters. The 2nd event is the present acidic fluid alteration resulting in the extensive argillic alteration and fumarolic activity. Regional hydraulic gradient, topography and water table changes greatly influenced the type and characteristic of thermal fluid.

The petrochemistry of peralkaline rhyolite lavas help interpret the inferred caldera model and provided an opportunity to describe the petrogenesis of the lavas. There is a slight change in chemistry between post and caldera pantelleritic rhyolitic lavas. Crystal fractionation of alkali-olivine basalt is possibly the dominant genetic process in the production of pantellerites of Corbetti caldera lavas such as ignimbrite, rhyolite, pumic etc.

The alkaline basalts are controlled by Wonji fault belt (NNE trend) and are direct products from the mantle.

As an output of the work in this paper it is worthnoting the following points:-

1. Petrogenesis of the peralkaline rhyolites are results of crystal fractionation of alkaline olivine basalts.

2. The dominant alteration product of peralkaline rhyolites is clay which serves as a caprock.

3. Morphologically the recharge for the system is from east and west rift shoulders.

4. Most thermal manifestations are structurally controlled.

5. The high resistivity anomalies on the volcanoes Chebbi and Urji do not preclude the possibility of the existence of reservoir under them, but rather due to topographic influence i.e. boundary of the field is not determined on the southern side.

6. The electrical resistivity work results showed the movement of the geothermal fluid (hot) from Corbetti caldera to Lake Shalla.

7. Existence of an intrusive body under the caldera is assumed.

The electrical resistivity work result has to be supported by measurements of temperature gradients in TG wells that have to be drilled in and around the caldera on selected sites.

From shallow hydrological point of view and results of resistivity surveys of Corbetti geothermal prospect and Aluto-Langano geothermal field, Shalla caldera appears to be a sink; i.e. hot geothermal fluids flow subsurface to Lake Shalla from Corbetti caldera and Aluto-Langano geothermal field. Shalla caldera is also most likely a separate geothermal system from volcanological aspect and needs further scientific investigations.

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